COOPERANT

Deliverable 1.4

Relevance and challenges of CPS-TES and KPI benchmarking at the EU and global level

WP1- Project Management and Coordination

Version 1.0

COOPERANT Key Facts

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COOPERANT Consortium Partners

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

This deliverable aims to evaluate the potential impact of COOPERANT outcomes by compiling and benchmarking a set of Key Performance Indicators (KPIs) that are consistent with the objectives of the European Strategic Energy Technology (SET) Plan for Concentrated Solar Power (CSP).

CSP combined with Thermal Energy Storage (CSP-TES) is recognised as a critical technology for Europe's clean energy transition, enabling dispatchable renewable electricity and providing flexibility to balance the variability of solar PV and wind. Nevertheless, CSP-TES still faces important barriers to wider deployment. Key challenges include improving efficiency and durability at high operating temperatures, achieving competitive cost levels relative to alternative renewable energy sources, and addressing sustainability issues such as material demand, environmental impact, and socio-economic value creation. To address these aspects, this deliverable establishes a benchmarking framework that covers four main categories of indicators: technical (e.g., Solar Multiple, TES hours, thermal efficiency, reliability), economic (e.g., Levelized Cost of Energy, CAPEX/OPEX, cost of storage), environmental (e.g., GHG emissions, water use, resource consumption, circularity), and socio-economic (e.g., job creation, industrial competitiveness, public acceptance). These categories provide a comprehensive baseline against which COOPERANT's development can be measured.

The benchmarking analysis confirms that CSP-TES technologies show strong potential for dispatchability and decarbonisation. Yet, costs remain above those of competing options, while long-term reliability, scalability, and environmental aspects still require improvement. In Europe, progress is broadly aligned with SET Plan objectives, but deployment is slowed by limited support frameworks, leaving the region behind global frontrunners such as China, Morocco, and the United Arab Emirates, where large CSP-TES projects provide valuable lessons on cost reduction and industrial scale-up.

COOPERANT's hybrid TES approach, which combines sensible and latent storage to achieve high energy density and stable high-temperature operation, represents a promising pathway to address these challenges. The deliverable concludes that such innovations, when combined with supportive policy frameworks and dedicated financing instruments, can enable CSP-TES to strengthen its role in the European energy system and industrial decarbonisation. Deliverable 1.4 thus provides both a methodological reference for assessing COOPERANT's progress in upcoming packages and a contribution to broader discussions with policymakers and stakeholders on the strategic role of CSP-TES in achieving Europe's climate and energy goals.

Table of Contents

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List of Figures

List of Tables

List of Acronyms

Acronym	Full Form
AM	Additive Manufacturing
CAPEX	Capital Expenditures
CC	Capital Costs
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CO_2	Carbon Dioxide
COOPERANT	Leading-edge cooperative advances towards the next generation of concentrated solar power (CSP) technology
CSP-TES	Concentrated Solar Power with Thermal Energy Storage
CRM	Critical Raw Materials
CSP	Concentrated Solar Power
DEC	Dissemination, Exploitation, Communication
DSO	Distribution System Operator
ENGI	Engicer SA
ES	Spain
FOAK	First of a Kind
GA	Grant Agreement
HORIZON-RIA	Horizon Europe Research and Innovation Action Programme
HOLOSS	Holistic and Ontological Solutions for Sustainability, LDA
HSLU	Fachhochschule Zentralschweiz Hochschule Luzern
IDE	Idener Research & Development Agrupación de Interés Económico
IWG	Implementation Working Group
IWG CSTT	Implementation Working Group for Concentrated Solar Thermal Technologies
KB	Kraftblock GmbH
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCOS	Levelized Cost of Storage
LCOE	Levelized Cost of Energy
MCI	Material Circularity Indicator
NPV	Net Present Value
O&M	Operation & Maintenance
OPEX	Operational Expenditures
OVR	Open Volumetric Receiver
PCM	Phase Change Material

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PCMP	Phase Change Material Products Ltd
PT	Portugal
PV	Photovoltaic
R&I	Research & Innovation
SET Plan	European Strategic Energy Technology Plan
SEN	Sensitive (dissemination level)
SM	Solar Multiple
SO	Specific Objective
SROI	Social Return on Investment
SRB	Stakeholder Replicability Board
s-LCA	Social Life Cycle Assessment
SERI	Swiss State Secretariat for Education, Research and Innovation
SSbD	Safe and Sustainable by Design
STE	Solar Thermal Electricity
TES	Thermal Energy Storage
TRL	Technology Readiness Level
TSO	Transmission System Operator
UK	United Kingdom
WP	Work Package

1 Introduction

1.1 Purpose of the document

The purpose of Deliverable 1.4 is to establish a comprehensive benchmarking of CSP-TES technologies at both the European and global levels. This deliverable is part of WP1, specifically Task 1.3.2, and its objective, as set out in the COOPERANT proposal, is to evaluate the impact of COOPERANT outcomes by compiling and benchmarking KPIs aligned with the SET Plan targets for CSP. The task is led by HSLU with contributions from all partners.

The document's scope is to provide a structured analysis of the relevance of CSP-TES, technological challenges, performance indicator definitions, and comparative benchmarking that places European developments in the global context. As a result, the deliverable acts as a benchmark for measuring progress within COOPERANT and ensuring that innovations are consistently aligned with European strategic objectives.

The document is structured into several sections:

- **Section 2 – Relevance of CSP-TES**: Contextualises the importance of CSP-TES within the EU energy transition and at the global level.
- **Section 3 – Challenges of CSP-TES**: Identifies barriers to wider deployment, including technical, economic, environmental, and socio-economic issues.
- **Section 4 – KPI Benchmarking Framework**: Defines the technical, economic, environmental, and socio-economic KPIs considered.
- **Section 5 – EU and Global Benchmarking Analysis**: Provides comparative results and positions COOPERANT developments in the broader landscape.
- **Section 6 – Conclusions and Recommendations**: Summarises insights and provides strategic directions for COOPERANT and for CSP-TES deployment.

By guiding the reader from the broader context of CSP-TES relevance, through the identification of challenges, the definition of performance metrics, and the comparative analysis of results, Deliverable 1.4 ensures that the COOPERANT project is anchored within the global CSP-TES landscape. It also provides a practical tool for measuring progress, informing project decisions, and strengthening the project's contribution to European and international energy objectives.

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2 Objectives

The goal of Deliverable 1.4 is to evaluate the impact of COOPERANT outcomes by compiling and benchmarking Key Performance Indicators (KPIs) that are aligned with the European SET Plan targets for Concentrated Solar Power (CSP). This benchmark document provides a structured assessment of all the technical, economic, environmental, and socio-economic dimensions of CSP-TES systems, ensuring that the innovations developed in COOPERANT can be measured against both European policy objectives and international references.

The scope of the deliverable covers three main areas:

1. **Relevance of CSP-TES at the EU and global level**, establishing the policy and market context.
2. **Challenges for CSP-TES deployment**, identifying the technical, economic, and sustainability barriers that need to be addressed.
3. **Definition and application of a KPI benchmarking framework**, which serves as the methodological baseline for assessing COOPERANT developments and situating them within the broader CSP landscape.

Deliverable 1.4 is directly linked to the General Objectives (O) and Specific Objectives (SO) of COOPERANT as defined in Section 1 of the Grant Agreement:

Relation to Project Objectives

- **Obj#1 (Novel efficient CSP concepts) & Obj#2 (High-temperature TES materials and systems)**: D1.4 supports these objectives indirectly by defining the KPIs against which new materials, designs, and hybrid TES systems developed in WP2 and WP4 will be evaluated.
- **Obj#3 (Digital tools for optimisation and integration)**: D1.4 contributes directly by delivering KPI datasets that WP3 will use to validate and calibrate TES and CSP system models.
- **Obj#4 (Holistic sustainability assessment)**: D1.4 contributes directly through the identification and benchmarking of environmental and socio-economic KPIs, providing input for WP5 analyses.
- **Obj#5 (Replication and stakeholder engagement)**: D1.4 contributes indirectly, as its benchmarking results from the evidence base for dissemination and replicability actions in WP6, including the Stakeholder Replicability Board (MS8).

Relation to Specific Objectives (SO)

- **SO2.1 / SO2.2 (development of TES materials and hybrid system design):** Addressed indirectly, as the deliverable sets the evaluation metrics that will later measure progress on material performance and integration.
- **SO3.1 (benchmarking and KPI definition for hybrid TES performance):** Addressed directly, since this is the core scope of D1.4.
- **SO4.1 (validated models of TES and CSP components):** Addressed indirectly by providing KPI data and methodology to WP3.
- **SO5.1 (reduce environmental impact, ensure circularity):** Addressed directly through the identification of environmental and socio-economic KPIs.
- **SO6.1 (replicability and exploitation):** Addressed indirectly by providing reference benchmarks for WP6 exploitation and replicability activities.

3 Framework for KPI Benchmarking

3.1 Alignment with SET-Plan CSP Targets

COOPERANT is fully aligned with the revised European Strategic Energy Technology Plan (SET Plan), adopted by the European Commission on 20th October 2023. The revised SET Plan's governance structure operates through **15 specialised Implementation Working Groups (IWGs)**, each dedicated to advancing specific technology domains and collectively executing the 10 SET Plan key actions (Figure 1) for research and innovation that underpin Europe's energy technology transformation.

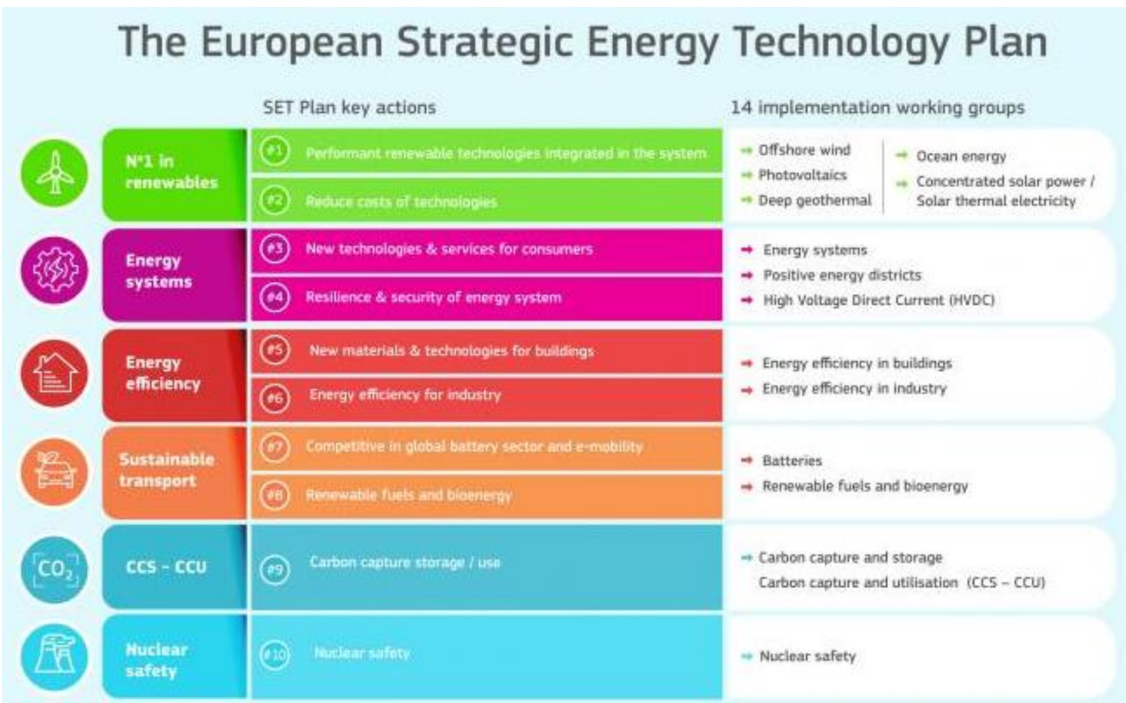

Figure 1. The 10 SET Plan Key Actions (extracted from SET Plan[1])

CSP technologies have their own IWM (**IWG CSTT**) established in 2016. It has been working with stakeholders, the European Commission, and the SET Plan countries to define ambitious CSP targets in its **2023 CSP Implementation Plan**, which aims to achieve two key actions: **i)** the integration of **high-performance** renewable technologies into the system, and **ii)** the **reduction of technology costs**.

This plan defines strategic objectives and specific targets for the **next generation of CSP technologies**. As outlined in Table 1, the goals include reducing **electricity production costs** to

[1] Strategic Energy Technology Plan (SET Plan) in Action (accessed September 2025)

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10 c€/kWh by 2030, lowering the cost of **thermal energy** (>200°C) **below 3c€/kWh**, and enabling the sustainable and cost-effective **24/7 production of green hydrogen and solar fuels**. These challenges highlight CSP's strong potential to meet the energy demands of large regions, enhance export opportunities for European industry, and support the decarbonisation goals of the Paris Agreement.

Table 1. Main goals of CSP in the Revised SET Plan, EC[2]

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 of 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 cost reduction or 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.

To achieve these objectives, the Implementation Plan promotes a set of **R&I priority technology actions** at low TRLs, aimed to improve efficiency, durability, and reliability, as well as reduce costs. Table 2 shows these actions focus on enhancing CSP system performance at higher operating temperatures, improving integration with thermal energy storage and turbomachinery. The plan also supports additional key applications, such as industrial process heat and the promising development of solar fuels.

Table 2. List of R&I Activities of the CSP Implementation Plan, EC [2]

Technology Area	Key Priorities / Challenges
Line-Focus solar power plant Technology	Improve efficiency with fluids >425°C, reduce solar field and maintenance costs, and assess molten salt suitability.
Central Receiver Power Plant Technology	Enhance molten salt systems, explore innovative designs (e.g. multi-tower, beam-down, particle receivers).
Thermal Energy Storage (TES)	Develop storage >600°C (Rankine) and >750°C (sCO_2), improve energy density and cost-effectiveness.
Turbomachinery	Design turbines tailored for CSP to increase efficiency, operational flexibility, and reduce maintenance costs.
Industrial Solar Heat (60–1000°C)	Automate solar fields, promote direct steam generation, develop high-temp materials, and standardise integration.
Solar Fuels Production	Advance the thermochemical/electrochemical processes, scale reactors, and integrate CST heat and electricity.
Crosscutting Issues	Hybrid CSP+PV plants, digitalisation for improved O&M, raise awareness among planners, TSOs, DSOs, policymakers.

[2] EC, Initiative for Global Leadership in Concentrated Solar Thermal Technologies, 2023

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COOPERANT has structured its goals and portfolio of activities to fully **align with the five main goals** for CSP in the revised SET Plan and the priority technology actions defined by IWG CSTT, ensuring that its innovations directly address EU policy and technology roadmaps. COOPERANT Specific Objectives (SO) are designed to deliver measurable progress towards SET Plan targets through high-impact developments in central receiver technology, high-temperature hybrid TES (>800–1000 °C), digitalised operation, and applications for electricity, industrial heat, and solar fuels. Table 3 presents the one-to-one mapping between COOPERANT **Specific Objectives (SO)** and the 5 main goals for CSP in the Revised SET Plan.

Table 3. COOPERANT Specific Objectives Alignment with SET Plan

COOPERANT Specific objectives (SO)	CSP SET Plan Goal (Table 1)
SO4.1. To increase the power plant efficiency of the next generation of CSP/STE technology to 42.4% by 2030	**Development of next generation** (2)
SO4.2. 1 First-of-a-Kind (FOAK) prototype validated at TRL4, to be integrated in the energy system by 2030	**First of a Kind prototype** (3) or CSP new concepts
SO4.3. To prove 24/7 economically viable solar thermal baseload production of green H2 and solar fuels by 2030	**Demonstration** (5)
SO5.2. To reduce electricity cost <10 c€/kWh and reduce thermal energy cost for industrial process >200°C heat applications <3 c€/kWh, by 2030	**Cost reduction** (1), **Thermal energy cost** (4)

To fulfil these specific objectives, **COOPERANT's developments** address the priority technology actions defined by the IWG CSTT. These developments encompass a full range of R&I activities for advanced CSP-TES systems, spanning **system-level integration**, **technical optimisation**, and **material-level innovations**. Table 4 presents the alignment between COOPERANT's developments and the R&I areas of the CSP Implementation Plan.

Table 4. COOPERANT's Development on the R&I areas of the Implementation Plan

Technology Area	COOPERANT Alignment
Central Receiver Power Plant Technology	**High-performance volumetric solar receiver** with custom-designed cellular morphology for temperatures up to 1000°C. **Novel 3D-design process using additive manufacturing (AM)** for volumetric absorbers.
Thermal Energy Storage (TES)	**Hybrid packed-bed TES system** for high temperatures (up to 1000°C), combining sensible and latent heat storage with storage capacity exceeding 600 kWh/m³
Turbomachinery	**Developing CSP-TES systems to be compatible with next-generation CSP plants** operating with more efficient power cycles like Brayton, sCO2, and Rankine cycles.
Industrial Solar Heat / Solar Fuel production	**Stakeholder engagement** to boost the scalable application of its solutions to industrial process heat applications and solar fuel production (60–1000 °C).
Cross-cutting Issues	**COOPERANT-AI TOOL** for holistic orchestration of the CSP-TES system, featuring real-time monitoring, reinforced learning-based control, scalability, and replicability. **COOPERANT-TRANSFER**: A knowledge transference programme with a multi-stakeholder approach, including a Stakeholder Replicability Board (SRB), Dissemination, Exploitation, Communication (DEC).

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3.2 Rationale for KPI Selection

The selection of Key Performance Indicators (KPIs) within the COOPERANT project is directly guided by the strategic objectives of the revised SET Plan and the 2023 CSP Implementation Plan. COOPERANT includes four categories of KPIs: i) Technical performance, ii) Economic, iii) Environmental, and iv) Socio-economic. Together, they provide a comprehensive framework for monitoring and evaluating progress toward the development and validation of next-generation CSP technologies at TRL 4 and beyond.

1. Technical performance KPIs will be established during the development of the novel CSP-hybrid TES materials, system design and prototyping in WP2. They will be refined through CSP-TES prototype modelling and the development of the COOPERANT-AI TOOL in WP3. These KPIs will be validated during the COOPERANT CSP-TES prototype demonstration in real conditions (WP4) to benchmark against state-of-the-art CSP systems and SET Plan performance targets.

2. Economic KPIs will be assessed in the techno-economic analysis (T5.3), using inputs from the design, optimisation, and demonstration activities in WPs 2–4. CAPEX and OPEX are investment parameters that are commonly used to estimate the initial costs of a project and also cost-energy parameters such as Levelized Cost of Energy (LCOE) and Levelized Cost of Storage (LCOS) are used to determine the selling prices of electricity in a power generation plant. In addition, metrics such as the Net Present Value (NPV) or Simple Payback Period are useful to complete the study of the project's profitability. The analysis of these parameters will enable benchmarking against market baselines and the SET Plan's cost objectives (<10 c€/kWh for electricity and <3 c€/kWh for industrial heat >200 °C).

3. Environmental KPIs will be defined in the Life Cycle Sustainability Assessment (T5.2) and Circularity & Safe and Sustainable by Design activities (T5.1), combining material-level data from WP2 with operational results from WP4. These KPIs will allow benchmarking of CO_2 emissions reduction, resource use efficiency, and circularity against current CSP plants and EU sustainability standards.

4. Socio-economic KPIs will be derived from T5.4-*Gender, Ethics, and Inclusion aspects*, and WP6, covering metrics such as job creation, Social Return of Investment (SROI), and industrial competitiveness. The results will be benchmarked against existing CSP deployment scenarios and policy expectations.

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3.3 Methodology and Data Sources

3.3.1 Technical Performance KPIs

COOPERANT's technical performance KPIs are directly linked to the project's objective of developing a high-efficiency CSP-TES system capable of operating at **temperatures up to 1000ºC** and designed to support future integration with **power cycles, such as Brayton cycles**.

During the project's testing activities (WP2-4) and upscaling activities (WP6), two overarching parameters will guide performance evaluation: **System Reliability** and **Technological Maturity**. These parameters ensure that the CSP-TES prototype can achieve consistent operation and robust performance throughout the development path from **TRL2 to TRL4**, and beyond.

Indicators for **Thermal Energy Storage (TES)**, including hours, energy density, round-trip efficiency, and power level, and for **thermal efficiency** of the CSP-TES system, will be applied from the early project stages. In WP2, key components such as the **Open Volumetric Receiver (OVR)** and the **hybrid TES system**, based on advanced materials, are designed, fabricated, and characterised. Under T2.5-*TRL3 testing and optimisation of storage systems and materials*, the baseline KPI values for benchmarking will be established.

In WP3, these KPIs will be refined as experimental results feed into multiphysics simulation modelling (T3.1) and into the development of a **Digital Twin** (T3.3), integrated with AI-based control models for the COOPERANT-AI TOOL. This tool enables operational optimisation and control strategies that account for real-world dynamic behaviour.

Finally, under T4.4, a validation Campaign at TRL4 will confirm KPI values by testing the fully integrated COOPERANT CSP-TES system under real solar conditions at the **CIEMAT CESA I Solar Tower**.

Additional technical performance KPIs will support broader system-level evaluation. For example, **Solar Multiple** will be a critical metric in T6.4 when assessing the scalability and replicability of the COOPERANT CSP-TES prototype compared to existing CSP plants.

3.3.2 Economic KPIs

COOPERANT aims not only to innovate technically, but also to ensure the economic feasibility of the new generation of CSP-TES systems. **Economic KPIs** are used to measure **financial performance and maximise revenues** by optimising operational and investment strategies, providing a basis to assess how cost-competitive the COOPERANT CSP-TES system is compared to benchmarking values.

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One of the most recognised indicators for analysing the profitability of power plants is the **Levelized Cost of Energy (LCOE)**, which estimates the minimum sale price of generated electricity over the plant's lifetime. In TES systems, such as the hybrid heat storage developed in COOPERANT (combining PCM and sensible storage materials), the **Levelized Cost of Storage (LCOS)** is equally relevant, as it quantifies the cost of thermal energy storage per unit of discharged energy.

Under **WP5**, the project calculates the total CSP-TES system costs across its life cycle at TRL 4 and TRL 9, including **Capital Expenditure (CAPEX)** and **Operational Expenditure (OPEX)**, which define the financial baseline for generating revenue from energy production. These indicators are complemented with other metrics defined in T5.3-*Technoeconomic and cost-effectiveness analyses* (TEA), such as **Cash Flows**, **Net Present Value (NPV), Internal Rate of Return (IRR), Depreciation Costs, simple Payback Period (SPB), and Marginal Costs**. This set of KPIs provides a comprehensive view of both economic viability and technical performance in relation to the plant's revenue streams.

Cost data for these KPIs is obtained from partner reporting on design and manufacturing costs, complemented with results from laboratory-scale testing in WP2 and WP3, and from the TRL4 validation campaign under WP4, and from scientific literature.

3.3.3 Environmental KPIs

In COOPERANT, **Environmental KPIs** are central to evaluating the project's impact on greenhouse gas emissions, resource efficiency, material circularity, and environmental safety. These KPIs will be assessed in Task 5.2 through a **Life Cycle Assessment (LCA)** conducted in accordance with ISO 14040/14044:2006, using SimaPro® and applying both the Product Environmental Footprint (PEF) and ReCiPe methods. In this case, some examples of the selected KPIs cover **climate-related impacts** (climate change, ozone depletion), **health-related impacts** (human toxicity, ionising radiation), **ecosystem-related impacts** (land use, freshwater ecotoxicity, eutrophication), and **resource-related impacts** (use of minerals and metals, use of fossil resources).

In parallel, **Circular KPIs** will be addressed in T5.1 – Circularity & Safe and Sustainable by Design (SSbD) premises, guiding material selection towards sustainable options by avoiding the use of **Critical Raw Materials (CRMs)** and implementing design strategies that minimise environmental and human health risks within CSP-TES technologies.

Data for these environmental KPIs will be obtained from material- and system-level developments in WP2 and from the integrated system performance during the COOPERANT CSP-TES demonstration in WP4.

Finally, these parameters will be evaluated on the results presented in the deliverables D5.1 and D5.6 (Circularity & Sustainable by Design) and D5.2 and D5.7 (Life Cycle Sustainability Assessment). These reports will document COOPERANT's performance relative to current CSP-TES technologies, highlighting reductions in carbon footprint, improvements in environmental indicators, and alignment with the SET Plan, Circular Economy Action Plan, and the Critical Raw Materials Act.

3.3.4 Socio-economic KPIs

COOPERANT acknowledges that innovation must go hand-in-hand with social responsibility and market relevance. **Socio-economic indicators** are critical for assessing the deployment of the COOPERANT CSP-TES system during its further commercialisation. These indicators will be implemented mainly under WP5 and WP6, in alignment with T.5.2 – *Life Cycle Sustainability Assessment (LCSA), integrating environmental (LCA), economic (LCC), and social (s-LCA) dimensions*. Indicators such as **Job Creation**, **Local Employment**, and **Social Return on Investment** are critical parameters that will guide the implementation of the COOPERANT CSP-TES system and assess the wider effects on the community at the commercial stage.

Another socio-economic indicator, **Equitable Job Opportunities**, will be assessed in T5.4, dedicated to Gender, Ethics and Inclusion aspects. This task will produce two reports (deliverables D5.4 and D5.9) containing mitigation actions to address ethics, gender, and inclusion issues throughout the COOPERANT project development.

Engagement activities are led by WP6 and include surveys, interviews, and co-creation sessions with stakeholders through the Stakeholder Replicability Board (SRB) and the PEDRC platform. T6.1 – *Dissemination, Communication and Training* and *T6.3 – Clustering for increased awareness, relevance, and competitiveness* include specific KPIs such as **Training and Education**, assessed on the COOPERANT-TRANSFER Handbook with training materials (D6.2), and **Industrial Competitiveness**, reflected in a dedicated report on the competitiveness of the COOPERANT CSP-TES technology (D6.3).

3.4 Sectoral and Geographical Scope (EU and Global)

The benchmarking framework developed in this deliverable takes into account both the **sectoral applications of CSP-TES and its geographical deployment patterns**, ensuring that COOPERANT outcomes are evaluated within the larger EU and international energy transition landscapes.

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At the **sectoral level**, CSP-TES is designed to support dispatchable renewable electricity generation in power systems with a high proportion of variable renewables, such as solar PV and wind. In Europe, this role is closely related to the SET Plan's priorities of improving grid stability and decarbonising the power sector.

Aside from electricity, CSP-TES is relevant for **industrial process heat, solar fuel production, and sector coupling applications** where high-temperature heat can contribute to decarbonisation of difficult-to-abate industries. In COOPERANT, the goal is to support this process, and this deliverable thus compares key performance indicators (KPIs) not only in terms of electricity system integration, but also in terms of broader contributions to industrial competitiveness and sustainability.

Geographically, Europe remains the leader in thermal storage innovation, with a strong industrial base and pioneering demonstration projects in Spain, Cyprus, and Italy. As reported by the IRENA report (2024)[3], CSP's global costs have fallen by 77% since 2010, with an **average LCOE of USD 0.092/kWh**, and capacity factors have increased to more than 40% in regions with high direct normal irradiance (DNI). While the European market for new CSP installations has slowed, the EU continues to promote excellence in TES components and digital integration. Globally, deployment is accelerating in **China, Morocco, South Africa, and the Middle East**, where advantageous irradiation and scale allow for cost savings and larger project pipelines.

This comparative analysis demonstrates that, while the **EU provides an innovation environment** for advanced TES materials, digitalisation, and hybrid system design, the global market provides **deployment experience and cost benchmarks** that are critical for assessing replicability.

COOPERANT's KPI benchmarking explicitly incorporates both perspectives: **European policy and innovation frameworks** on the one hand, and international deployment data and performance trends on the other. This ensures that the assessment of COOPERANT outcomes is consistent with both the **European SET Plan objectives** and the global realities of CSP-TES development.

[3] RENEWABLE POWERGENERATIONCOSTS IN 2024, IRENA 2025, ISBN: 978-92-9260-669-5

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4 Technical Performance KPIs

4.1 CSP plant KPIs

The **Solar Multiple (SM)** is a design parameter in CSP systems, particularly in central receiver systems (CRS), also known as power tower (PT), and parabolic trough collectors (PTC) configurations. It establishes the relationship between the solar field's energy collection capability and the thermal demand of the power block. This parameter **directly influences plant output, storage utilisation, and overall performance**. Understanding and optimising the SM is important to balance capital investment, dispatchability, and operational efficiency, especially in next-generation CSP plants where high-temperature operation and extended storage are expected.

4.1.1 Definition and relevance of Solar Multiple

The SM is a **dimensionless parameter that quantifies the ratio between the maximum thermal power output** from the solar field under design-point or nominal conditions and the thermal power required by the power block to operate at full nominal load. It is formally defined as:

$$SM = \frac{Q_{field,design}}{Q_{turbine}}$$

Where:

- **$Q_{field,design}$ [MWth]** is the thermal power delivered by the receiver at the design-point Direct Normal Irradiance (DNI), typically 900–950 W/m².
- **$Q_{turbine}$ [MWth]** is the thermal power required to drive the turbine at nominal capacity, including cycle losses.

The SM is an important design parameter in CSP plants, since it defines the extent to which the solar field can satisfy or surpass the turbine thermal requirements. Thus, this parameter refers to the operating hours, the size of the thermal energy storage, and the plant's economic performance.

4.1.2 Relation between the solar field aperture and the turbine demand

The **field aperture** accounts for the total reflective area of the heliostat field projected to the receiver that is placed on the top of the tower, and it is denoted as $A_{aperture}$ [m²]. The solar field thermal power output, at design conditions, can be estimated as:

$$Q_{field,design} = \eta_{opt} \cdot DNI_{design\text{-}point} \cdot A_{aperture}$$

Where η_{opt} is the optical efficiency of the solar field, accounting for the cosine effect, shadowing/blocking, reflectivity, atmospheric attenuation, and tracking accuracy.

The relation between solar multiple and aperture area of the solar field is direct: increasing $A_{aperture}$ area raises $Q_{field,design}$ and thus the SM. However, the economic optimum depends on the CSP design and the operational strategy, which would require a yield analysis. Generally:

- **SM ≈ 1.0–1.2 —** Solar field sized only for solar hours operation, without or with minimal thermal energy storage.
- **SM > 1.2–2.5 —** A Larger solar field allows charging of thermal energy storage and extends operation into night hours.

4.1.3 Design trade-offs

The choice of the solar multiple is a trade-off between capital cost, operational hours, and dispatchability (size of the thermal energy storage):

- **Lower SM reduces heliostat field cost** but limits the number of equivalent full-load hours.
- **Higher SM increases thermal energy storage charging capability** and annual output but raises CAPEX and potential thermal losses during overproduction periods.
- **Optimal SM is identified through techno-economic optimisation**, typically aiming to minimise Levelised Cost of Electricity/Energy (LCOE) while ensuring required dispatchability.

The factors that affect the optimal SM are:

- DNI profile at site location.
- Thermal energy storage capacity (hours of storage).
- Cycle type (Rankine, supercritical CO_2, Brayton).
- Hybridisation options (e.g., gas burners, electric heaters).

4.1.4 Example: Gemasolar CSP Tower Plant

Plant characteristics:

- Location: Fuentes de Andalucía, Spain.
- Technology: Central receiver system / Power tower with molten salt receiver.
- Turbine gross capacity: 19.9 MWe.
- Turbine thermal demand $Q_{turbine}$ ≈ 47.4 MWth (assuming ~42% thermal-to-gross efficiency).
- Field aperture $A_{aperture}$: 265,000 m2 (approx. 2,650 heliostats, each ~115 m^2).
- Optical efficiency η_{opt}: ~0.60 at nominal conditions.

- Design DNI: 950 W/m^2.

Calculation:

- $Q_{field,design}$ = 0.60·950·265,000 = 151.1 MW_{th}
- SM = 151.1/47.4 ≈ 3.2

Interpretation:

With a SM of approximately 3.2, Gemasolar's solar field is more than three times the size required to run the turbine at nominal load under design conditions. This large oversizing enables sustained charging of its 15-hour molten salt TES system, allowing continuous generation through night hours and periods of low irradiance. The design maximises annual capacity factor (≈ 75 %) while supporting dispatchable power delivery, illustrating the balance between higher CAPEX in the solar field and enhanced operational flexibility.

4.1.5 Implications for next-generation CSP systems

The Gemasolar case illustrates how a high Solar Multiple, around 3.2, can be a design choice in plants aiming for extended TES autonomy. Oversized solar fields allow simultaneous delivery of full-load turbine power and substantial charging of storage during peak DNI hours, enabling long-duration operation without direct solar input.

For **next-generation CSP** concepts (>700 °C) in **the COOPERANT framework**, the optimal SM may differ from existing plants due to:

- **Increased thermal losses at elevated receiver temperatures**, which require careful field oversizing to compensate.
- **Higher cycle efficiencies (e.g., supercritical CO_2 Brayton > 45 %), reducing the turbine's thermal demand**, potentially allowing similar output with smaller SM values.
- **Longer-duration TES (>15 hours)** that shifts the economic optimum toward SM values in the 2.5–3.5 range, depending on DNI availability and cost trade-offs.
- **Hybrid heating integration** (e.g., electric resistive, hydrogen combustion) provides additional flexibility, potentially reducing the need for extreme oversizing in certain operating modes.

In this context, selecting the SM becomes a **strategic balance between field CAPEX, TES capacity, and dispatchability targets**. While moderate SM values (~1.5–2.0) may be sufficient for shorter storage durations, high-storage plants, as seen in Gemasolar, demonstrate that SM values above 3 can significantly enhance capacity factor and operational reliability in high-DNI regions.

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4.2 CSP-TES KPIs

Thermal Energy Storage (TES) is a central element of CSP plants, determining their ability to shift generation in time, provide **dispatchable capacity, and reduce costs.** TES systems in CSP are assessed by a set of technical KPIs that capture their ability to provide dispatchable, high-temperature heat and electricity[4][5]. Table 5 summarises the most relevant KPIs for CSP-TES systems, particularly for hybrid designs combining sensible and latent heat storage.

Table 5. Key Technical KPIs for CSP-TES systems.

KPI	Definition	Relevance for CSP-TES
Storage Capacity (MWh, kWh/m³)	Total thermal energy stored	Determines available energy per unit volume; higher densities reduce footprint and cost.
TES Duration (hours)	Continuous discharge at rated power	Primary measure of dispatchability and firm capacity.
Round-trip Efficiency (%)	Ratio of discharged to charged energy	Captures total cycle losses in charging, storing, and discharging.
Exergy Efficiency (%)	Quality of stored energy	Indicates how well high-grade heat is preserved.
Mean Thermal Power (kW/MW)	Average output during discharge	Reflects the capacity to deliver stable downstream process heat or electricity.
Thermal Losses (%/day)	Stand-by and dynamic losses	Determines effective duration and economic value.

Within COOPERANT, each KPI addresses specific challenges and opportunities for TES in CSP:

- **Storage Capacity & TES Duration:** Determine the plant's ability to provide dispatchable renewable energy. Conventional molten salt **TES delivers 6–15 hours at ~565 °C**. In COOPERANT, the hybrid system targets **an energy density of over 600 kWh·m⁻³ and a TES Duration aligned with SET Plan goals, enabling high-density and compact systems at temperatures of** up to 1000 °C.
- **Mean Thermal Power:** Defines the average discharge power. For COOPERANT, this is **20–30 kW_{th} at lab-scale**, matching OVR–TES coupling requirements and validating hybrid operation under high flux conditions.
- **Thermal Losses & Storage Efficiency:** Loss minimisation is essential for cost competitiveness. COOPERANT targets **round-trip efficiency >90%**, with a hybrid sensible–latent design reducing gradient-induced losses.
- **Storage Exergy Efficiency:** At high operating temperatures (800–1000 °C inlet), exergy efficiency becomes critical for coupling TES to power cycles. Hybrid storage helps

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4 Cabeza, L. F., Borri, E., Gasa, G., Zsembinzski, G., Lopez-Roman, A., & Prieto, C. (2021). *Definition of Key Performance Indicators (KPIs) to Evaluate Innovative Storage Systems in Concentrating Solar Power (CSP) Plants*. *Proceedings of the ISES Solar World Congress 2021*. https://doi.org/10.18086/swc.2021.33.02

5 *https://www.sunson.eu/2023/05/03/technical-specifications-and-kpis-for-the-sunson-box-prototype/*

maintain outlet temperatures within optimal ranges, extending exergy value compared to molten salts.

- **Utilisation Rate:** High cycling stability ensures TES contributes to daily dispatch. The hybrid system combines sensible fillers (high durability) with PCM zones to **stabilise performance** under frequent cycling.
- **Auxiliary Power Consumption:** Reduced parasitics (e.g., fan and pump demand) **increase net output.** Compact hybrid design and efficient integration aim to minimise these loads.
- **Reliability & Cycling Stability:** Hybridisation addresses the limitations of PCMs (e.g., supercooling, degradation) by embedding them in robust ceramic matrices, improving lifetime performance.
- **Operating Temperature Range:** The hybrid design extends **TES to >1000 °C,** beyond the 565 °C limit of molten salts, unlocking coupling with next-generation CSP cycles.

4.2.1 Storage modes operation

In COOPERANT, TES is designed as the buffer between the open volumetric receiver (OVR) and downstream processes. The prototype targets include an **energy density of up to 600 kWh·m⁻³, a round-trip efficiency above 90%, and a continuous thermal output of 20–30 kW** within an operating window of 800–1000 °C at the inlet and 500–750 °C at the outlet. The hybrid approach (Figure 2 and Figure 3), which combines a structured ceramic matrix for sensible storage with embedded PCMs for latent storage, ensures thermal stability, stabilises outlet temperatures, and extends usable storage time to provide firm and dispatchable heat and power. The sensible material operates up to 800-1000ºC °C, while the latent heat material stores heat at around 700ºC. The combination of both storage modes allows for an operation in three different modes as described below.

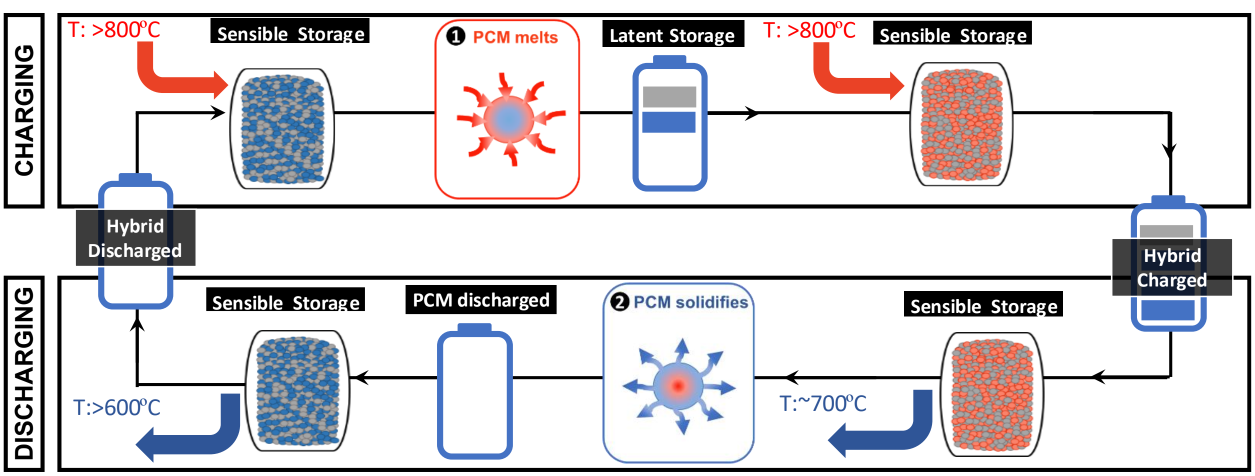

Figure 2. COOPERANT hybrid storage charging/discharging cycles operation modes.

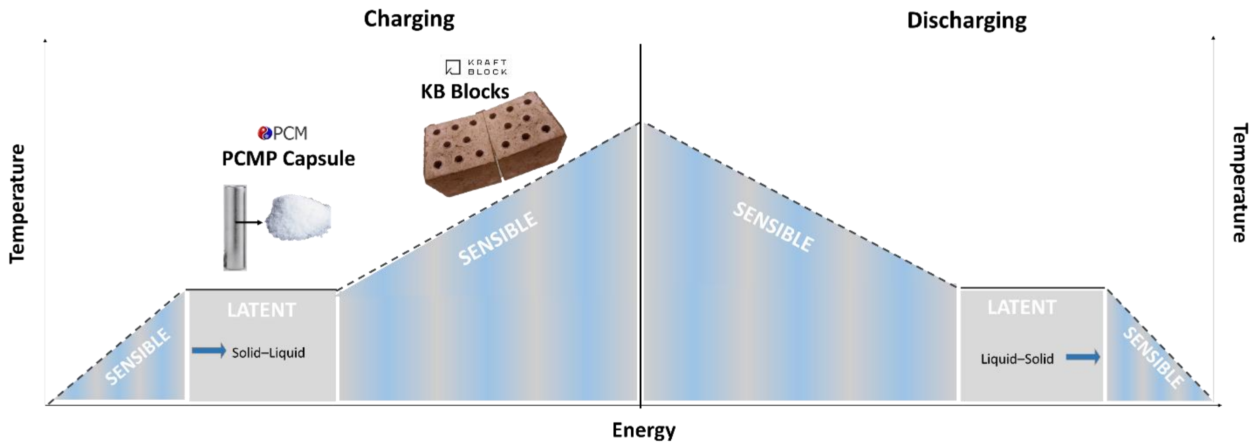

Figure 3. COOPERANT hybrid storage modes.

- **Sensible Storage Model.**

In sensible mode, energy is stored by raising the temperature of the ceramic matrix, see Figure 3. The stored energy, $E_{sensible}$, depends on the mass, m, heat capacity, c_p, and permissible temperature swing (ΔT). As the heat capacity of ceramics can vary with temperature, the usable energy also changes across the operating window.

$$E_{\text{sensible}} = m\, c_p\, \Delta T$$

- **Latent Storage Model.**

In **latent mode**, energy is absorbed or released nearly isothermally through the phase change of the embedded PCM, see Figure 3. The stored energy, E_{latent}, is a function of PCM mass and latent fusion enthalpy, L_f. Practical effects such as supercooling, hysteresis, and limited thermal conductivity of capsules influence both recoverable energy and achievable power density.

$$E_{\text{latent}} = m\, L_f$$

- **Hybrid Storage Model.**

The **hybrid configuration** combines sensible and latent modes, allowing both mechanisms to operate in parallel, see Figure 2. In COOPERANT, this is achieved by embedding or cascading PCM tubes within a structured ceramic matrix. The combined contribution, E_{hybrid}, is governed by packing density, capsule geometry, and the distribution of PCM melting points along the flow path. These factors determine overall energy density, pressure drop, and the stability of the outlet temperature.

$$E_{\text{hybrid}} = m_s\, c_{p,s}\, \Delta T_s + m_l\, L_f$$

As detailed in D2.1, the reference design combines a channel-structured ceramic block for sensible storage with replaceable PCM tubes. **By arranging cascaded melting points and applying targeted mass flow control, the outlet temperature can be held within a narrow band for longer periods.** This extends TES Duration beyond that of pure sensible systems, increases operational flexibility, and ensures reliable performance at the required power level. The PCM filling level and the geometry of the ceramic channels can be tailored for various applications, thereby balancing energy density, efficiency, and hydraulic performance.

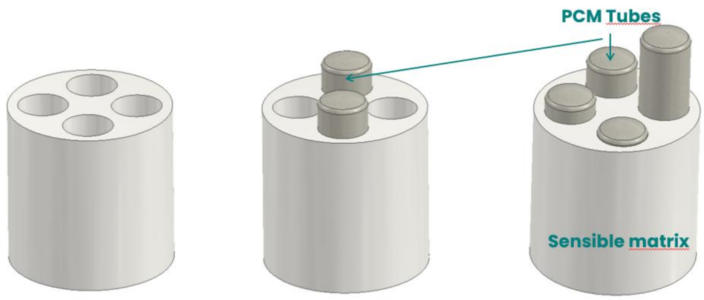

Figure 4: Embedded Matrix Approach, macro encapsulated PCM in a sensible storage material.

This hybrid approach directly enhances the stability of the CSP plant output by smoothing thermal load peaks, extending discharge duration, and maintaining high exergy efficiency at elevated temperatures. As a result, the COOPERANT system not only increases TES Duration but also improves flexibility and reliability, aligning with the technical KPIs defined for benchmarking in this deliverable.

4.2.2 Dispatchability: TES duration

The **key indicator of dispatchability is TES Duration**, defined as the time, t, a system can continuously deliver a specified power output, P_{out}, while maintaining outlet temperature within the required range.

$$t = \frac{E_{\text{usable}}}{P_{\text{out}}}$$

In practice, $\mathbf{E_{usable}}$ is reduced by round-trip losses, finite internal heat-transfer rates, material/gradient limits, and control constraints**. Hybrid TES helps keep the outlet temperature within range for longer and thus increases realised storage time at constant power.**

TES Duration is governed by a set of interrelated parameters (Table 6):

- **Energy density and design.** Higher density increases available hours. In COOPERANT, porosity, capsule fraction, and channel geometry are optimised to raise density while keeping pressure drop and manufacturability under control.

- **Round-trip efficiency.** Determines how much of the stored energy is usable. Improving efficiency from 85% to 90% in a 1 m³ module increases usable output by ~30 kWh at constant power.
- **Power level and outlet stability.** A nearly constant outlet temperature is essential for CSP operation. COOPERANT achieves this through controlled HTF mass flow and cascaded PCMs with graded melting points.
- **Insulation and standby losses.** Multi-layer insulation reduces self-discharge to ≤1% per day, extending effective duration and improving high-temperature reliability.
- **Heat transfer vs. pressure drop.** Smaller channels and denser packing improve transfer but raise auxiliary demand. Capsule geometry and channel optimisation in COOPERANT aim to keep *Δp* within acceptable limits while ensuring sufficient transfer.

TES duration at fixed module size can be extended by increasing recoverable energy through embedded or cascaded PCM, improved heat transfer, and reduced thermal losses with multi-layer insulation and careful vessel design. It can also be prolonged by operating at lower discharge power during periods of the highest system value. Practical factors such as channel geometry, capsule dimensions, and the need for inert atmospheres at high temperature define the feasible design space. Structured sensible blocks with PCM may extend duration by about 30%, though with higher cost and complexity, while insulation upgrades provide smaller gains at lower cost and improve reliability at elevated temperatures.

Table 6: Parameter impact on TES duration, low value vs high value

Parameter	Low value	High value	Impact on TES-duration
Energy density	400 kWh/m³	600 kWh/m³	Higher density increases duration
Round-trip efficiency	0.80	0.90	More usable energy (at 600 kWh·m⁻³: **24 h** → **27.0 h** at 20 kW).
Discharge power	30 kW	20 kW	Higher power shortens duration (at 540 kWh usable: **18 h** → **27 h**).
Standing losses (24 h standby)	2 %/day	1 %/day	Less self-discharge preserves hours (at 540 kWh: **~26.5 h** → **~26.7 h** at 20 kW after 1 day).
Hot-side temperature	800 °C	1000 °C	Larger operating window can raise effective energy density (potentially longer hours, materials/limits permitting).
Outlet temperature setpoint	600 °C	750 °C	Higher setpoint tightens the usable window; duration tends to **decrease** unless compensated by control/ packaging.

4.2.3 Thermal Efficiency: Conversion of sunlight to thermal energy

Thermal efficiency is a core KPI for CSP plants with integrated TES, as it defines how much of the incident solar energy is effectively converted into usable heat. In practice, it is the fraction of incoming solar radiation that is captured, transferred to the heat transfer fluid (HTF), and stored or delivered with minimal losses. High thermal efficiency reduces required collector areas and balance-of-plant components, increases output temperatures, and directly improves economic viability.

In COOPERANT, thermal efficiency is pursued through the combination of an **open volumetric receiver (OVR)** and a **hybrid sensible–latent storage system**. Concentrated radiation penetrates into the porous receiver, where air (as HTF) flows through and collects heat efficiently, reducing optical and surface losses compared with flat absorbers. The downstream TES unit, combining a structured ceramic matrix with embedded PCM, ensures that this heat is delivered on demand with stable outlet conditions. At prototype scale, COOPERANT targets efficiencies high enough to deliver **20–30 kW_{th} at outlet temperatures up to 750 °C** with **round-trip storage efficiencies above 90%**.

Thermal efficiency is not static. While snapshot values can be high under ideal conditions, true performance is measured by **seasonal and annual efficiency**, which accounts for variations in irradiance, ambient conditions, soiling, and system operation. A summary of the parameters affecting efficiency are shown in Table 7. In COOPERANT, dynamic control via a digital twin will adjust mass flow, receiver tracking, and charging strategies to optimise real-world efficiency across different operating conditions.

Efficiency is also strongly linked to **temperature level and exergy**. Higher efficiency enables higher operating temperatures, which increases the "quality" of heat available for electricity generation or energy-intensive industrial uses. The COOPERANT system, designed for operation up to 1000 °C, explicitly targets such high-temperature applications, thereby expanding its relevance beyond electricity to process heat markets.

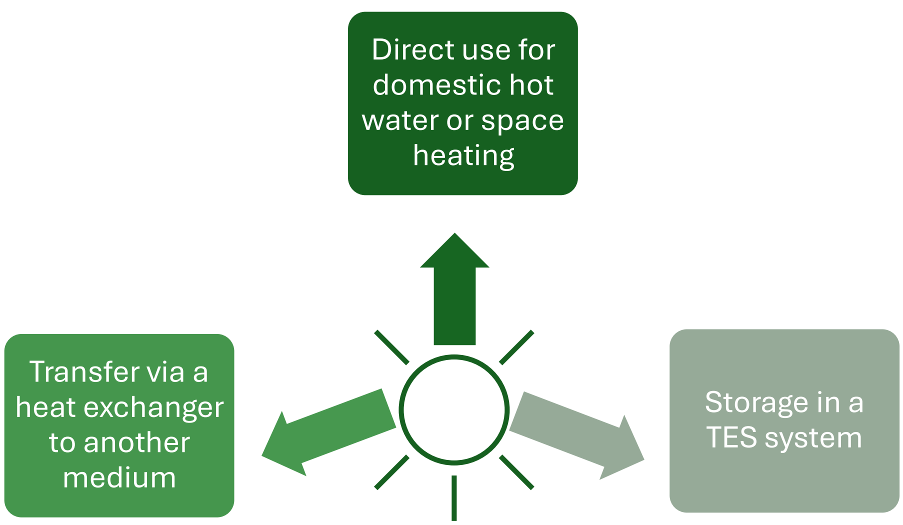

Figure 5. Pathways for the use of thermal energy: direct consumption for domestic or industrial heating, transfer to another medium via heat exchangers, or storage in a TES system.

Finally, efficiency depends on the way heat is coupled into and out of storage. Every additional transfer stage or unnecessary temperature lift introduces losses. **The hybrid storage in COOPERANT is designed to minimise these, using short flow paths, careful insulation, and stable charge/discharge rates.**

Table 7. Parameters affecting thermal efficiency and implications for COOPERANT

Parameter	Effect on Efficiency	Relevance for COOPERANT
Optical performance (reflectivity, alignment, soiling)	Determines how much solar radiation is absorbed vs. lost	Use of clean, aligned optics and a volumetric receiver reduces reflection losses
Receiver absorption & heat transfer	Governs the conversion of solar radiation to HTF heat	Porous OVR with air as HTF ensures deep absorption and efficient transfer
Thermal losses (convection, radiation, conduction)	Reduce net captured heat, especially at high T	Multi-layer insulation and compact design minimise losses
Storage round-trip efficiency	Fraction of energy retained through the charge–discharge cycle	Hybrid sensible–latent system targets >90% efficiency
Auxiliary consumption (pumps, blowers)	Reduces net useful energy output	Optimised flow geometry limits Δp and blower demand
Operating temperature window	Higher T increases exergy and process relevance	800–1000 °C inlet, 500–750 °C outlet enable industrial-grade heat
Seasonal variability (irradiance, ambient)	Defines long-term, real-world efficiency	Digital twin adjusts operation dynamically to maintain seasonal efficiency

4.2.4 TES Control Strategies and Monitoring

In COOPERANT, a **digital-twin-based controller** estimates state-of-charge (SoC) from axial thermocouple strings, pressure drops, and flow; it coordinates receiver and TES in real time. These strategies will be validated in WP2.4/2.5 through the laboratory-scale prototype.

Core tactics.

- **Constant-temperature discharge** via mass-flow control. Start with a higher air mass flow to meet the power setpoint, then gradually reduce it to dwell longer in latent-heat plateaus, smoothing the outlet profile and stretching duration.
- **Cascaded packing** (hybrid packed bed). Place higher-melting-point PCMs near the hot inlet and lower-melting PCMs downstream within a structured sensible matrix.
- This stabilises temperature, limits local gradients, and extends useful duration at a given power.
- **Demand-response blending.** During high demand with high irradiance, combine direct receiver heat and TES discharge to avoid deep cycling; preserve reserve duration for later peaks.

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- **Stand-by / heat-hold.** When demand is low or irradiance is absent, use minimal purge flow and strong insulation to keep daily losses low; maintain an inert atmosphere in PCM domains to protect materials.

Standardised parameters help in design; in operation, reliable data matter: irradiance, inlet/outlet temperatures, ambient temperature, mass flow, pressure drops, and storage state. Continuous monitoring reveals deviations (e.g., soiled optics, aged coatings, tracking errors) and enables predictive maintenance. Just as important is the operating strategy: shifting heat demand into sunny hours or using price/load signals (in CHP or power-coupled systems) can raise annual efficiency without extra collector area.

Monitoring in COOPERANT. The plan is tight monitoring of irradiance, receiver temperatures, air mass flow, and storage state. These data feed digital operating strategies (up to a digital twin) that continuously optimise maintenance and dispatch.

In the end, high thermal efficiency means capturing more of the sun's energy as heat—with minimal losses. High thermal efficiency results from the sum of many small optimisations:

- **Optics & cleanliness:** precise alignment, smooth surfaces, high-quality mirrors/covers, and soiling management (cleaning, hydrophobic coatings) safeguard optical capture. Even a few per cent reflection or dust can dent the annual balance.
- **Receiver & emission:** selective absorbers with high absorptance and low emissivity reduce radiative losses; vacuum or double glazing suppresses convection. Volumetric receivers couple radiation deep into porous structures and improve heat transfer into the fluid.

4.3 System Reliability & TRL: Operational maturity and innovation

For the next generation of CSP and TES systems, achieving high efficiency and competitive costs is not enough to ensure long-term viability. **Reliability and technological maturity are essential to guarantee that systems can operate consistently and cost-effectively** throughout their entire service life. The ability of a plant to perform over decades, withstanding extreme thermal cycling and adapting to varying environmental conditions without significant performance loss directly influences the LCOE, investor confidence and market adoption.

In COOPERANT, reliability and technological maturity are fundamental pillars that will be assessed through rigorous testing and upscaling activities carried out during the project and beyond. By aligning with the SET Plan, the CSP Implementation Working Group[6] and other European projects, COOPERANT ensures a common and robust framework to develop, measure

[6] https://setis.ec.europa.eu/working-groups/concentrated-solar-thermal-technologies_en

and benchmark these crucial indicators. The specific reliability and maturity indicators considered in this project are presented in the following subsections.

4.3.1 Reliability

In CSP and TES systems, reliability stands for **consistent performance across all components**, including mirrors, receivers, heat transfer fluids, storage units and mechanical systems. It reflects the system's capacity to resist failures, material degradation and other issues that could reduce energy output and increase operational costs.

Ensuring the reliability of CSP and TES systems requires monitoring specific performance indicators that reflect the system's ability to operate consistently over time **without unexpected failures or significant degradation**. The following five indicators have been identified as critical benchmarks in the European Strategic Energy Technology (SET) Plan and various Horizon Europe projects:

- **Availability factor:** Often referred to as uptime, it measures the percentage of time a CSP or TES plant operates at full or near full capacity. It is a key indicator of operational readiness since maximising uptime directly increases energy production and revenue while reducing maintenance costs.
- **Thermal cycle durability:** It reflects the ability of TES systems to endure repeated charge and discharge cycles without significant performance loss. This indicator is critical because TES undergoes frequent thermal cycling, and degradation can lead to costly replacements or efficiency drops.
- **Mirror degradation rate:** It quantifies the annual loss in reflectivity of CSP mirrors, which reduces solar concentration efficiency. Minimising this degradation is essential to maintain high plant performance and reduce cleaning or replacement costs.
- **Molten-salt freeze events:** This counts the number of times storage salt solidifies unexpectedly, requiring emergency defreezing. Such freezing events can cause mechanical damage and lead to unplanned downtime, making them a critical reliability concern for TES systems using molten salts.
- **Component reliability:** It covers the failure rates and operational stability of essential subsystems. For example, heat transfer fluid (HTF) stability should be guaranteed for a minimum number of operational hours, while receiver components should withstand a determined number of thermal stress cycles. Pumps and valves in commercial CSP plants typically achieve times before failure measured in years of operation.

4.3.2 Technological Maturity

Technological maturity, commonly assessed by Technology Readiness Levels (TRL), provides a standardized framework to measure the development stage of emerging technologies, from initial concept (TRL 1) to full commercial deployment (TRL 9). In the context of 3rd generation

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CSP-TES, many core components remain at relatively low TRLs. Specifically, volumetric receivers operating with air as the heat transfer fluid, combined with sensible and latent thermal storage concepts and solid-state mixtures or phase change materials (PCMs) designed to withstand high temperatures between 800 and 1000°C, are **mostly positioned around TRL 2 or 3**. At these stages, research focuses on fundamental principles and analytical or laboratory proof-of-concept validation under controlled conditions. This highlights the early phase of maturity of these advanced components, underscoring the need for further prototype development and testing.

The SET Plan and the CSP Implementation Working Group establish clear expectations for new technologies in CSP-TES systems to reach maturity levels between **TRL 4 and 6 in the following 5 years**, corresponding to basic technological components integrated together to show that they work together. This phase requires preliminary system validations, including test facilities that combine volumetric receivers, thermal storage, heat exchangers and power cycles operating under solar irradiation.

COOPERANT represents an essential step toward achieving the long-term targets set by the SET Plan by demonstrating the viability of CSP-TES system prototypes at TRL 4. Beyond this initial milestone, the project incorporates a well-defined upscaling strategy designed to progressively increase the technological maturity of these systems. This approach ensures continued advancement toward the SET Plan's objectives of reaching TRL 6 and beyond, where fully integrated, pilot-scale demonstrations validate the technical and operational capabilities necessary for commercial deployment.

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5 Economic KPIs

5.1 Levelized Cost of Energy (LCOE)

The LCOE is a well-known indicator of the profitability of an energy production-related project, such as concentrated solar power (CSP) plants. This KPI is a metric used to assess the average cost of electricity produced over the lifespan of a generating asset. It gives an idea of the minimum price at which energy should be sold to earn money with the performance of the plant throughout a specific period, usually the project lifetime. To define the LCOE, other parameters are needed:

- The total cost of the plant, including both the initial (I) and continuous investments (I_t) during the duration of the project (e.g., replacement of old or damaged equipment) and the annual operations and maintenance (O&M) costs.
- Electrical energy produced in the CSP plant over the years (E_t).
- The considered discount rate (r), which introduces the devaluation of money over the years since the investment in the plant.

The expression that gives the LCOE is the following:

$$\text{LCOE} = \frac{\sum_{t=1}^{lt} \frac{I + I_t + O\&M_t}{(1+r)^t}}{\sum_{t=1}^{lt} \frac{E_t}{(1+r)^t}}$$

In this expression, t is the number of years of the plant's lifetime, and it gives the required energy cost (€/kWh) so that the plant is profitable and gets income from the electricity market.

5.2 Levelized Cost of Storage (LCOS)

The **Levelized Cost of Storage (LCOS)** is a metric that assesses the profitability of an energy storage system (ESS), parallel to the Levelized Cost of Energy (LCOE). The average cost per unit of electricity generated by a power plant's energy storage system (ESS) is determined over the plant's operational period. For facilities such as CSP, where the thermal energy storage (TES) system is essential for profitability and efficiency, this KPI is crucial. Energy storage is decisive in such projects for **increasing efficiency because it allows electricity to be distributed during periods of low or absent generation**, such as at night with solar technologies.

The equation is similar to that of LCOE, with the energy (E) representing the thermal energy released by the TES during plant operation.

5.3 Capital and Operational Expenditures (CAPEX/OPEX)

Both CAPEX and OPEX are widely used indicators in the economic analysis of a project, since they give the basis for the project to operate and generate income from the production of energy:

- **Capital expenditure (CAPEX)**: funds a company uses to acquire, upgrade or maintain assets such as property, industrial buildings, equipment or technology. These investments are intended to provide long-term benefits that extend beyond the current fiscal year and are typically capitalised and depreciated over the components' useful life. A relative indicator derived from CAPEX can be defined to give the cost of installed capacity in the plant, named capital costs (CC):

$$CC = \frac{CAPEX}{P} \text{ (€/kW)}$$

  Where P is the total capacity installed in the plant during a period of time, typically represented by the initial inversion of the installation.
- **Operational expenditure (OPEX):** ongoing costs required for the daily operation of a business, such as labour, utilities, maintenance, consumables and rent. These expenses are necessary to keep facilities functional during the period in which the plant is active, and they are fully expensed in the income statement when they are incurred. The marginal costs (MC) are an indicator of the costs of energy production in the plant during a period:

$$MC = \frac{OPEX}{E} \text{ (€/kWh)}$$

  E is the total energy generated in the plant during the period of time considered for the OPEX.

These indicators should be determined for each of the components of equipment; in CSP, the main components that are usually considered are the receiver, the TES system and the power cycle. At the present state of the project (TRL4), only the first two components have been included in the analyses, so the power cycle will be considered in future upscaling of the project.

5.4 Other economic indicators

In addition to CAPEX and OPEX, several KPI indicators have been taken into consideration under the scope of the task T5.3 - *Technoeconomic and cost-effectiveness analysis*. These indicators, included in Table 8, define both the costs and the profitability of an electric power generation plant, and go beyond a single metric, providing a comprehensive view of the economic viability and technical performance within the incomes of the plant. On the right-hand side of this table, estimated mean values of the CSP-related KPIs are provided based on references; in some cases, these indicators depend on the specific kind of CSP plant (tower, parabolic trough, lineal Fresnel, parabolic dishes) as well as the installed capacity.

Table 8. Economic KPIs included in T5.3- Technoeconomic and cost-effectiveness analysis

KPI	Description	Component system	Units	Reference value
Cash flows (CF)	The total amount of money being transferred into and out of a business	Global	€	0.81M/MW
Net present value (NPV)	The present value of all future cash flows	Global	€	0.602M/MW
Internal rate of return (IRR)	The discount rate that makes the NPV of all future cash flows	Global	-	10 %
Depreciation cost (DC)	Annual value cost of the plant	Global	€	5% CAPEX
Simple payback period (SPB)	Number of years needed to cover the bills of the project	Global	Years	16
Effective cost (EC)	Cost of TES energy capacity installation	TES	€/kWh	0.101

These indicators help to characterise not only the logistic costs and benefits but also capture operational factors that affect overall plant profitability and sustainability. This comprehensive approach allows for more reliable forecasting, investment decisions, and comparisons between different technologies or project options in the same power sector.

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6 Environmental and Socio-Economic Impact KPIs

6.1 Life Cycle Assessment (LCA) indicators

6.1.1 Indicators

The use of Life Cycle Sustainability Assessment is considered a valid support tool for assessing the potential environmental impacts of energy technologies[7]. The KPIs associated with the environmental aspect will be evaluated in the COOPERANT project in T5.2 'Life Cycle Sustainability Assessment (LCSA): LCA + LCC + s-LCA' using the LCA approach. The technology developed in the project will be assessed in accordance with ISO 14040/14044:2006, using SIMAPRO to assess the Product Environmental Footprint (PEF) and ReCiPe methods. The PEF method is based on 16 mid-point environmental impacts with a European scope. The ReCiPe method has 18 mid-point environmental impacts and 3 categories of damage as an endpoint, with a global scope. The methods will be used simultaneously for a more comprehensive assessment. Table 9 presents and relates the mid-point indicators of the two methods. The end-point indicators of the ReCiPe method will not be used to establish KPIs, as these are calculated according to the mid-point indicators.[8,9]

Table 9. Midpoint impact category of a Product Environmental Footprint and ReCiPe methods[10,11]

PEF		ReCiPe	
Impact category	**Unit of measure**	**Impact category**	**Unit of measure**
Climate change	kg CO_2 eq	Climate change	kg CO_2 eq
Ozone depletion	kg CFC-11 eq	Ozone depletion	kg CFC-11 eq
Human Toxicity, cancer	CTUh	Human toxicity: cancer	kg 1,4- DCB
Human toxicity, non-cancer	CTUh	Human toxicity: non-cancer	kg 1,4- DCB
Particulate Matter (PM)	disease incidence	Fine particulate matter formation	kg PM2.5

[7] Asdrubali F., et al. Life cycle assessment of electricity production from renewable energies: Review and results harmonization. 2015. https://doi.org/10.1016/j.rser.2014.10.082
[8] Mikosch N. et al. Relevance of Impact categories … perspective. 2022. - link
[9] European Platform on LCA – EPLCA. Life Cycle Assessment (LCA) - link
[10] European Platform on LCA – EPLCA. Life Cycle Assessment (LCA) - link
[11] Luu L.Q., et al. A Comparison of the Life-Cycle Impacts … methods. 2024 - link

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Ionising radiation, human health	kBq U-235 eq	Ionizing radiation	kBq Co-60 eq
Photochemical ozone formation, human health	kg NMVOC eq	Photochemical oxidant formation: human health	kg NO_x eq
-	-	Photochemical oxidant formation: ecosystem quality	kg NO_x eq
Acidification	mol H+ eq	Terrestrial acidification	kg SO_2
Eutrophication, terrestrial	mol N eq	-	-
Eutrophication, freshwater	kg P eq	Freshwater eutrophication	kg P to fresh water
Eutrophication, marine	kg N eq	Marine eutrophication	Kg N to marine water
-	-	Terrestrial ecotoxicity	kg 1,4- DCB eq
Ecotoxicity, freshwater	CTUe	Freshwater ecotoxicity	kg 1,4- DCB eq
-	-	Marine ecotoxicity	kg 1,4- DCB eq
Land use	Dimensionless – pt	Land use	m^2 ×yr annual cropland eq
Water use	m3 world eq	Water use	m^3 water eq consumed
Resource use, Minerals and metals	kg Sb eq	Mineral resource scarcity	kg Cu eq
Resource use, fossils	MJ	Fossil resource scarcity	kg oil eq

To establish the KPIs, sources such as legal frameworks, public research, peer-reviewed scientific articles and industry reports were identified. The COOPERANT project proposal was also analysed to identify the objectives mentioned for the development of this technology. The KPIs obtained for each impact category are described in the following sub-section.

6.1.2 Life Cycle Assessment (LCA) KPI

Life Cycle Assessment (LCA) is a valuable method for evaluating the environmental impacts of technologies throughout their entire life cycle, from raw material extraction to manufacturing, use, and end-of-life. In the case of CSP-TES systems, LCA helps identify critical environmental KPIs that capture the main ecological pressures associated with the technology.

In assessing the environmental impacts of CSP-TES technology, several categories emerge as critical. Table 10 presents a summary of the main activities related to CSP-TES that influence each impact category of the chosen methods.

Table 10. Influence of CPS-TES activities to each environmental impact category

PEF indicators	ReCiPe indicators	Activity related to CPS-TES	Reference
Climate change	Climate change	Material extraction, manufacturing	[12]
Ozone depletion	Ozone depletion	From refrigerants/chemicals in auxiliary systems	[13]
Human toxicity, cancer, and non-cancer	Human toxicity, cancer, and non-cancer	Heavy metals, persistent pollutants from mining and manufacturing	[14]
Particulate matter	Fine-particulate matter formation	Combustion in material production, transport	[15]
Ionising radiation, human health	Ionizing radiation	Electricity use (nuclear share) in the supply chain	[16]
Photochemical ozone formation and human health	Photochemical Oxidant Formation (Human Health & Terrestrial Ecosystems)	NOx/VOCs from material production and transport	[17]
Acidification	Terrestrial acidification	SO_2/NO_x emissions from material production	[18]
Land use	Land use	Land occupation for mirrors, towers, and infrastructure	[19]
Water use	Water use	Cooling, mirror cleaning (operational phase)	[20]
-	Terrestrial ecotoxicity	Heavy metals, persistent pollutants from mining and manufacturing	[21]
-	Marine ecotoxicity	Heavy metals, persistent pollutants from material extraction	

[12] Gasa G. et al. LCA of CSP plant in tower … salts. 2022 - link
[13] Lassio J.G., et al. LCA of CSP technologies. 2024 – link
[14] Luu L.Q., et al. A Comparison of the Life-Cycle Impacts … methods. 2024 - link
[15] Botejara-Antúnez M. et al. Life cycle and environmental … CSP plants. 2025 - link
[16] Paulillo A., et al. Radiological impacts in LCA. 2020 - link
[17] Kley D., et al. Photochemical oxidants. 1999 - link
[18] Lebrun M. N., et al. Novel endpoint characterization … acidification. 2025 - link
[19] Cellura M., et al. A review on LCA of CSP. 2025 - link
[20] Rohani S., et al. Optimizations of water management for CSP… data. 2021 - link
[21] EPA. Wire and cable insulation and jacketing. 2008 - link

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Ecotoxicity, freshwater	Freshwater ecotoxicity	Heavy metals, chemical leaching from upstream processes	[22]
Eutrophication (freshwater, Terrestrial, Marine)	Freshwater eutrophication	Phosphorus/nutrient emissions from upstream processes	[23]
Resource use, minerals and metals	Resource use, minerals and metals	Use of steel, copper, and rare earths for plant and TES components	[24]
Resource use, fossils	Resource use, fossils	Fossil energy in the supply chain (manufacturing, transport)	[25]

The KPIs identified are described in Table 11 with their corresponding target within the scope of the COOPERANT project. Each objective is supported by the literature, as mentioned in the previous subsection.

Table 11. Environmental KPIs in the COOPERANT project.

KPI - indicator	Method	Reference	COOPERANT Target reduction (%)
Climate change	PEF/ReCiPE	[26,27]	>25%
Ozone depletion	PEF/ReCiPE	[28]	>10%
Human toxicity, cancer, and non-cancer	PEF/ReCiPE	[29]	>15%
Fine-particulate matter formation	PEF/ReCiPE	[30]	5-10%
Ionizing radiation	PEF/ReCiPE	[31]	5-10%
Photochemical Oxidant Formation (Human Health & Terrestrial Ecosystems)	PEF/ReCiPE	[32]	>10%

[22] Oginah S. A., et al. Linking freshwater … life cycle assessment. 2023 - link
[23] EEA. Freshwater eutrophication assessment. 2010 - link
[24] Lassio J.G., et al. LCA of CSP technologies. 2024 – link
[25] Mubarrat M, et al. Research advancement … in CSP application. 2023 - link
[26] Murphy C, et al. The Potential Role of Concentrating Solar Power within the Context of DOE's 2030 Solar Cost Targets. 2019
[27] IRENA. Climate action and the energy transition. 2024 - link
[28] U.S. Department of energy. Solar Futures. 2021 - link
[29] Heath G., et al. Environmental and Circular … Grid. 2022 - link
[30] Heath G., et al. Environmental and Circular … Grid. 2022 - link
[31] U.S. Department of energy. Solar Futures. 2021 - link
[32] European Commission. EU Action Plan: 'Towards Zero Polluion for Ait, Water and Soil'. 2021 - link

Terrestrial acidification	PEF/ReCiPE	[33]	>20%
Terrestrial ecotoxicity	Recipe	[34]	>10%
Land use	PEF/ReCiPE	[35]	5-10%
Water use	PEF/ReCiPE	[36,37]	>15%
Marine Ecotoxicity	ReCiPE	[38]	>10%
Freshwater Ecotoxicity	PEF/ReCiPE	[39]	>10%
Freshwater eutrophication	PEF/ReCiPE	[40]	>20%
Resource use, Minerals and metals/Mineral resource scarcity ReCiPe	PEF/ReCiPE	[41]	>10%
Fossil resource scarcity	ReCiPE	[42]	>20%

The most relevant impact categories identified for CSP-TES technology include **climate change**, due to its extensive GHG emissions; **land use**, given the substantial space requirements; **water use**, because of its high operational demand; and **human toxicity**, linked predominantly to materials extraction and processing. The environmental impact assessment will be presented in **2 reports**, namely D5.2 and D5.7, in months 24 and 44 of the COOPERANT project, in compliance with **SO5.1**, to achieve an overall **reduction in environmental impacts of >20%.**

[33] Heath G., et al. Environmental and Circular ... Grid. 2022 - link
[34] Mehos M, et al. Concentrating Solar Power Best Practices Study. 2020 - link
[35] Murphy C, et al. The Potential Role of Concentrating Solar Power within the Context of DOE's 2030 Solar Cost Targets. 2019
[36] European Commission. Water consumption solution for efficient CSP. link
[37] Murphy C, et al. The Potential Role of Concentrating Solar Power within the Context of DOE's 2030 Solar Cost Targets. 2019
[38] European Commission. Commission raises climate ambition ... 2030. 2020 – link
[39] Hernández-López D.A., et al. Does recycling solar ... dimensions. 2022 - link
[40] European Commission. Towards an integrated nutrient management action plan. 2025 - link
[41] European Commission. A new Circular Economy Action Plan. 2020 - link
[42] International Energy Agency. Technology Roadmap. link

6.2 Circularity and Material Use

The different policy documents, namely the Strategic Energy Technology Plan (SET Plan)[43], the Circular Economy Action Plan (2020) [44], and the Critical Raw Materials Act[45] demonstrate a common approach towards incorporating circularity, eco-design and the responsible use of materials into the next generation of CSP technologies. The SET Plan has no quantitative targets for recycled or secondary materials, but emphasises the availability and longevity of materials, which is in line with the principles of the circular economy and eco-design. The Critical Raw Materials Act (2024) aligns with the Circular Economy Action Plan (2020) in promoting eco-design that improves durability, facilitates dismantling, reuse and recovery, as well as the use of non-critical materials.

Circularity and material use are both key considerations in the development of renewable energy technologies, especially for CSP-TES systems. These aspects aim to reduce dependency on virgin resources, minimise waste generation, and promote long-term sustainability through design choices that facilitate reuse, recycling, and durability. In the case of CSP-TES, where large volumes of steel, concrete, phase change materials (PCM), and molten salts are employed, it is essential to consider these aspects to establish strategies to reduce environmental impacts and improve resource efficiency.

In the COOPERANT project**, circularity** is initially guided by the principles of Safe and Sustainable by Design (SSbD), as presented in the framework published by the Joint Research Centre (JRC). This framework supports early identification of safer and more sustainable materials and processes. Further in-depth evaluation will be carried out within the scope of Task 5.1 "Circularity & Safe and Sustainable by design (SSbD) premises" by HOLOSS, focusing on specific circular indicators related to key materials, notably PCM and solid salts.

To assess circularity, the circularity indicator presented by the Ellen MacArthur Foundation and ANSYS Granta, the Material Circularity Indicator (MCI), will be used in the COOPERANT project.[46] This metric evaluates the circularity of material flows, considering factors such as the ratio of recycled content, end-of-life recyclability and product lifespan. This methodology allows for a structured and quantitative analysis of circular performance and supports decision-making aligned with the principles of a circular economy. Carrying out the LCSA in conjunction with the MCI allows the assessment of the change from linearity to circularity to be holistic, but it is not yet a standardised method. Table 12 presents a life cycle-based circularity assessment

[43] European Commission. On the revision of the Strategic Energy Technology (SET) Plan. 2023 - link
[44] European Commission. A new Circular Economy Action Plan. 2020 - link
[45] European Commission. European Critical Raw Materials Act. link
[46] Ellen MacArthur Foundation, ANSYS Granta. Circularity Indicators: An Approach to Measuring Circularity, Methodology. 2019 - link

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framework that covers all three dimensions of sustainability through LCSA methodologies (LCA, LCC and s-LCA).[47,48, 49]

Table 12 - Requirements for implementing a sustainable circular economy [50]

Sustainability aspects	Requirements
Environmental	R1: Reduction in virgin resource use as inputs.
	R2: Increase in the use of renewable and recyclable resources.
	R3: Decrease in emissions (greenhouse gas emissions and pollutants).
	R4: Decrease in waste and resource loss
	R5: Maximisation of utility and durability of the products/ services.
Economic	R6: Increase in value-added creation.
	R7: Increase in job creation.
Social	R8: Increase in social welfare.

The MCI methodology can be applied to the R's categorised as environmental in Table 12, except for R3, which is addressed through the "Climate change" impact category in the LCA. The requirements presented for social and economic will be presented in the following section. Thus, the KPIs identified are described in Table 13, with their respective target. The targets were determined in alignment with the Strategic Energy Technology Plan (SET Plan)[51], the Circular Economy Action Plan (2020) [52], and the Critical Raw Materials Act[53].

Table 13 - Circular KPI within the COOPERANT project.

KPI	Target COOPERANT
Increased use of material from recycled sources	>10% of weight
Improve years of operation	>25 years
Decrease use of CRM	Reduction of 10-20%

Some aspects of **material use** are being addressed through various indicators within the COOPERANT project. The LCA methodology considers material efficiency and consumption, especially through the KPI for mineral resource scarcity. The environmental impact of raw material extraction and processing is measured by this indicator, as presented in section 6.1.2. The MCI also addresses KPIs related to recycled content and material recyclability.

[47] A. Farooq, et al. Application of LCA for Evaluating Circular Product Systems. 2024 - link
[48] Corona B., et al. Towards sustainable development … metrics. 2019 – link
[49] Ellen MacArthur Foundation, ANSYS Granta. Circularity Indicators: An Approach to Measuring Circularity, Methodology. 2019 - link
[50] A. Farooq, et al. Application of LCA for Evaluating Circular Product Systems. 2024 - link
[51] European Commission. On the revision of the Strategic Energy Technology (SET) Plan. 2023 - link
[52] European Commission. A new Circular Economy Action Plan. 2020 - link
[53] European Commission. European Critical Raw Materials Act. link

One of the six environmental goals of the EU Taxonomy Regulation is the transition to a circular economy. This emphasizes the crucial material efficiency, recycled content, and product durability. Thus, methodologies and indicators presented for the COOPERANT project, such as the application of SSbD, MCI, and LCA-based KPIs, contribute to achieving this objective, demonstrating the alignment with EU sustainability goals. The results of the analysis and strategies will be published in **2 reports**, namely D5.1 and D5.6 'Circularity & Sustainable by design report' in months 18 (preliminary) and 40(final) respectively. Thus, the project establishes a robust foundation for evaluating and enhancing both circularity and material use within CSP-TES technologies.

6.3 Socio-economic indicators

6.3.1 Social Assessment

The updated UNEP Guidelines for Social Life Cycle Assessment (s-LCA)[54], released in late 2020, presents a comprehensive and consensus-driven framework for evaluating social impacts across all phases of a product's life cycle. These revisions advance both methodological rigour and practical implementation, offering refined impact categories, enriched indicators, and newly introduced subcategories designed to enhance the precision and robustness of social assessments. Additionally, supporting this framework, we also highlight the new ISO 14075:2024 standard—Environmental Management – Principles and Framework for Social Life Cycle Assessment[55] —that also establishes a globally recognised protocol for conducting s-LCA. Furthermore, the use of the PSILCA database helps provide a comprehensive and globally sourced dataset on social risks associated with economic sectors and countries, enabling the systematic assessment of social impacts.

In this regard, the selection of social KPIs was carried out in alignment with the principles outlined in T.5.2 – Life Cycle Sustainability Assessment (LCSA), integrating environmental (LCA), economic (LCC), and social (s-LCA) dimensions. These KPIs were contextualised within an ongoing mapping of the COOPERANT value chain, ensuring that social considerations are embedded throughout the assessment framework. In this view, the results of this assessment will be further developed and detailed in the deliverable D5.7 in month 44.

In this sense, given the project's overarching aim to drive innovation in next-generation CSP technologies, a comprehensive evaluation of social impacts was imperative. On that account, for this assessment, we had to consider all five different stakeholders, delineated by the UNEP

[54] UNEP. Guidelines for social life cycle assessment … 2020. link
[55] ISO14075:2024 Environmental management – Principles and framework for s-LCA. link

guidelines[56], crucial for identifying and assessing all relevant social impacts throughout a product's life cycle, which includes **workers, value chain actors, local community, society, and consumers**. Based on this choice, the varying levels of influence of each stakeholder will provide a perspective on how the diverse human involvements impact the CSP technologies deployment. Following this, the subcategories corresponding to each stakeholder group were carefully selected to ensure both relevance and methodological rigour, as detailed in the section below.

In this context, given that the main objectives and scope of the s-LCA within this project are to assess the prototype manufacturing process, the stakeholder category "workers" is expected to be the most prominent. This is due to the significant implications that manufacturing activities have on occupational safety, ethical standards, and sustainability.

- Stakeholder: Worker

The social KPIs for assessment can comprise[57, 58]:

➢**Child labour**: This subcategory aims to analyse if there are cases, along the COOPERANT value chain, whether it exists (conforms with international laws and standards (ILO)), or not, work that deprives children of their childhood, their potential, and their dignity, and that is harmful to physical and mental development.

➢**Health and safety**: This subcategory aims to assess both the rate of incidents and the status of prevention measures and management practices in the COOPERANT value chain related to work activities.

➢**Equal Opportunities/Discrimination**: This subcategory aims to analyse the multiple forms of discrimination that can occur, based on political ideas, gender discrimination or ethnicity. Therefore, for the COOPETANT project, the gender discrimination will be analysed.

➢**Collective Bargaining**: This assessment aims to verify the compliance of the organisation with freedom of association and collective bargaining standards, within the COOPERANT project.

[56] UNEP. Guidelines for social life cycle assessment … 2020. link
[57] ILO Conventions on child labour. link
[58] UNEP. Guidelines for social life cycle assessment … 2020. link

In addition to the "workers" stakeholder category, the analysis of "local communities" emerges as a critical subcategory within the s-LCA framework, given that both small- and large-scale CSP plants can significantly reshape regional landscapes and economic dynamics.[59]

- Stakeholder: Local Community

The social KPIs for assessment can comprise[60]:

➢ **Access to material resources**: This subcategory aims to analyse how communities and organisations may share the use of material resources (natural and man-made) and have a mutual interest in protecting and enhancing the quantity and quality of local resources and infrastructure. Additionally, the idea behind this subcategory is to assess whether the access of local communities to material resources is restricted because of commercial or industrial activities in their regions.

➢ **Delocalisation and migration**: This subcategory aims to analyse whether organisations contribute to delocalisation, migration, or "involuntary resettlement" within communities and whether populations are treated adequately, along the COOPERANT value chain related activities.

Furthermore, attention will be directed toward the stakeholder category of "value chain actors" to understand interactions across various stages of the CSP value chain. This is particularly relevant given the global sourcing of essential CSP components, as analysing these interdependencies contributes to a more comprehensive understanding of social impacts across upstream and downstream processes.

- Stakeholder: Value chain actors

The social KPIs for assessment can comprise[61]:

➢ **Promoting social responsibility**: This subcategory aims to analyse whether the enterprise promotes social responsibility among its suppliers and through its own actions.

In addition, the "society" stakeholder category also warrants detailed consideration, especially regarding broader health, safety, and environmental implications. As CSP technology plays a

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[59] Shankar A., et al. Concentrating solar power plants with storage. 2024 - link
[60] UNEP. Guidelines for social life cycle assessment … 2020. link
[61] UNEP. Guidelines for social life cycle assessment … 2020. link

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pivotal role in decarbonising the energy sector, assessing societal impacts helps ensure that its benefits, such as reduced greenhouse gas emissions and enhanced energy accessibility.[62]

- Stakeholder: Society

The social KPIs for assessment can comprise[63]:

➢ **Corruption:** This subcategory aims to analyse and assess whether an organisation has implemented appropriate measures to prevent corruption and if there is evidence that it has engaged in or has been engaged in corruption.

➢ **Technology Development:** This subcategory aims to analyse and assess whether the organisation participates in joint research and development for efficient and environmentally sound technologies.

➢ **Public commitment to sustainability issues**: This subcategory aims to analyse and assess to what extent an organisation is engaged in reducing its sustainability impacts. Public promises entail a higher binding character than mere internal goals.

Lastly, the stakeholder category "consumers" will be incorporated into the s-LCA analysis, with a particular focus on evaluating the social implications of CSP, generated electricity and components as they reach residential, industrial, and public service end-users. Assessing consumer-related impacts, including affordability, accessibility, and user satisfaction, is essential to ensure that social value is generated beyond technical and economic performance. [64]

- Stakeholder: Consumers

The social KPIs for assessment can comprise[65]:

➢ **End-of-life responsibility**: This subcategory aims to analyse and examine management efforts to address the social impacts of product or service end-of-life.

As a result, within the COOPERANT project, the Reference Scale Approach will be employed to assess both actual and potential social risks along various stages of the value chain. This method enables a structured and comparative evaluation of stakeholder categories based on predefined reference points. The assessment framework will align with the 2020 UNEP

[62] Seyboth K., et al. Renewable Energy … Mitigation. 2012 - link
[63] UNEP. Guidelines for social life cycle assessment … 2020. link
[64] Seyboth K., et al. Renewable Energy … Mitigation. 2012 - link
[65] UNEP. Guidelines for social life cycle assessment … 2020. link

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Guidelines for s-LCA, thereby ensuring methodological robustness and consistency. This reference scale will be used to characterise and quantify the social performance associated with each stakeholder group, as illustrated in Table 14 below.[66]

Table 14. Reference scale for social performance evaluation[67]

Scale level	Description
-2	No data, or Non-compliant situation; no action taken.
-1	Non-compliant situation, but actions to improve have been taken.
0	Compliance with local laws and/or aligned with international standards.
1	Progress beyond compliance is made and monitored.
2	Ideal performance; a positive output achieved and reported.

In this context, as aligned with the LCA KPI's, the social KPI's were established using sources such as legal frameworks, public research, peer-reviewed scientific articles and industry reports. The COOPERANT project proposal was also analysed to identify the objectives mentioned for the development of this technology. The KPIs obtained for each impact category are described in Table 15.

Table 15. Social KPIs within the COOPERANT project

KPI - subcategory	Indicator	Unit of measurement	COOPERANT Target
Stakeholder: Workers			[68,69,70]
Child Labour	Children in employment, total	% of all children, under the age of 15, in employment	**From 0 to +2***
Health & Safety	Accident rate at the workplace	% of fatal and non-fatal job accidents per year	
Equal Opportunities/ Discrimination	Gender wage gap	% of wage gap	
Collective Bargaining	Trade union density	% of employees organised in trade unions	
Stakeholder: Local Community			[71,72]
Access to Material Resources	Certified environmental management systems (CEMs)	CEMs (ISO 14001) in the sector per 10,000 employees	**From 0 to +2***

[66] UNEP. Guidelines for social life cycle assessment … 2020. link
[67] UNEP. Guidelines for social life cycle assessment … 2020. link
[68] United Nations. The 2030 agenda for sustainable development. link
[69] COOPERANT proposal
[70] IRENA. Renewable energy and jobs. 2024 - link
[71] European Commission. COM (2023)160 final. 2023/0079 (COD). link
[72] United Nations. The 2030 agenda for sustainable development. link

Delocalisation and Migration	Number of international migrant workers in the sector	% of total international migrant workers in the sector	
Stakeholder: Value Chain Actors			[73]
Promoting Social Responsibility	Membership in an initiative that promotes social responsibility	Number of companies	**From 0 to +2***
Stakeholder: Society			[74]
Corruption	Active involvement of enterprises in corruption and bribery	Number of bribery cases reported, attributable to specific activity sectors	**From 0 to +2***
Technology Development	Investments in technology development	Number of participating initiatives	
Public Commitments to Sustainability Issues	Presence of publicly available documents as promises or agreements on sustainability issues	Number of publicly available documents or agreements	
Stakeholder: Consumers			[75]
End-of-life Responsibility	Incidents of non-compliance with regulatory labelling requirements	Number of incidents of non-compliance with regulatory labelling requirements	**From 0 to +2***

6.3.2 Social-economic aspect

CSP projects offer a wide spectrum of socio-economic benefits that go beyond their contribution to sustainable energy, supporting a lasting multiplier effect. Integrating socio-economic indicators into every stage of CSP initiatives is essential to ensure fair and equitable outcomes and to promote inclusive development, guaranteeing a socially acceptable transition to renewable energies. [76,77]

In fact, socio-economic indicators play a key role in guiding and evaluating the implementation of CSP by assessing the wider effects on the community's well-being and development. CSP systems, often located near rural communities, can enhance civil society engagement through more equitable employment opportunities, accompanied by

[73] IRENA. Renewable energy and jobs. 2024 - link
[74] United Nations. The 2030 agenda for sustainable development. link
[75] IRENA. Renewable energy and jobs. 2024 - link
[76] European Commission. On the revision of the Strategic Energy Technology (SET) Plan. 2023 - link
[77] Karim M., et al. Systems study of CSP-related socio-economic and livelihood issues. 2019

educational and training programs to support a skilled workforce. These opportunities can reshape living and economic conditions, as they reduce poverty and migration rates, improving regional prosperity and increasing access to essential services through local entrepreneurship and investment in green technologies.[78] When supported by strategic policies and regulations, this investment is further enhanced, as it ensures that the socio-economic benefits of this CSP technology are widely distributed, contributing to local value creation. Furthermore, it contributes to mitigating health and environmental externalities and aligns project goals with broader community needs.[79]

Overall, socio-economic indicators are essential for assessing the impacts of CSP implementation. In turn, these projects actively contribute to improving these indicators, promoting long-term sustainability and strengthening community development. [80]Through a comprehensive analysis of the literature, following the SET Plan perspectives and IRENA's reports on the current state of renewable energies worldwide, the most relevant indicators were selected and attributed to the subcategories in Table 16. The targets presented in the COOPERANT project proposal were also assigned to the indicators, where applicable.

Table 16. Socio-economics KPI within the COOPERANT project

KPI	COOPERANT Target
Job creation	**> 8 jobs/M€** invested in actions aligned with COOPERANT
Local employment	**> 10 jobs/year**
Training and education	**1 Handbook**. COOPERANT-TRANSFER Handbook with training materials. (D6.2)
Equitable Job Opportunities	**2 reports** with mitigation actions to tackle all forms of discrimination. (D5.4 and D5.9)
Energy access and affordability	**1 report** with storage material results, to prove 24/7 solar thermal baseload production. (D3.1) **1 report** assessing energy cost, including <3-10 c€/kWh energy cost reduction by 2030 SET targets. (D5.8)
Industrial competitiveness	**1 report** on COOPERANT CSP-TES competitiveness, supporting the EU's economic growth goals, and enhancing global competitiveness. (D.6.3)
Social return on investment (sROI)	**1 report** accessing the socio-economic benefits of the project, including a sROI >1.

[78] Karim M., et al. Systems study of CSP-related socio-economic and livelihood issues. 2019
[79] IRENA. Leveraging local capacity for concentrated solar power. 2025. ISBN:978-92-9260-644-2
[80] IRENA. Leveraging local capacity for concentrated solar power. 2025. ISBN:978-92-9260-644-2

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7 Comparative Benchmarking Analysis

7.1 KPI Benchmarking Approach and Metrics

The benchmarking approach builds upon the framework defined in D1.3, which established the performance requirements of CSP-TES for key applications (power generation, solar fuels, and industrial heat), and the conceptual and technical designs outlined in D2.1. Data collection combines:

- **COOPERANT Project-specific outputs**: material properties (i.e., PCMs, ceramics), hybrid TES design parameters (cascade-packed beds, modular configurations), and system KPIs (energy density up to 600 kWh/m³, >90% round-trip efficiency, cyclability of 1000 cycles at 800°C).
- **Reference datasets**: targets defined by SET Plan CSP (LCOE < 0.10 €/kWh by 2030, efficiency > 42%), IRENA cost reports, and NREL/IEA datasets, or other international references.
- **Mapping exercise**: COOPERANT KPIs were explicitly linked to SET Plan indicators, including working temperature, energy density, storage capacity, efficiency, and cost

When placed against historical and projected KPI trends for CSP, COOPERANT's performance ambitions go beyond targeted values, see Table 17. Conventional molten salt systems, as deployed in Gemasolar and other EU reference plants, operate at ≤565 °C with storage densities typically below 150 kWh/m³. Current global projects, such as Cerro Dominador in Chile, have pushed storage duration to 17.5 hours but remain constrained by volumetric energy density and thermal stability at higher operating temperatures. The COOPERANT hybrid TES design raises the benchmark by targeting operating windows up to 1000 °C, a storage density of ~600 kWh/m³, and round-trip efficiencies above 90%. These values anticipate and, in some cases, exceed the Gen3 CSP targets of 700 °C operation and ~55% gross cycle efficiency.

Economically, the global LCOE for CSP has gone down from USD 0.40/kWh in 2010 to USD 0.092/kWh in 2024, and the goal is to get it down to USD 0.05/kWh in the future. COOPERANT indirectly helps this trend by making TES solutions that are more compact, have higher temperatures, and higher densities. This leads to lower system CAPEX (<15 €/kWh_{th} for TES) and better competitiveness in EU contexts where land and cost constraints are more severe.

Table 17. KPI Benchmark Matrix (Past / Current / Future vs. COOPERANT)

KPI	Past targets 2010–2015	Current Targets 2024-2025	Future Targets ≈2030+	COOPERANT targets 2024-2028
Operating temperature (receiver/HTF/TES)	Nitrate salts ≤565 °C (e.g., Gemasolar)[81]	Molten-salt tower ~574 °C[84]	Gen3 CSP ≥700 °C³	~800–1000 °C hybrid TES[82]
TES hours (discharge duration)	Gemasolar 15 h[81]	Typical 10 h²; Cerro Dominador 17.5 h[83]	≥12–15 h for firm output[85]	Compact design ~600 kWh/m³ enabling extended hours[82]
Energy density (TES, kWh/m³)	Molten salts ~100–150; PCMs up to 300[84]	Molten salts ≤150 (system-level)[85]	Higher density via higher ΔT[85]	~600 kWh/m³ hybrid sensible+latent[82]
Solar Multiple (SM)	Early plants ~2	NREL baseline SM = 2.4[84]	Higher SM for long-duration TES[85]	>3 recommended for hybrid design[86]
Capacity Factor (CF)	40–50% typical with ~6 h[84]	51–67% with 10 h TES[84]	Higher CF with advanced TES[85]	Improved CF via stable outlet T and cascaded PCM[82]
Thermal-to-electric (gross) efficiency	Limited by ≤565 °C salts[81]	~41% gross at 574 °C[84]	~55% gross at 700 °C[85]	Round-trip storage efficiency >42%[82]
LCOE (utility CSP)	USD 0.402/kWh (2010)[87]	USD 0.092/kWh (2024)[85]	USD 0.05/kWh (SunShot 2030)[85]	CAPEX <15 €/kWh$_{th}$ for TES components[82]
O&M costs	Limited data in early projects	FOM ~74.6 USD/kW-yr (2022)[85]	~55–45 USD/kW-yr by 2030[84]	Lower O&M expected via modular ceramics + AI control[82]

[81] Torresol Energy (2011), *Gemasolar Plant Factsheet*. Molten salt tower, 565 °C, 15 h TES.
[82] COOPERANT Deliverable D2.1 (2024), *Hybrid TES conceptual design*. Specifies hybrid TES: ~600 kWh/m³, ~800–1000 °C, >90% round-trip efficiency, CAPEX target <15 €/kWh-th.
[83] Cerro Dominador (2021), *Project Data Sheet*. 110 MW tower, 17.5 h molten salt TES, Atacama Desert.
[84] NREL (2024), *Annual Technology Baseline*. CSP tower (10 h TES, SM 2.4): gross efficiency ~41%, CF 51–67%, FOM ~74.6 USD/kW-yr.
[85] DOE/NREL (2021), *Gen3 CSP Roadmap*. ≥700 °C target for receiver/TES; projected ~55% gross cycle efficiency; SunShot 2030 LCOE goal ~USD 0.05/kWh.
[86] COOPERANT Deliverable D1.3 (2024), *CSP-TES requirements for potential applications*. Defines TES ranges (100–300 kWh/m³), SM guidance.
[87] IRENA (2024), *Renewable Power Generation Costs in 2024*. CSP LCOE fell from USD 0.402/kWh in 2010 to USD 0.092/kWh in 2024.

7.2 EU and Global Performance Comparison

COOPERANT is developing an innovative **hybrid packed bed TES system** that combines latent and sensible storage with operational temperatures reaching up to ~1000 °C and a **storage density of ~600 kWh/m³** as outlined in the conceptual design in D2.1. This stands in contrast to established global CSP-TES projects that typically employ **molten salt storage** operating at lower temperatures (<600 °C) and rely on either through or tower configurations.

While large-scale commercial CSP installations (such as Noor, Crescent Dunes, and Solana) serve as useful deployment benchmarks, COOPERANT is more closely aligned with research-centric, innovation-focused R&D projects that share its goal of **advancing high-temperature TES technologies** (Table 18). The table below shows how COOPERANT compares to similar initiatives, particularly those funded by the EU or Horizon, in terms of deployment year, storage technology, TRL (research readiness), and storage capacity/density.

Table 18. R&D-Oriented CSP-TES Project Comparison

Project / System	Year Initiated	Storage Technology	TRL Status (at Project End)	Storage Capacity / Density
COOPERANT	2024	Hybrid sensible + PCM	TRL3–TRL4 (Pilot under development)	**~600 kWh/m³** (high-density packed-bed)
InnoSolPower (H2020)[88]	~2020	Micro-thermal TES (μTES)	TRL4-5 (lab to pilot)	Small-scale TES for small applications
TES4Trig (ERA-NET)[89]	~2021	CSP + ORC + TES system	TRL4 (demonstration planned)	Integrated TES for trigeneration systems
CSPplus (ERA-NET)[90]	~2021	Comparative TES concepts	TRL3 (analytical & comparative tools)	Decision-support only; not physical TES
HORIZON-STE (H2020)[91]	~2019	Solar Thermal Electricity	TRL3 (innovation-focused)	Broad STE sector improvements

[88] InnoSolPower (H2020, ~2020), project factsheet. Development of micro-TES (μTES) systems, TRL4–5 lab to pilot, targeting niche distributed applications.

[89] TES4Trig (ERA-NET, ~2021), project summary. CSP–ORC hybrid with TES integration, TRL4 demonstration planned.

[90] CSPplus (ERA-NET, ~2021), project description. Comparative analysis of TES concepts, TRL3, focused on analytical decision-support tools.

[91] HORIZON-STE (H2020, ~2019), Coordination & Support Action. Sector-wide initiative for Solar Thermal Electricity innovation, TRL3 activities only.

PYSOLO[92]	2024	Solar-driven biomass pyrolysis with integrated TES	TRL3–4	TES coupled to pyrolysis for bioenergy valorisation
SUNSON[93]	2023	Thermal-to-electric via advanced TES & phase-change cycles	TRL3–4 (lab scale)	High-temp TES enabling solar-to-electric conversion
ABraytCSPfuture[94]	2023	Redox-oxide structured thermochemical TES	TRL3	Thermochemical TES for Brayton cycle CSP
ASTERIx-CAESar[95]	2023	Air-based solar TES + Compressed Air Energy Storage (CAES)	TRL6–74	Coupled TES + CAES for grid integration
BLAZETEC[96]	2023	High-temperature static thermal-to-electric converters (thermal batteries)	TRL3	Zero-emission thermal-to-electric battery
HERCULES[97]	2023	Hybrid TES for CSP and industrial applications	TRL3	Conceptual hybrid TES solutions
THERMOBAT[98]	2023	Advanced thermal battery concepts	TRL3	Novel TES for electricity/heat coupling

[92] PYSOLO (2024). Solar-driven pyrolysis of biomass coupled with TES, TRL3–4, targeting bioenergy valorisation.
[93] SUNSON (2023). Solar-to-heat-to-electricity conversion, TRL3–4, lab-scale advanced TES and phase-change integration.
[94] ABraytCSPfuture (2023). Redox-oxide thermochemical TES for Brayton cycle CSP, TRL3, structured thermochemical heat exchangers.
[95] ASTERIx-CAESar (2023). TES combined with Compressed Air Energy Storage, TRL3–4, enabling efficient renewable energy integration.
[96] BLAZETEC (2023). High-temp static thermal-to-electric converters ("thermal batteries"), TRL3, zero-emission TES to electricity.
[97] HERCULES (2023). Hybrid TES solutions for CSP and industrial uses, TRL3, early-stage conceptual development.
[98] THERMOBAT (2023). Advanced thermal battery systems, TRL3, novel TES designs for electricity/heat coupling.

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Key takeaways from COOPERANT:

1. **Focus on Innovation:** Unlike utility-scale deployments, these R&D projects—InnoSolPower, TES4Trig, CSPplus, HORIZON-STE and sisterhood projects—are designed to push technical boundaries, explore new configurations, and enable early-stage demonstrations. COOPERANT shares this positioning, operating at the cutting edge of hybrid TES innovation.
2. **TRL Comparison:** COOPERANT is on track to move from TRL3 (lab-scale hybrid TES) to TRL4 (pilot validation), similar to InnoSolPower's lab-to-pilot trajectory. TES4Trig also targets TRL4, but within the specific context of trigeneration systems. With this, COOPERANT is maintaining alignment with Europe's R&D ambitions in CSP.
3. **Storage Density Advantage:** COOPERANT's hybrid TES design—featuring ~600 kWh/m^3 density—is significantly more compact than traditional molten salt systems. This compactness marks a distinct innovation frontier vis-à-vis other R&D projects, most of which focus on system architecture rather than storage density.
4. **Multi-disciplinary Approach:** While CSPplus focuses on modelling and analysis, COOPERANT integrates materials science, sensor control, AI tools, and system design—a comprehensive "lab-to-demo" path that embodies the Horizon framework's ideal for impactful innovation.

At the EU level, COOPERANT's hybrid TES has the potential to outperform conventional molten salt storage by providing higher storage density (>600 kWh/m^3) and stability at temperatures above 1000°C. This represents a step-change compared to reference EU plants such as Gemasolar (565°C molten salts, 15 h storage).

Modelled scenarios from WP3 show that COOPERANT systems can extend storage flexibility while maintaining efficiency >90%, directly supporting SET Plan objectives on dispatchability. Alignment with EU Green Deal priorities is evident in the system's ability to supply firm renewable power and provide industrial heat at scale. Case comparisons highlight the relevance for Spain, Italy, and Cyprus, where solar resource and CSP expertise already exist, but next-generation TES is required for competitiveness.

8 Key Challenges and Strategic Recommendations

8.1 Key Challenges for CSP-TES Deployment

- **Technical:**
  - Ensuring long-term durability of advanced phase-change materials (PCMs) and solid-state mixtures under high-temperature operation levels (~1000 ºC).
  - Addressing thermal stress, corrosion and containment issues in ceramic and metal components and receiver materials.
  - Achieving stable and efficient integration of latent and sensible storage blocks in cascade-packed bed configurations.
  - Demonstrating safety, reliability, and reproducibility of novel hybrid CSP-TES designs, as the COOPREANT CSP-TES, under continuous cycling conditions.
- **Economic:**
  - Current levelised cost of energy (LCOE) for CSP remains higher than PV plus batteries, challenging competitiveness in EU energy markets.
  - High material and manufacturing costs for PCMs and ceramics need optimisation to meet project cost targets (< 15€/kg PCM and < 15€/kWh TES CAPEX).
  - Lack of large-scale industrial manufacturing chains for CSP-specific materials and components limits economies of scale.
- **Policy/Regulatory:**
  - Fragmented and inconsistent EU frameworks for dispatchable renewables hinder investment certainty.
  - Absence of CSP-specific support mechanisms, with most policy incentives currently favouring PV and wind.
  - Limited visibility of CSP's role in the EU's decarbonisation pathways despite its alignment with SET-Plan objectives for dispatchable clean energy.
- **Social/Environmental:**
  - Land use intensity and permitting delays, particularly in southern EU and MENA regions.
  - Need for proactive engagement with local communities to secure acceptance of large-scale CSP facilities.
  - Environmental considerations around raw material sourcing, recyclability, and life-cycle sustainability of the TES components.

8.2 Strategic Recommendations

- **KPI-driven optimisation**:
  - Apply the benchmarking matrix developed in D1.4 to guide material selection, CSP receiver design and TES integration, ensuring alignment with SET-Plan targets for CSP and Horizon Europe Key Performance Indicators.
  - Establish cross-link between material-level KPIs and system-level techno-economic performance indicators.
- **Accelerated testing and validation**:
  - Prioritise accelerated ageing and validation campaigns of TRL3 prototypes (WP2) to assess PCM durability, corrosion resistance, and containment performance.
  - Support early TRL4 pilot integration (WP4) with operational data to validate hybrid TES under representative cycling conditions, feeding the exploitation plan.
- **Cost reduction pathways**:
  - Implement recycled and low-cost ceramics, as identified in D2.1, and pursue scalable encapsulation techniques to reduce material intensity.
  - Encourage industrial partnerships to prepare cost-competitive manufacturing processes for large-scale TES deployment.
- **Policy engagement**:
  - Position CSP-TES as a complementary solution to PV and wind in the EU's decarbonisation mix by emphasising dispatchability, flexibility, and grid stability.
  - Advocate for dedicated auctions, contracts-for-difference, and recognition in EU taxonomy frameworks for firm renewable capacity.
  - Feed project results into EU and national policy dialogues through WP6 knowledge transfer activities and the Stakeholder Replicability Board (SRB).
- **Replication and roadmap alignment**:
  - Integrate benchmarking outputs into D6.4 (Replication Roadmap) to facilitate industrial readiness, scalability, and replicability.
  - Leverage digitalisation (i.e., COOPERANT-AI Tool) for monitoring and replicability assessment, ensuring smooth technology transfer beyond project duration.
  - Align results with the SET-Plan Implementation Working Group on CSP to strengthen Europe's positioning in global markets.

In summary, COOPERANT's hybrid TES benchmarking confirms that, although Europe is currently behind other regions in the scope of CSP deployment, it is uniquely positioned to lead the development of **next-generation thermal energy storage**. The consortium is establishing a cost-effective and replicable pathway for dispatchable solar power by advancing enduring high-temperature PCMs, hybrid packed-bed systems, and AI-enabled orchestration. COOPERANT can ensure competitiveness, sustainability, and a contribution to the **2030 and 2050 decarbonisation objectives by securing EU leadership in the global CSP-TES** sector through adequate policy support, industrial engagement, and replication strategies.

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