LONG-TERM IMPACT

Solar transportation fuels for decarbonization of mobility

Replicability
SUN-to-LIQUID ensures scalability by using only abundant feedstock (H_2O, atmospheric CO_2) and solar energy for fuel production. Analogous to CSP for electricity generation, solar fuel plants are most suitable for areas with high solar irradiation found e.g. in Southern Europe and most Middle Eastern and North African countries. The size of a typical solar fuel plant will be equivalent to about 1000 barrels of crude oil per day; about 6000 solar fuel plants are required to meet the current jet fuel consumption of 6 million barrels per day.

Socio-economics
The technology adds great fuel production potential to the renewable fuel portfolio and enables regional diversification, as solar fuel production does not require arable land and does not compete with food production. The technology is suitable to create economic benefits, to enhance fuel supply security and to generate jobs through replicability in a global market.

Environment
Solar fuel production is truly scalable as less than 1% of the arid land is sufficient to meet the global fuel demand. Adverse effects due to direct or indirect land use change are very low compared to biofuel pathways. Furthermore, low water consumption is a distinct feature of solar thermochemical fuel production. The environmental analysis reveals a significant greenhouse gas reduction potential of at least 80% in comparison to fossil fuels.

Market Transformation
SUN-to-LIQUID aims at a sustainable production of "drop-in" transportation fuels, which will transform an existing market from the upstream side. This transformation is expected to result in more distributed fuel production and fuel logistics. In addition, a global plant construction will generate a new market for CO_2 capture from air and high-performance solar concentration technology.

Policy
Besides the profound environmental benefits from using renewable CO_2 and solar energy, SUN-to-LIQUID fuels contribute to supply security and can stimulate job creation in economically challenged regions.

SUN-TO-LIQUID INFORMATION EXCHANGE: GET INVOLVED

The Technology Transfer and Stakeholder Exchange Platform (TTSEP)

You can be part of the SUN-to-LIQUID journey towards solar fuel production technology beyond the state of the art and support the scale-up towards a future industrial realization by **joining the SUN-to-LIQUID Community** fostering experts exchange on **perspectives and implementation requirements** of SUN-to-LIQUID fuels.

The SUN-to-LIQUID Community gathers leading experts and stakeholders, such as researchers, renewable energy investors, end-users of solar fuels or alternative fuels in general, representatives of related industries, members of social and environmental groups as well as policy makers.

- **Be informed about the latest SUN-to-LIQUID news**
- **Join discussion groups**
- **Contribute to the development of solar thermochemical fuels**

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Pictures courtesy of the SUN-to-LIQUID Project Partners

SUN to LIQUID
Fuels from concentrated sunlight

UNLIMITED RENEWABLE FUEL SUPPLY FROM H_2O, CO_2 AND SOLAR ENERGY

The technology developed by SUN-to-LIQUID has the potential to cover future fuel demand as it establishes a radically different path to the synthesis of renewable liquid hydrocarbon fuels from abundant feedstocks of H_2O, CO_2 and solar energy. The complete integrated fuel production chain will be experimentally validated at a pre-commercial scale and with record-high energy conversion efficiency.

FROM THE LABORATORY TO THE FIELD

Reduction-oxidation cycle for solar thermochemical fuel production

SUN-to-LIQUID develops a technology to synthesize renewable liquid hydrocarbon fuels from abundant feedstocks of H_2O, CO_2 and solar energy. Concentrated solar radiation drives a **thermochemical redox cycle**, which operates at high temperatures and utilizes the full solar spectrum. Thereby, it provides the potential of **high energy conversion efficiency** and economic competitiveness.

The primary objective of SUN-to-LIQUID is the scale-up and experimental validation of the complete process chain to solar liquid hydrocarbon fuels from H_2O, CO_2 and solar energy. The technological readiness level (TRL) of solar thermochemical fuels will be advanced from TRL 3-4 (4 kW setup in the laboratory) to a TRL 5 (50 kW plant in the field).

SUN-to-LIQUID joins leading European research organizations and companies in the field of solar thermochemical fuel research, namely ETH Zurich (CH), IMDEA Energía (ES), DLR (DE), Abengoa Solar New Technologies (ES) and HyGear Technology & Services B.V. (NL). The coordinator, Bauhaus Luftfahrt (DE), takes responsibility for system and technology analyses, and ARTTIC (FR) supports the Research Consortium with project management and communication.

Core technology

Development of a two-step solar thermochemical fuel cycle based on metal oxide redox material

SUN-to-LIQUID uses concentrated solar radiation as the source of high-temperature process heat to drive endothermic chemical reactions for solar fuel production. The core process is a two-step thermochemical cycle for **splitting H_2O and CO_2 using metal oxide redox materials.**

1st step, reduction $\quad MO_{ox} \longrightarrow MO_{RED} + \frac{1}{2} O_2$

2nd step, oxidation

with H_2O $\quad MO_{RED} + H_2O \longrightarrow MO_{ox} + H_2$

with CO_2 $\quad MO_{RED} + CO_2 \longrightarrow MO_{ox} + CO$

The project uses **non-stoichiometric cerium oxide** (ceria) which has emerged as an **attractive redox active material** due to its high oxygen conductivity and cyclability, while maintaining its structure and phase.

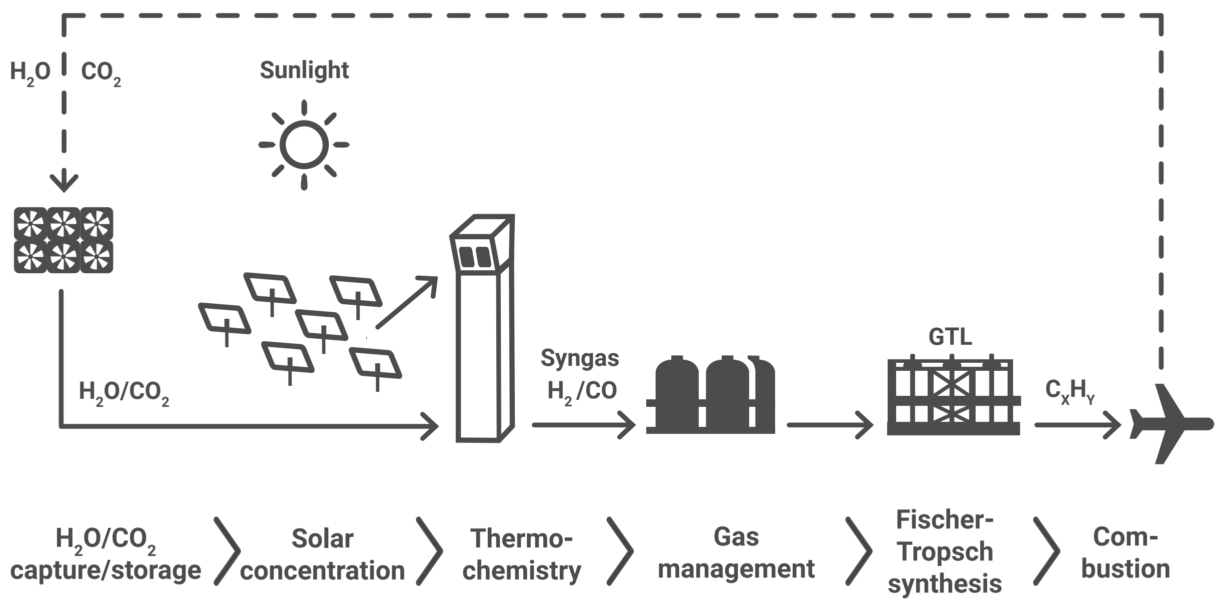
SUN-to-LIQUID Innovations

Key innovations from pioneering solar fuel plant

The following key innovations are expected from the SUN-to-LIQUID project:

- Advanced modular solar concentration technology for high-flux/high-temperature applications.
- Solar modular reactor technology for the thermochemical production of syngas from H_2O and CO_2 at field scale and with record-high solar energy conversion efficiency.
- Optimization of high-performance redox materials and RPC structures, favourable thermodynamics, rapid kinetics, stable cyclic operation, and efficient heat and mass transfer.
- 50 kW pre-commercial integration of all subsystems of the process chain to solar liquid fuels, namely: the high-flux solar concentrator, the solar thermochemical reactor, and the gas-to-liquid conversion unit.

TECHNICAL IMPLEMENTATION

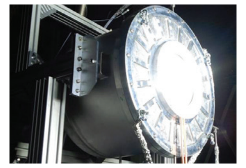


A pioneering solar fuel plant which consists of three basic sub-systems:

1. High-flux ultra-modular solar heliostat field:

A high-flux solar concentrating subsystem, consisting of a sun-tracking heliostat field and a small tower. The solar concentrating system achieves an average energy flux beyond 2500 suns at the solar reactor's aperture, exceeding solar concentration ratios typically obtained in Concentrated Solar Power (CSP) plants for electricity generation.

2. Scaled-up solar thermochemical reactor:



A solar thermochemical reactor subsystem for syngas production from H_2O and CO_2 via the ceria-based thermochemical redox cycle, with optimized heat transfer, fluid mechanics, material structure, and redox chemistry, as well as the reliable integration of all peripheral components of the upstream solar concentrating subsystem and of the downstream gas-to-liquid (GTL) conversion subsystem.

3. Gas-to-liquid conversion subsystem:

A gas-to-liquid conversion subsystem, comprising compression and storage units for syngas and a dedicated micro Fischer-Tropsch unit for the synthesis of liquid hydrocarbon fuels.

All subsystems are integrated for a close-coupled operation of the fuel production chain under field conditions. The research infrastructure is located at IMDEA Energía within the Móstoles Technology Park, South-West of Madrid. SUN-to-LIQUID will parametrically optimise the solar thermochemical fuel plant and run a **long-term operation campaign** on a daily basis **under realistic steady-state and transient conditions** relevant to later commercial implementations.

PROGRESS AND PERSPECTIVES

High solar-to-fuel energy conversion efficiency as a driver for economic competitiveness

The most relevant performance indicator and the key to economic competitiveness is the solar-to-fuel energy conversion efficiency $\eta_{solar\text{-}to\text{-}fuel}$ defined as:

$$\eta_{solar\text{-}to\text{-}fuel} = \frac{\text{heating value of liquid fuels produced}}{\text{solar radiative energy input}}$$

$$= \eta_{optical} \cdot \eta_{solar\ reactor} \cdot \eta_{gas\text{-}to\text{-}liquid}$$

The main objective of SUN-to-LIQUID is to improve the solar reactor efficiency. The EU-funded FP7 project SOLAR-JET (www.solar-jet.eu) achieved unprecedented experimental record values of $\eta_{solar\ reactor}$ of 1.73% on average and 3.53% at peak for the solar splitting of CO_2 to CO and O_2 with a lab-scale 4 kW solar reactor. A detailed thermodynamic analysis indicates a potential for $\eta_{solar\ reactor}$ exceeding 30%. SUN-to-LIQUID aims at experimentally demonstrating $\eta_{solar\ reactor} \geq 10\%$ peak, about three times the record value obtained in the ETH Zurich laboratory (Figure 1). Finally, a design study at MW scale will prepare for the next steps along the consortium's roadmap to develop the technology for commercial solar fuel production at large scale. Thus SUN-to-LIQUID results will contribute to the long-term perspective of increasing production of liquid transportation fuels from sustainable resources.

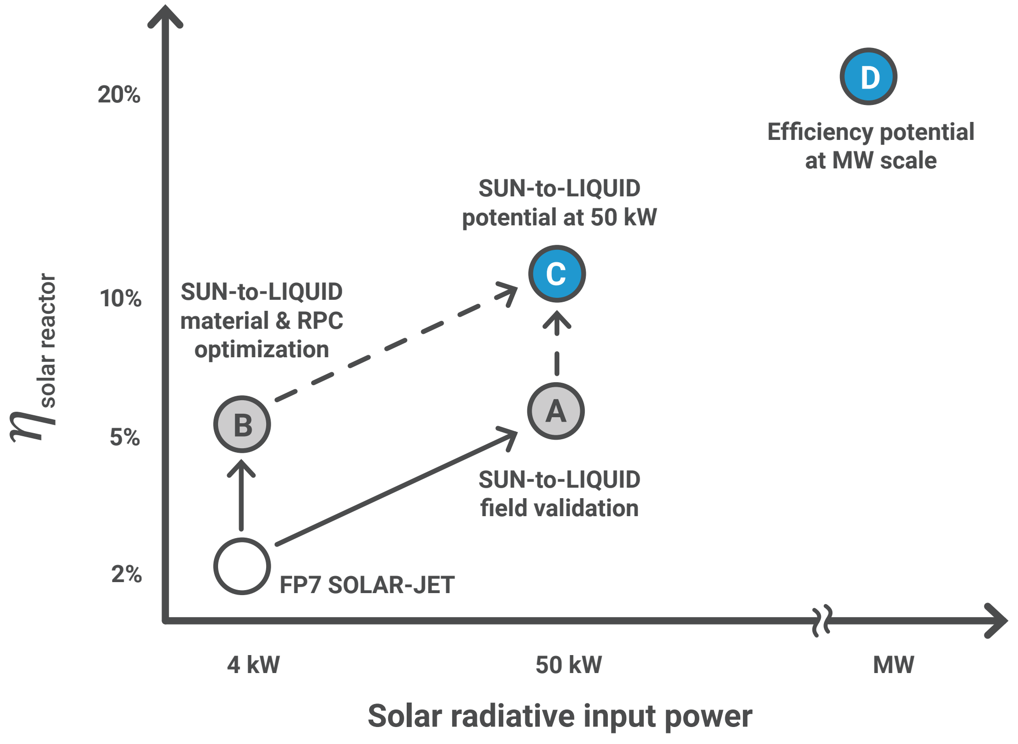


Figure 1: Roadmap towards competitive solar fuel production at large scale. The EU-FP7 project SOLAR-JET has achieved a solar reactor efficiency of 1.7% in a laboratory 4 kW setup. SUN-to-LIQUID aims at a solar reactor efficiency beyond 5%, enabled by scaling to a higher radiative power level (A) and material optimization (B). A combination of advanced materials and scaling up has the potential to achieve 10% peak efficiency at the 50 kW scale (C). Prospectively a solar reactor efficiency target of >20% can be achieved by further material development, scale-up and the implementation of advanced thermal management concepts (D).