



Solar Thermal Energy Assessment (D2.1)

Energytran

Research infrastructures cooperation for energy transition between European and Latin American and the Caribbean countries.



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In addition, the D 2.1. “Paper about solar thermal energy assessment” is also included in Zenodo webpage: [Concentrated Solar Power \(CSP\): Technological Innovations, Hybrid Systems, and Environmental-Social Impacts in the Renewable Energy Transition](#)

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1. Executive Summary

This deliverable presents a comprehensive evaluation of solar thermal energy technologies, with a focus on Concentrated Solar Thermal (CST) and Concentrated Solar Power (CSP) systems. Drawing on insights from more than 200 peer-reviewed studies published between 2018 and 2025, it assesses recent technological advancements, performance improvements, hybrid system configurations, environmental impacts, and socio-economic dimensions relevant to strategic planning and policy development (doi.org/10.5281/zenodo.17641362).

The review highlights significant progress in thermal energy storage (TES), including nanoencapsulated phase-change materials that enhance energy density and cycling stability, as well as nanofluid-based heat transfer fluids—such as Ti_3C_2 and CuO —that improve thermal conductivity by up to 85%. Hybrid CSP/CST systems integrating photovoltaics, geothermal energy, biomass, or hydrogen production demonstrate notable gains in exergy efficiency, water–energy synergies, and CO_2 reductions of up to 90%.

Environmental analyses show current life-cycle greenhouse gas emissions below 50 g CO_2/kWh , with projections indicating potential reductions to around 18 g CO_2/kWh by 2050. Socio-economic assessments underscore the role of CSP and CST in job creation, decentralized electrification, and improved energy sovereignty—particularly in off-grid and Indigenous communities—while also acknowledging challenges related to water use, land transformation, material toxicity, and cultural sensitivities.

Overall, the findings position CSP and CST as cornerstone technologies for a sustainable energy transition, with future development expected to center on modular, hybrid, and community co-designed systems supported by robust policy frameworks and strong environmental safeguards.

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2. Objectives of the review

The review aims to:

- **Assess Technological Advancements**

Evaluate recent developments in Concentrated Solar Thermal (CST) and Concentrated Solar Power (CSP) technologies, including improvements in thermal energy storage, heat transfer fluids, and system integration.

- **Analyze Performance and Efficiency Metrics**

Review and compare performance indicators—such as thermal conductivity, energy density, exergy efficiency, and system reliability—based on evidence from over 200 peer-reviewed studies (2018–2025).

- **Evaluate Hybrid Renewable Configurations**

Examine the technical and environmental benefits of hybrid CST/CSP systems combining photovoltaics, geothermal, biomass, and hydrogen production, focusing on synergies, flexibility, and decarbonization potential.

- **Assess Environmental and Life-Cycle Impacts**

Quantify greenhouse gas emissions, water consumption, land use, and material sustainability, including projected reductions in life-cycle emissions by 2050.

- **Examine Socio-Economic and Community Impacts**

Investigate the socio-economic contributions of CSP/CST, such as employment, decentralized electrification, and benefits for rural and Indigenous communities, while identifying challenges related to cultural sensitivity and resource use.

- **Identify Barriers and Risks**

Highlight technical, environmental, and socio-cultural challenges—such as nanomaterial toxicity, land transformation, and water requirements—that may constrain deployment.

- **Support Strategic Planning and Policy Development**

Provide evidence-based insights to guide policymakers, industry stakeholders, and research institutions in designing robust regulatory frameworks, supporting innovation, and accelerating sustainable CSP/CST deployment.

3. Context and Relation to the Project

This deliverable directly supports the EU-SOLARIS ERIC mission to strengthen European leadership in solar thermal research infrastructures by consolidating scientific knowledge and guiding strategic planning. It aligns with broader energy transition objectives and contributes to coordinated work among partners engaged in CST technology development, thermal energy storage, beam characterization, and hybrid renewable energy solutions.

Within the project framework, this assessment also serves as a joint Europe–Latin America and the Caribbean (LAC) initiative aimed at identifying the most viable, impactful, and urgent applications of solar thermal energy in both regions. The analysis focuses on solutions with high potential to reduce environmental impacts and accelerate the decarbonization of national and regional energy systems.

The deliverable further supports the production of academic publications—including research papers and technical analyses—derived from the scientific knowledge generated through collaborative mobility actions. These efforts are implemented in close coordination between EU-SOLARIS ERIC researchers and the participating LAC research infrastructures and institutions, ensuring that the outcomes advance shared scientific goals and contribute to innovative pathways for the global energy transition.

4. Methodology

The assessment presented in this deliverable is based on a structured and multi-dimensional approach, including:

Comprehensive Literature Review: Examination of over 200 peer-reviewed studies published between 2018 and 2025, covering technological advancements, performance metrics, environmental impacts, and socio-economic aspects of CST and CSP systems.

Techno-Economic and Environmental Analysis: Evaluation of system performance, cost-effectiveness, and sustainability using techno-economic data and life-cycle assessment (LCA) methodologies.

Case Study Review: Analysis of CST and hybrid CSP system deployments across Europe, Africa, Asia, and Latin America to identify best practices, operational challenges, and regional adaptation strategies.

Integration of Project and Database Insights: Incorporation of findings from SolarPACES databases and project-specific research outputs to provide a comprehensive understanding of technological trends, hybrid system performance, and regional applicability.

This methodology ensures a robust, evidence-based assessment of CST and CSP technologies, supporting strategic planning, policy development, and cross-regional collaboration.

5. Assessment of Solar Thermal Energy. Assessment of Solar Thermal Energy

5.1. TECHNOLOGY OVERVIEW

Concentrated Solar Thermal (CST) and Concentrated Solar Power (CSP) systems encompass a range of architectures, including Parabolic Trough Collectors (PTC), Solar Power Towers (SPT), Linear Fresnel Reflectors (LFR), Parabolic Dish Systems (PDS), and next-generation receivers such as Falling Particle Receivers (FPR) and star-shaped geometries. Key technological innovations include:

- **Multi-tower receiver systems** that reduce spillage and optical attenuation losses.
- **Adaptive AI-based control systems** to optimize optical alignment and tracking.
- **Advanced materials** such as MXenes, WS₂ nanofluids, and ALD-coated phase-change materials (PCMs) enhancing heat transfer performance.
- **Particle receivers** capable of operating above 700°C, enabling high-efficiency Brayton cycles.
- **Integration of liquid lead heat transfer fluids (HTFs)** and circular-economy approaches for sustainable material use.

These innovations collectively improve thermal performance, scalability, and sustainability of CST/CSP systems.

5.2. PERFORMANCE AND EFFICIENCY

Thermal efficiency varies by technology:

- PTC: 38–42%
- SPT: 40–45%
- PDS: up to 50%

High-temperature systems (>700°C) enable supercritical CO₂ cycles, offering improved exergy efficiency. Nanofluid-enhanced HTFs increase thermal conductivity by up to 85%, while hybrid configurations achieve additional benefits:

- 2–10% efficiency improvements through AI-enabled tracking and control.
- Up to 90% reductions in CO₂ emissions depending on hybrid configuration.
- Stable 24/7 energy output when coupled with biomass or geothermal systems.

These results underscore the potential of CSP to provide reliable, high-efficiency energy in both centralized and decentralized applications.

5.3. ENVIRONMENTAL ASSESSMENT

Life-cycle assessments indicate that CSP systems currently emit less than 50 g CO₂/kWh, with projections suggesting reductions to 18 g CO₂/kWh by 2050. Key environmental considerations include:

- **Water Use:** Dry cooling technologies can reduce consumption by up to 93%.
- **Material Impacts:** Steel and concrete dominate embodied energy and environmental footprint.

- **Biodiversity:** Large-scale deployments can cause habitat fragmentation and microclimate alterations.
- **Pollution Risks:** Chemicals, dust suppressants, and end-of-life waste must be managed responsibly.
- **Recycling:** Recycling of steel and aluminum components can reduce environmental impact by up to 50%.

Sustainable design and environmental safeguards are essential to minimize adverse effects.

5.4. ECONOMIC & SOCIAL ASSESSMENT

CSP contributes to regional development by generating construction and operation employment. Key points include:

- **High CAPEX:** Remains a primary barrier to large-scale deployment.
- **Thermal Energy Storage (TES):** Enhances market value and dispatchability.
- **Grid Services:** Supports stability and ancillary services.
- **Socio-Cultural Challenges:** Land-use conflicts and community acceptance must be addressed.
- **Indigenous Engagement:** Programs co-designed with Indigenous communities demonstrate positive socio-economic outcomes.

These insights highlight the need to balance economic feasibility with social inclusivity and community participation.

5.5. COMPARATIVE EVALUATION

- **PTC:** mature, cost-effective, limited to ~400°C.
- **SPT:** higher temperatures, scalable, ideal for hybridization.
- **LFR:** low cost but lower efficiency.
- **PDS:** highest efficiency, best for off-grid modular supply.
- **FPR:** enables ultra-high-temperature cycles. Hybrid systems (CST+biomass, CST+geothermal, CST+PV) offer superior reliability, exergy rates, and water-energy synergies.

Hybrid systems (e.g., CST+biomass, CST+geothermal, CST+PV) offer superior reliability, improved exergy efficiency, and enhanced water–energy synergies, making them highly promising for future energy transitions.

6. Key Findings

CSP as a Critical Renewable Solution:

- CSP technologies provide dispatchable renewable energy, enable high-temperature industrial processes, and integrate effectively with thermal energy storage, making them a key component of the energy transition.

Technological Advancements:

- Innovations in nanomaterials, thermal fluids, artificial intelligence, and wireless monitoring have improved CSP efficiency, storage capacity, reliability, and economic viability.

Hybrid System Potential:

- Coupling CSP/CST with photovoltaics, geothermal, hydrogen, biomass, and other energy vectors enhances grid flexibility, energy security, and CO₂ reduction, offering a promising route to replace fossil fuels.

Environmental and Life-Cycle Considerations:

- Despite being renewable, CSP systems involve material use, land transformation, water consumption, and potential chemical pollution. Life-cycle and environmental assessments are essential to minimize negative impacts.

Socio-Cultural Dimensions:

- Large-scale deployments must consider community participation, cultural sensitivity, and equitable access, particularly in Indigenous and remote communities.
- Examples from Costa Rica, Mexico, and Chile show that CSP can improve energy access and support sustainable development in historically marginalized populations.

Institutional and Policy Needs:

- Successful CSP adoption requires robust policy frameworks, culturally appropriate designs, equitable financing mechanisms, and long-term technical support.

7. Conclusions & Recommendations

Concentrated Solar Thermal (CST) and Concentrated Solar Power (CSP) systems are a cornerstone of high-temperature renewable energy, offering both dispatchable electricity and industrial process heat. To fully realize their potential, future priorities should focus on:

- **Scaling Hybrid Multigeneration Systems:**

Promote integration of CSP/CST with photovoltaics, geothermal, hydrogen, biomass, and other energy vectors to maximize flexibility, efficiency, and decarbonization potential.

- **Expanding Long-Duration Thermal Storage:**

Enhance storage capacity and reliability through advanced thermal fluids, phase-change materials, and innovative storage technologies to ensure continuous energy supply.

- **Strengthening Environmental Safeguards:**

Incorporate life-cycle assessments, responsible material selection, and careful site planning to minimize impacts on land, water, and ecosystems.

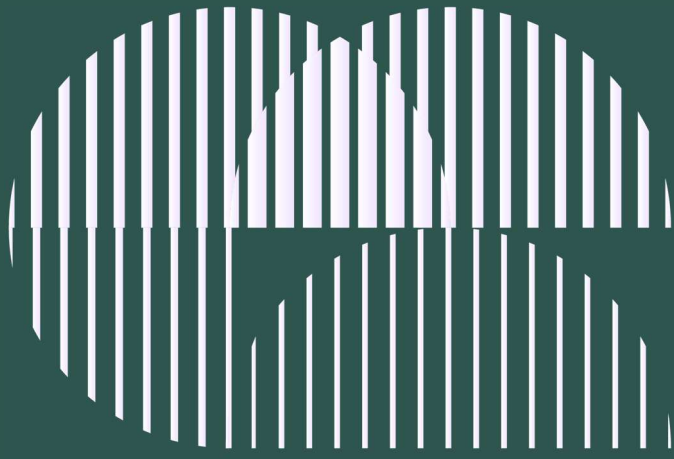
- **Enhancing Community Engagement:**

Involve local and Indigenous communities in co-design, decision-making, and benefit-sharing to ensure socially inclusive and culturally sensitive deployment.

- **Increasing Demonstration Projects:**

Expand pilot and demonstration projects to lower capital expenditure (CAPEX), reduce technical and financial risks, and accelerate broader market adoption.

These strategic actions position CST/CSP as a key enabler of a sustainable, reliable, and socially inclusive energy transition.



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