Additively Manufactured Ceria Architectures for Efficient Solar Thermochemical Fuel Production

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INTRODUCTION

Decarbonization of fossil fuel–intensive sectors such as aviation requires renewable fuels with high energy density. Among the various sustainable fuel pathways under development, solar thermochemical fuel production using concentrated solar power (CSP) has emerged as a promising route for producing renewable hydrocarbon fuels from carbon dioxide and water (Romero and Steinfeld, 2012) and is being investigated in the framework of the SUNlight-to-LIQUID II (STL-II) project (Fig. 1).

Solar thermochemical cycles based on metal oxides enable the direct conversion of high-temperature solar heat into chemical energy. In a typical two-step redox cycle, a metal oxide is first thermally reduced using CSP, releasing oxygen. In a subsequent oxidation step, the reduced oxide reacts with CO_2 and H_2O to produce H_2 and CO, forming synthesis gas (syngas). Syngas can then be converted into liquid hydrocarbons using established catalytic processes such as Fischer–Tropsch synthesis (process summarized in Fig.1).

Cerium oxide (CeO_2, also known as ceria) is one of the most promising redox active materials due to its non-volatile nature, stability, and reversible oxygen storage capacity (Fig. 2)

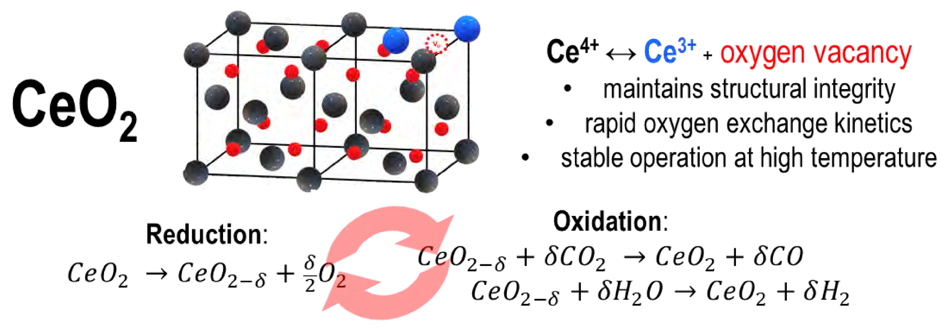

Fig. 2 Properties of cerium oxide as active material in solar-driven thermochemical redox cycles

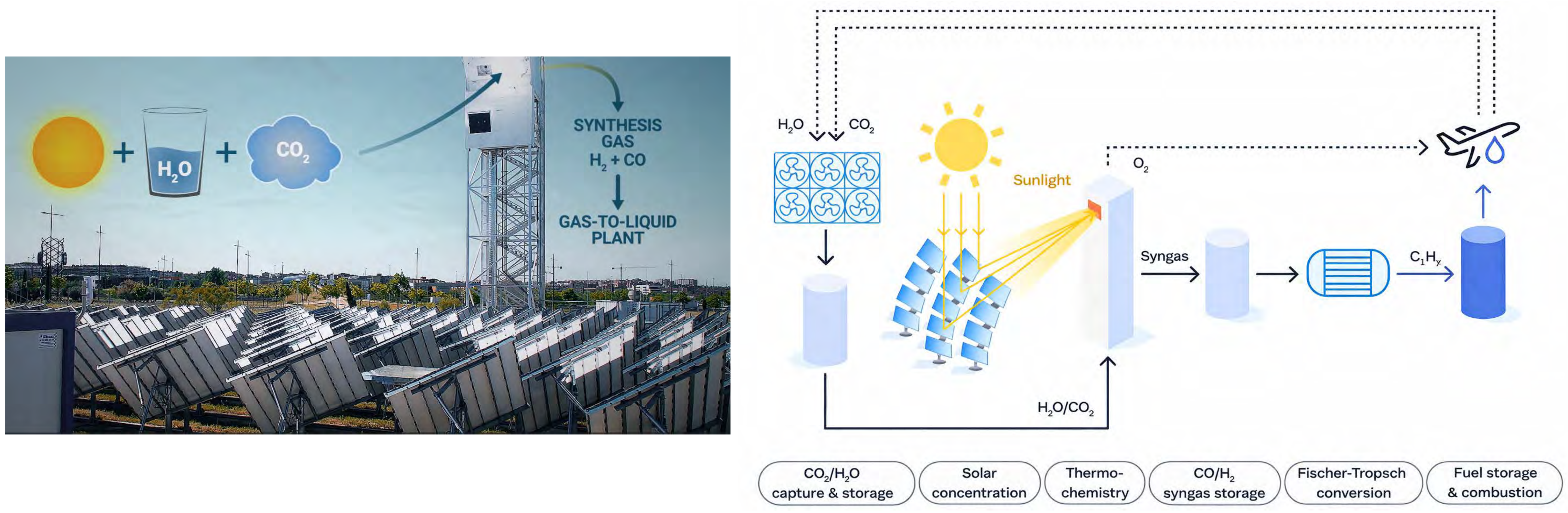

Fig. 1 SUN-to-LIQUID process for solar hydrocarbon fuel production via thermochemical redox cycles with a view of the IMDEA Energy solar field

The performance of ceria-based redox systems strongly depends on the material morphology and internal architecture, which determine optical penetration depth, heat transfer, and reaction kinetics (Sas Brunser and Steinfeld, 2023).

STL-II builds upon the achievements of the first SUN-to-LIQUID project, which demonstrated the production of solar kerosene from H_2O and CO_2 in a solar tower reactor using reticulated porous ceramic (RPC) ceria structure, achieving a solar-to-fuel efficiency of approximately 4.1% (Zoller et al., 2022). STL-II aims to significantly advance this technology by introducing new structured redox materials, improved solar reactor concepts, and advanced heat recovery strategies to substantially increase the overall efficiency of the process.

CHALLENGES OF SUN-TO-LIQUID II AND CERIA MATERIAL FABRICATION

The central STL-II target is to reach 15% solar-to-fuel efficiency at 50 kW scale, corresponding to roughly a threefold improvement over the current state-of-the-art (Fig. 3). A multidisciplinary approach is adopted to tackle this challenge by combining the development of (summarized in Fig. 4):

- novel structured redox materials
- high-temperature heat recovery
- advanced solar reactor concepts
- enhanced solar concentrating and tower operation for reliable on-sun operation
- upscaled syngas-to-kerosene processing

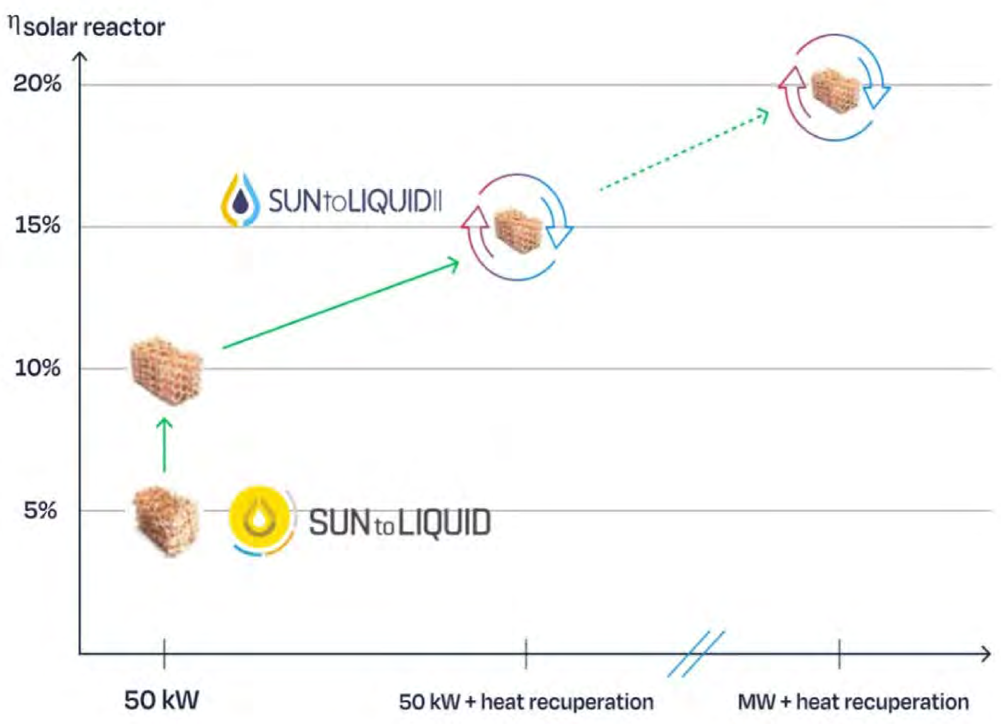

Fig. 3 SUN-to-LIQUID II roadmap regarding the advancement of solar energy conversion efficiency

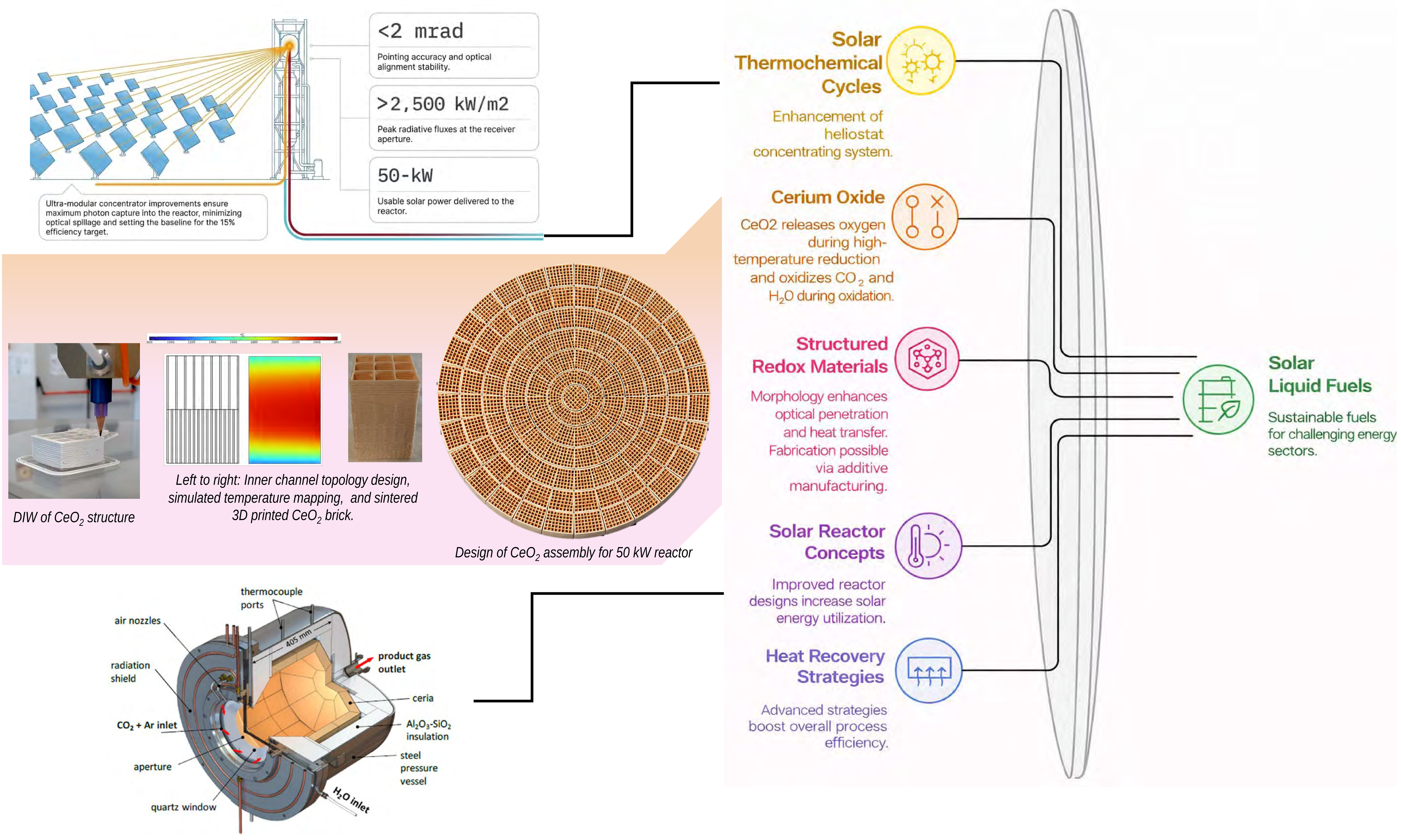

Fig. 4 Strategies of the SUN-to-LIQUID II project to achieve the world-record efficiency of 15 %

Ceria is treated as both an active redox medium and an engineered solar-absorbing structure. The thermal properties at ~1500ºC reached by direct solar irradiation make the internal temperature field and effective absorptance strongly dependent on the architecture morphology. Consequently, the design of the porous structure of ceria, meaning porosity and channel topology, govern optical penetration depth and effective thermal conductivity, which determine the grade of reduction (δ, see Fig. 2) of CeO_2 and cycle efficiency.

Hierarchically structured ceria architectures with engineered channel topology have been designed to promote more homogeneous temperature fields and enhance the δ of the ceria material and fuel productivity. Additive manufacturing, or 3D printing via direct ink writing (DIW), offers enough flexibility to fabricate such hierarchically porous structures with wall size down to 0.5 mm and channel size down to 1 mm. These structures have been tested under high-flux conditions at both single-brick and 5-kW scales. In parallel, recyclability and circularity have been investigated by recovering ceria after sintering and redox cycling, indicating that recycled ceria-based structures can be reprocessed without major performance penalties, supporting future resource-efficient deployment.

Current efforts concentrate on scaling these porous 3D printed ceria monoliths from lab-scale to the 50-kW field reactor. The strategy focuses in designing a self-supporting and modular assembly of 3D printed ceria bricks (Fig. 4)

CONCLUSIONS

- The SUN-to-LIQUID II project constitutes a significant effort to advance solar thermochemical fuel production toward higher conversion efficiencies and increased technological maturity. Despite the inherent system complexity and the multidisciplinary nature of the challenges involved, the project is currently progressing in line with its primary objectives.
- The fabrication via additive manufacturing of the engineered CeO_2 ceramic porous structure was implemented for the 50-kW scale. Enhanced radiative absorption, improved thermal uniformity, and high thermal stability of the modular monolith assembly have been validated through simulations and experimental testing at the 5 kW scale, demonstrating strong potential for scale-up.
- With the 15 % sun-to-fuel efficiency performance expectations, the STL-II trajectory indicates the potential to achieve at the multi-MW scale >80% greenhouse-gas emission reduction and fuel production cost below 1.5 € L^{-1}.
- The next phase of the project will focus on experimental validation under real solar conditions, with on-sun testing campaigns in a solar tower facility planned to begin in the last trimester of 2026. These experiments will represent a crucial step toward demonstrating the viability of solar thermochemical fuel production at relevant scale.

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REFERENCES

M. Romero, A. Steinfeld (2012). Concentrating solar thermal power and thermochemical fuels. *Energy & Environmental Science* 5 (11) 9234.

S. Zoller, E. Koepf, D. Nizamian, M. Stephan, A. Patané, P. Haueter, M. Romero, J. González Aguilar, D. Lieftink, E. De Wit, S. Brendelberger, A. Sizmann, A. Steinfeld (2022). A solar tower fuel plant for the thermochemical production of kerosene from H2O and CO2. *Joule* 6 (7) 1606.

S. Sas Brunser, A. Steinfeld (2023). Design and Optimization of Hierarchically Ordered Porous Structures for Solar Thermochemical Fuel Production Using a Voxel-Based Monte Carlo Ray Tracing Algorithm. *ACS Engineering Au* 3 (5) 32

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