ISSN 1831-9424

European Commission

CLEAN ENERGY TECHNOLOGY OBSERVATORY

DIRECT SOLAR FUELS IN THE EUROPEAN UNION

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS AND MARKETS

2022

Joint Research Centre

EUR 31253 EN

Contact information
Name: Nigel TAYLOR
Email: nigel.taylor@ec.europa.eu

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC130836

EUR 31253 EN

PDF ISBN 978-92-76-57685-3 ISSN 1831-9424 doi:10.2760/361656 KJ-NA-31-253-EN-N

Luxembourg: Publications Office of the European Union, 2022

How to cite this report: Taylor, N., Joanny, G., Eulaerts, O. and Grabowska, M., *Clean Energy Technology Observatory: Direct Solar Fuels in the European Union - 2022 Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, 2022, doi:10.2760/361656, JRC130836.

Contents

Foreword

This report is an output of the Clean Energy Technology Observatory (CETO). CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

CETO is being implemented by the Joint Research Centre for DG Research and Innovation, in coordination with DG Energy.

Acknowledgements

The authors are very grateful for the contributions received from Philippe Schild (RTD), Thomas Schleker (RTD) and Francesco Matteucci (EISMEA), and for Giulia Serra's (ENER) support.

Special thanks are due to Frederic Chandezon (CEA), Carine Faber and Ann Magnuson (U. Uppsala) for their review of the draft at short notice.

Last but not least, thanks also to JRC colleagues Marco Buffi for his review, to Simon Letout for venture capital information and to Andreas Schmitz and Ana Vazquez Diaz (CETO co- project leaders) for their support, review and comments.

Authors

Nigel Taylor, JRC.C.2

Geraldine Joanny, JRC.I.3 Technology Innovation Monitoring Team

Oliver Eulaerts, , JRC.I.3 Technology Innovation Monitoring Team

Marcellina Grabowski, JRC.I.3 Technology Innovation Monitoring Team

Executive Summary

Solar fuel technologies, also known as sunlight-to-X, convert solar energy directly into chemical energy in the form of liquid or gaseous fuel. In the EU energy transition solar fuels have potential to directly substitute fossil fuels, as well as fuels, feedstock and commodity chemicals for industrial processes. Starting from a combination of carbon dioxide, water and nitrogen, typically the process produces intermediates such as hydrogen, ammonia or carbon compounds. These can be shaped in different chemical classes as drop-in fuels depending on the use. In the following we will use the word fuels for all those applications. Currently the technology is at low to medium TRL, with focus is on R&D and practical demonstration of promising concepts. This provides an essential base for large-scale deployment of solar fuels in the short (2025) as well as medium to long –term, i.e. after 2030. Fuels from solar power can be demonstrated at large scale by 2025, linking surplus of green electricity and electrochemical processes to develop technologies adapted to existing infrastructures. Direct solar fuels (the focus of this report) can contribute to a partially decentralised production already by 2030. In the longer term (2030 to 2050 and beyond), efficient solar energy conversion of CO2 into long-lasting materials can contribute to a CO2-neutral circular economy, net-climate neutral mobility, and to cost-effective and negative emission technologies.

There are three main routes for producing solar fuels:

- Electrochemical, using solar electricity from photovoltaic or concentrating solar power systems followed by an electrolytic process.
- Photochemical/photobiological route makes direct use of solar photon energy for photochemical and photobiological processes;
- Thermochemical route uses solar heat at moderate and/or high temperatures, e followed by an endothermic thermochemical process. Here concentrating solar systems provide the heat.

The first route corresponds to solar e-fuels, whereas this report focusses on direct solar fuels using the second and third routes a conversion processes of solar to chemical energy, typically involving the splitting of water, carbon dioxide or nitrogen to produce hydrogen or ammonia. This report focuses only on upstream processes producing such energy carriers, while the CETO report on “Renewable Fuels of Non-Biological Origin status, trends, value chains, global markets and EU position” addresses the conversion of hydrogen and CO2 into upgraded fuels.

The thermochemical route is most advanced and 2022 saw demonstrations of pilot plants at the 50 kWt scale or larger in Germany and Spain. Up to now the photochemical/photobiological route is focussed at laboratory level, although this year the EIC Fuel from the Sun Artificial Photosynthesis Prize concluded with a successful demonstration event for continuous outdoor operation over 72 hours.

With increasing performance testing of solar fuel processes, there is also a growing need for benchmarking protocols and technical performance and reliability standards, noting that the field photovoltaics benefited fom timely adoption of such measures. This regards in particular direct solar to hydrogen conversion, but can also relevant to integrated concepts for syngas and drop-in fuels. The EU can play a prominent role in such developments.

For research, EU organisations have a strong but not leading role in solar fuel science. The EU has been increasing its budget in this area, from EUR 30 million in FP6/7 to EUR 62.5 million in H2020. It has also promoted networking and cooperation within Europe and at a wider international-level in the Mission Innovation framework. The SUNERGY initiative for fossil-free fuels and chemicals for a climate-neutral Europe brings together 300+ stakeholders across academia, industry, public institutions and civil society. The recently launched SUNER-C CSA project (2022 to 2025) will support this and plan for future t large scale European R&I initiatives. In parallel, the inclusion of solar fuels in the strategic plan of the new Clean Energy Transition Partnership CETP can reinforce their medium-to-long strategic role for achieving the EU energy transition.

Table 1 provides a SWOT analysis for the current state of competitiveness of direct solar fuels.

Table 1. CETO SWOT analysis for the competitiveness of direct solar fuels.

Strengths – Exploits direct and integrated conversion processes for a range of product forms – Energy storage as fuel – Sustainable materials and processes – Use existing fuel transport and delivery infrastructure	Weaknesses – Current low TRL (no industrialisation yet) – Current low conversion efficiencies – Lack of performance standards – Long-time scales for cost reductions
Opportunities – Large future demands for RFNBOs in the energy transition – Use for CO2 can support carbon capture in materials and products – Higher yield than biomass-based processes – Decentralised production – Flexible deployment options (degraded lands, built environment, infrastructure etc. – Scalable technology (viable solutions from small scale to large scale) – Can contribute to energy security	Threats – Land-use requirements – Competition from hydrogen produced by electrolysis, and related products – Long-term stability of processes

Source: JRC analysis

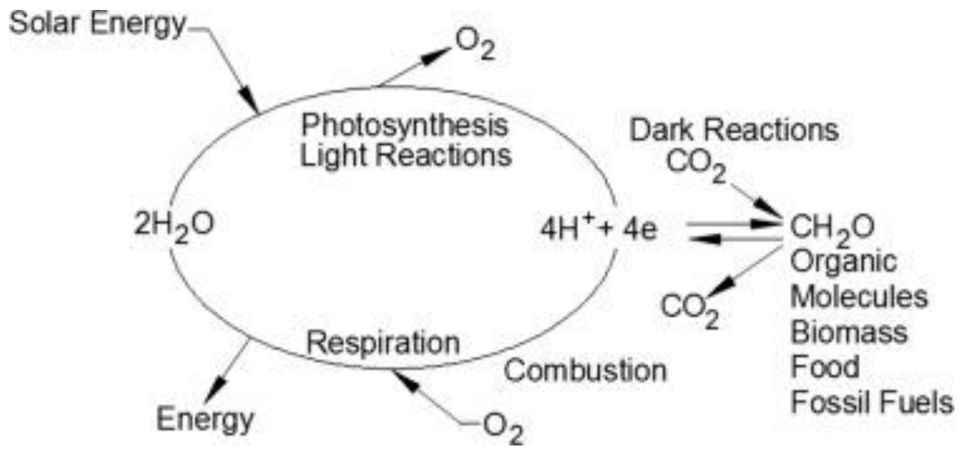
1 Introduction

1.1 Scope and context

This report looks at direct solar fuels and is one of an annual series of reports from the Clean Energy Technology Observatory (CETO). It addresses technology maturity status, development and trends; value chain analysis and global market and EU positioning, and builds on previous Commission studies in this field (Chartier et al, 2016; European Commission, 2021).

Solar fuel technologies, also known as sunlight to X, use solar energy to convert precursors such as carbon dioxide, water and nitrogen to intermediates such as hydrogen, ammonia or carbon compounds. These can be further converted in chemical fuels, as a means of storing and transporting solar energy. **Figure 1** (Ganesh, 2015) shows a schematic of the process for water and CO2.

Figure 1. Schematic of the sunlight to X processes. Note that there are also photochemical processes allow to combine the water and carbon dioxide transformations, as opposed to doing these in separate "light" and "dark" steps.



Source: Ganesh, 2015.

There are three main sunlight-to-x routes:

- Electrochemical, using solar electricity from photovoltaic or concentrating solar power systems followed by an electrolytic process.
- Photochemical/photobiological route makes direct use of solar photon energy for photochemical and photobiological processes;
- Thermochemical route uses solar heat at moderate and/or high temperatures, e followed by an endothermic thermochemical process. Here concentrating solar systems provide the heat.

The first route corresponds to solar e-fuels, whereas this report focusses on direct solar fuels using the second and third routes a conversion processes of solar to chemical energy, typically involving the splitting of water, carbon dioxide or nitrogen to produce hydrogen or ammonia. Subsequent steps that do not involve direct solar-assisted conversion are addressed in the CETO report on renewable fuels of non-biological origin (Buffi et al, 2022a). The term artificial photosynthesis is also commonly used to describe the synthesis of solar fuels from carbon dioxide (CO2) and water using solar energy.

It is also noted biomass-to-hydrogen processes also include photochemical and thermochemical pathways – these are not specifically considered here. Readers are referred to the recent review by (Buffi et al, 2022b) for details.

For the EU energy transition, solar fuels have potential to directly substitute fossil fuels since they are fully drop-in fuels for transports, as well as fuels and chemicals for industrial processes. Currently the technology is at low to medium TRL, with focus is on R&D and practical demonstration of promising concepts. This provides an essential base for large-scale deployment of solar fuels in the medium to long –term, i.e. after 2030.

For the EU energy transition solar fuels have potential to substitute fossil fuels for transport and heating, as well as fuels, feedstocks and commodity chemicals for industrial processes. In the following we will use the word fuels for all those applications. Currently the technology is at low to medium TRL, with focus is on R&D and practical demonstration of promising concepts. This provides an essential base for large-scale deployment of solar fuels in the short (2025) as well as medium to long –term, i.e. after 2030. Fuels from solar power can turn into reality by 2025, linking surplus of green electricity and electrochemical processes to develop technologies adapted to existing infrastructures. Direct solar fuels (the focus of this report) can contribute to a partially decentralised production already by 2030. In the longer term (2030 to 2050 and beyond), efficient solar energy conversion of CO_2 into long-lasting materials can contribute to a CO_2-neutral circular economy, net-climate neutral mobility, and to cost-effective and negative emission technologies.

1.2 Methodology and Data Sources

The annual CETO technology reports are typically organised in three main sections, each of which foresees a series of specific topics or indicators: technology maturity status, development and trends, value chain analysis and global markets and EU positioning. Since solar fuel technology is currently subject of R&D and demonstration projects, and not yet available as commercially, a simplified format is used, covering the following topics:

- Technology Readiness Level
- Future value chains and markets
- RD&I funding
- Patenting trends
- Scientific publication trends
- R&I project developments

The report uses the following information sources

- Existing studies and reviews published by the European Commission
- Information from EU-funded research projects
- JRC review and data compilation

2 Technology Status

2.1 Technology readiness level (TRL)

Solar fuel producing systems are still at a relatively early stage of development and there are no commercially available devices. Laboratory efficiency of photelectrochemical devices are in the range 10 to 15% (Segev et al, 2022), but the research and engineering to ensure durability and support scale-up is at an early stage.

In 2019 the SUNRISE CSA project (funded under H2020) produced a comprehensive technological roadmap (Faber et al, 2019) solar energy for a circular economy, covering the recycling of CO2 into a variety of products, the combination of nitrogen with hydrogen to produce ammonia for fertilizers and, more generally, the direct solar-powered production of fuels and chemicals. **Table 2** is an extract showing the TRL of the various processes considered and the proposed targets for 2030. It is noted that although SUNRISE also considered sustainable CO2 supply, this is not considered here – the CETO carbon capture and storage report (Kapetaki et al, 2022) provides more information on this aspect. The roadmap also stressed a set of cross-cutting enablers as follows:

1. Computational materials modelling: from novel materials to solar fuel devices

2. Development of new methods and software tools for early quantitative sustainability assessment of emerging SUNRISE technologies: bridging environmental, economic and social impacts

3. Redesigning photosynthesis for the biocatalytic production of chemicals and fuels

4. Synthetic Biology

5. Bottom-up chemical engineering of bioinspired artificial photosynthesis reactor materials and cascades

6. Upscaling artificial photosynthesis systems for a sustainable larger scale production of energy carriers

7. Oxygen evolution (water oxidation)

A subsequent independent study (EC, 2021) for the Commission performed an analysis of technology and market outlook of both direct and indirect photo-electrochemical, thermochemical and biochemical pathways, as well as proposed value chain cost analysis for hydrogen, methanol, ethanol and methane production to 2100.

Thermo-chemical approaches are the most advanced, with focus increasingly on improved performance, both mechanical and thermodynamic, ways mitigate the effects of solar intermittency and provide a continuous feed for downstream gas-to-liquid processing (Warren & Weimer, 2022).

Table 2. SUNRISE assessment of technology readiness level for sustainable solar hydrogen, ammonia, chemical and fuels

Product	**Process/route**	**TRL end 2019**	**TRL target 2030**	**Key enabling technologies**
Sustainable H2	Advanced electrolysis (PV-driven)	4-6	9	Noble-metal free catalysts and membranes, operating at different pH and impurity content), automated manufacturing technologies, system integration and upscaling.
	Photoelectrochemical devices	2-4	5-8	Photon management technologies, non-adiabatic conversion of reactants into products, catalyst and semiconductor materials science and development, bio-inspiration (control of auto-assembly and charge photo-accumulation and transfer processes, development of responsive matrices and interfaces, development of self-repair/self-healing processes, discovery of noble-metal free and non-toxic catalysts inspired by enzymes,

Product	**Process/route**	**TRL end 2019**	**TRL target 2030**	**Key enabling technologies**
				function-based systems engineering across length scales
	Transparent baggie systems (microorganisms and photocatalytic systems)	3-4	6-8	System engineering for the separation, collection and storage of hydrogen, photobioreactor design, photon management, fundamental understanding of natural photosynthesis and cell metabolism, enzyme chemistry and material science and development, advanced theoretical and experimental techniques, synthetic biology toolboxes and other molecular technologies.
Sustainable ammonia	Low emission Haber-Bosch (with green H_2)	5-6	9	Advances in green hydrogen production, high-throughput computing for materials science and development. Rational design of bioinspired catalysts for N_2 reduction derived from nitrogenases that operate at ambient temperature.
	Electrochemical and plasma-assisted ammonia synthesis	1-2	4-5	It relies on advances in the development of photo(electro)chemical devices for direct solar water splitting and electrochemical NRR.
	Microorganisms for direct fertilizer production	1-2	4-6	New metabolic engineering strategies to develop novel and efficient ammonium producers, identification of efficient, low energy-demanding (or ATP-independent) and O_2 resistant nitrogenases via mining and introduction of these enzymes in living systems through synthetic biology.
Sustainable chemicals and (jet) fuels	Electrochemical water splitting and thermocatalytic conversion of CO_2 (two stage process)	6	9	Catalysis research with ab-initio modelling and high-throughput screening, multi-scale modelling for thermo-chemical electrically heated reactors, systems engineering for dynamic life-cycle cost analysis, advanced manufacturing for new reactor concepts, systems engineering.
	Direct electro-reduction of CO_2	3	6	Catalysis research with ab-initio modelling and high-throughput screening, in-operando analytical tools, multi-scale modelling, systems engineering, life-cycle cost analysis.
	Direct solar-thermochemical	4-5	6	Materials engineering, materials research with ab-initio modelling and

Product	Process/route	TRL end 2019	TRL target 2030	Key enabling technologies
	conversion of water and CO_2			experimental screening, solid particles technologies, membrane technologies, smart process control and interfaces.
	Photo(electro)chemical devices	1-3	6-7	Advances in the development of photo(electro)chemical devices for direct solar water splitting and electrochemical CO_2 reduction.
	Biocatalytic production of carbon-based solar fuels and chemicals	1	4-9	Efficient engineering and synthetic biology tools, combined with strain characterization and optimization. Engineered new strains with enhanced metabolic pathways for the synthesis and excretion of various chemical and fuel products. Construction of cost-efficient dedicated photobioreactors for cultivation and production phases. Improvement of photosynthetic performance and carbon metabolism; upscaling, including cheap bioreactor construction and operation as well as downstream processing.

Source: Faber et al, 2019

2.2 Future Value Chains and Markets

The target market for solar fuels is part of that for green hydrogen and for electro-fuels. The 2021 IEA Net Zero Energy scenario (IEA,. 2021) foresees that hydrogen-based fuels (so hydrogen itself, together with synthetic or e-fuels) would account for approximately 20% (480 Mtoe) of transport energy final consumption (the other sources are electricity, bioenergy and fossil fuels). Other uses in industry such as for chemicals and downstream products are not detailed. In addition, the potential for solar fuels to be deployed at small and intermediate scale, and in distributed and off-grid systems can offer a range different markets.

For the EU, the Commission's 2050 longer-term strategy (EC, 2018) for climate neutral Europe considers the role of H2, e-gas and e-liquids in both 1.5 degree compliant scenarios (1.5TECH and 1.5LIFE). These indicate annual requirements of 150 Mtoe and 140 Mtoe respectively. Direct solar fuels (as opposed to indirect e.g. PV-powered electrolysers) can potentially contribute significantly to this future market.

The SUNRISE roadmap (Faber et al, 2019) provides considerable data on the product costs needed for the specific pathways to become cost-competitive with current products.

The 2021 Commission-funded techno-economic analysis (EC, 2021) used a levelised Cost of Energy parameter to assess the potential competitiveness of several solar fuel pathways (both direct and indirect) to produce hydrogen, methanol, ethanol and methane compared to that of fossil-based counterparts. In general, the direct solar pathway studied struggled to become competitive even at extended time-horizons (2050-2100). It also highlighted the strong role of costs for energy and other process inputs.

2.3 R&I funding

There is little information available on the current public or private R&I budgets for solar direct fuels at global level. Concerning the EU research programmes, a Commission study in 2016 found that approximately EUR 30 m of grants were awarded in FP6 and FP7 (Chartier et al, 2016). However, it also noted that "*Europe occupies a frontline position in AP research, with 60% of the estimated 150 leading global research groups located in Europe. However, AP research in Europe is relatively less well-funded than elsewhere, notably in the US and*

Japan. European research efforts are also fragmented, driven by national-level strategies and research programmes."

For Horizon 2020 the funding amounts to EUR 63.6 million, based on a listing of funded projects extracted from the Cordis and Compass databases using "solar fuel" and "artificial photosynthesis" are search terms (relevance was also checked manually). The resulting 36 projects are reported in Annex 1. Table 3 summarises the project type, costs and number. An additional EUR 5 million was allocated to the EIC Fuel from the Sun Artificial Photosynthesis Prize, due to be awarded in the final quarter of 2022.

In Horizon Europe EU funding for solar fuels continues, with calls involving an indicative budget of EUR 25 million already in the 2021-20220 work programme.

- HORIZON-CL5-2022-D3-02-04: Technological interfaces between solar fuel technologies and other renewables RIA, EUR 10 m
- HORIZON-CL5-2022-D3-03-03: Efficient and circular artificial photosynthesis, RIA, EUR 10 m
- HORIZON-CL4-2021-RESILIENCE-01-16 Creation of an innovation community for solar fuels and chemicals (CSA) EUR 5 m

Table 3. Summary of the H2020 projects on solar fuels (see Annex 1 for full project list)

Project type	Cost	No. Projects
CSA	263,000	1
ERC	11,816,958	7
FET FLAG	2,707471	2
MSCA	2,707,471	15
RIA	46,799,767	11
Grand Total	63,648,310	36

Source: JRC elaboration of CORDIS data

2.4 Scientific Publishing and Patenting trends

The JRC's Technology Innovation Monitor system (TIM) was used to analyse the scientific articles published over the period 2010 to 2022. Distinct search strings were used for each of the three main solar fuel pathways: photobiological, photoelectrochemical and thermochemical as shown in **Table 4**. A large majority of these address the photoelectrochemical pathway.

Figure 2 shows the time trend for publications on all pathways the EU and leading countries and regions. China, Rest-of-World[1], EU and USA are most prolific. **Figure 3** shows the % of highly cited papers for each country/region from the same data set. Switzerland, USA and UK lead on this metric. **Table 5** considers the h-index values for the countries/regions in the three pathways. The EU and Rest-of-World lead for scientific publications on the photobiological pathway, where USA leads on the photoelectrochemical and thermochemical. **Figure 4** looks at the publications of the individual EU countries, for which German organisations are clearly lead, followed by France, Italy and Spain.

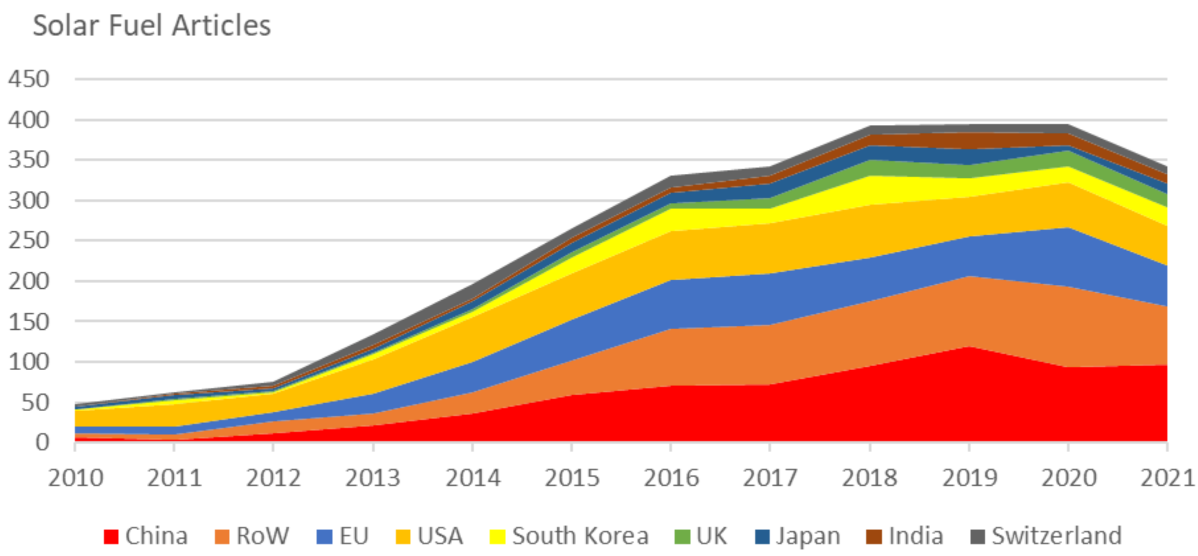
[1] Here Rest-of-World covers all countries other than EU, USA, UK, China, Switzerland, India, Japan and South Korea.

Table 4. TIM search strings for the bibliometric analysis for direct solar fuels 2010 to 2022 and the total articles identified for each.

Pathway	**TIM search string**	**Articles 2010-2022**
Photo-biological	topic:(("solar fuel"~1 OR "solar water splitting"~3 OR "solar to fuel" OR "solar H2 production"~2 OR "solar hydrogen production"~2 OR "photobiological H2 production"~2 OR "photobiological hydrogen production"~2) AND (photobioreactor OR photobiological OR "photosyntetic microorganism" OR microalgae OR cyanobacteria OR "Chlamydomonas reinhardtii")) AND class:article	109
Photo-electro-chemical	topic:(("solar fuel"~1 OR "solar water splitting"~3 OR "solar to fuel" OR "solar H2 production"~2 OR "solar hydrogen production"~2 OR "photoelectrochemical hydrogen production" OR "photoelectrochemical h2 production") AND (photoelectrochemical OR "photosensitized electrode" OR "photoelectrode" OR "photo electrode" OR "photo cathode" OR "photoelectrolysis")) AND class:article	1717
Thermo-chemical	topic:(("solar fuel"~1 OR "solar water splitting"~3 OR "solar to fuel" OR "solar H2 production"~2 OR "solar hydrogen production"~2) AND("thermochemical water splitting"~2 OR "thermochemical h2o splitting"~2 OR "solar thermochemical" OR "cerium oxide cycle" OR "copper chlorine hybrid cycle"))	344

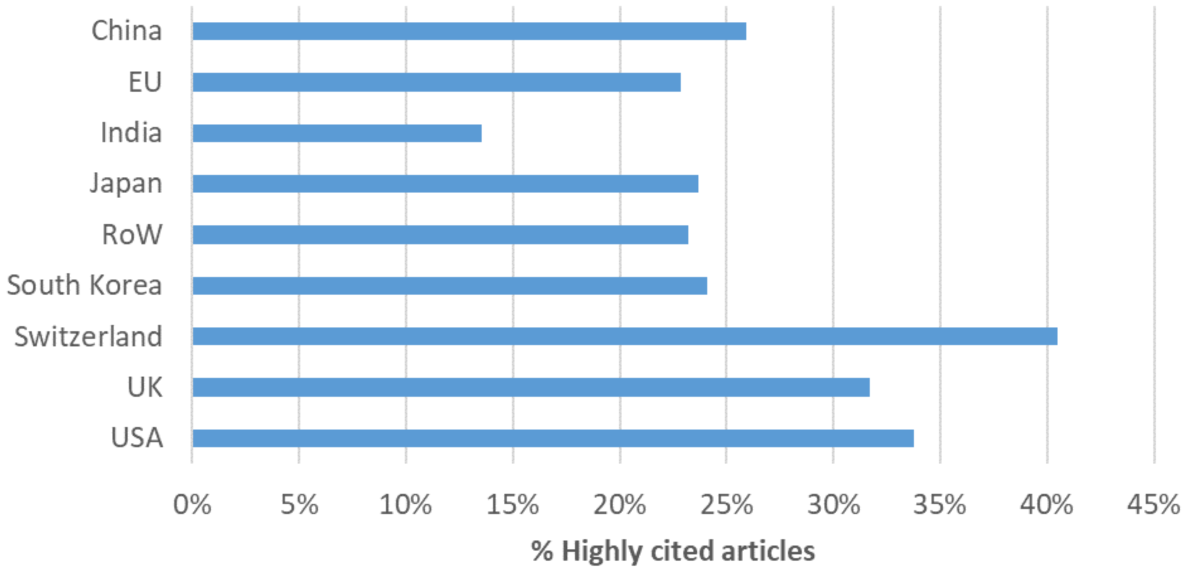
Source: JRC

Figure 2. Trend in scientific publications on solar fuels for the leadings countries and regions



Source: JRC TIM data and elaboration

Figure 3. Breakdown of leading countries and regions by % of highly cited articles from all publications on solar fuels in the period 2010 to 2022.



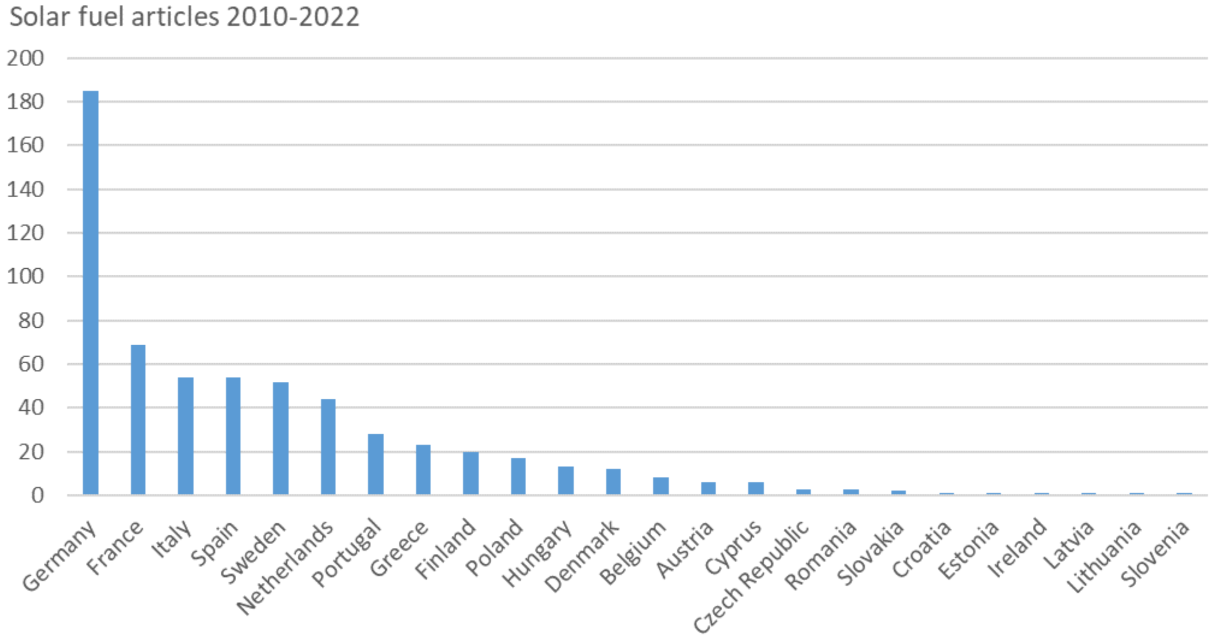
Source: JRC TIM data and elaboration

Table 5 Analysis of the h-index of the EU and leading countries and regions (the largest number h such that at least h articles in that country for that topic were cited at least h times each).

Country	**Photobiological**	**Photoelectrochemical**	**Thermochemical**
China	11	73	16
EU	18	58	25
India	4	22	4
Japan	5	32	15
RoW	18	59	25
South Korea	4	40	5
Switzerland	0	37	17
UK	5	32	1
USA	14	88	30

Source: JRC TIM data and elaboration

Figure 4. Ranking of EU countries for scientific publications on solar fuels 2010 to 2022.



Source: JRC TIM data and elaboration

2.5 Impact and Trends of EU-supported Research and Innovation

2.5.1 Recent demonstrators

There have been several important recent demonstrations of pilot industrial processes using the thermochemical pathway. In August 2002, Synhelion (Germany) announced the production of syngas at an industrial scale had been demonstrated on the solar tower of the German Aerospace Center (DLR) in Jülich (Synhelion, 2021). The system is reported to have a production capacity of 100 standard cubic meters of syngas per hour when fully commissioned in 2023, which would potentially yield 150 000 litres of liquid fuel per year. This plant is as part of the SolarFuels project funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) which contributed EUR 3.92 million of grant funding October 2021. The company also raised €14.74M of Early Stage VC (Series B) in a deal led by Swiss KMU Partners in September 2021.

Synhelion is a spin-off from ETH Zurich, which has been working on solar fuels for over fifteen years, also with the support of several EU R&I framework programmes. ETH Zurich have themselves run a modular 5 kWt pilot system under field conditions (Schaeppi et al, 2022). In parallel the EU project Sun-to-Liquid with ETH, IMDEA Energy, DLR, Bauhaus and Hygear have developed and tested a 50-kW solar reactor and achieved solar-to-syngas energy conversion efficiency of 4.1% was achieved (Zoller et al, 2022). They envisage that scale-up to commercial-scale would involve a cluster of 10 x 100 MWt plants that would produce about 34 million litres kerosene jet fuel/year.

2.5.2 R&I coordination

The EU-funded Sunrise project (2019-2020) brought together the key European actors on solar fuels and lead to the Sunrise Roadmap as mentioned in section 2.1. This group has subsequently merged with the Energy-X consortium that produced a roadmap on sustainable production of fuels and chemicals in 2019 (Norskov et al, 2019) in the SUNERGY initiative for fossil-free fuels and chemicals for a climate-neutral Europe. In June 2022 the 3-year SUNER-C programme "SUNERGY Community and eco-system for accelerating the development of solar fuels and chemicals" was launched with EUR 4 million EU funding. The SUNERGY initiative is backed by a 300+ continuously expanding community of 300+ supporters (currently from 18 EU and 14 from non-EU countries), across academia, industry, public institutions, civil society and other stakeholders. In particular, there is a significant participation of industrial partners from various sectors the value chain, from large corporations to SMEs. It already has in place a well-functioning governance structure and a wide network at EU, national and international level.

Solar fuels have not been explicitly addressed under the SET Plan up to now. However the new Clean Energy Transition Partnership CETP Challenge 3: Enabling Climate Neutrality with Storage Technologies, Renewable Fuels and CCU/CCS will include solar fuels, as noted in the its strategic agenda (CETP, 2020) CETP is a joint programming initiative to boost and accelerate the energy transition, building upon regional and national RDI funding programmes and support the implementation of the SET-Plan.

At international level, the initial Mission Innovation programme (2015-2020) included the Converting Sunlight Innovation Challenge, targeting the discovering affordable ways to convert sunlight into storable solar fuels. It was co-lead by the European Commission and Germany, and included Australia, Brazil, Canada, Chile, China, Denmark, Finland, France, India, Italy, Japan, Mexico, Norway, Saudi Arabia, Sweden, the Netherlands, the United Arab Emirates, the United Kingdom, and the United States. Under Mission Innovation 2.0, launched in June 2021, this work continues and a "Sunlight-to-X" collaborative innovation platform is expected to be approved in Q4 2022. It will be co-led by the EC, USA and China and has already received expressions of interest from Australia, Austria, France, Germany, Italy, Japan, Republic of Korea and the United Kingdom.

2.5.3 Standards

As an emerging technology, the solar fuel sector has yet to develop a body of performance and reliability standards. In 2019 the Mission Innovation group strategy paper identified the need for best practices for standardized comparison of results as a priority (Hammarstroem & Durant, 2019). This message is stressed again in the 2022 solar fuels roadmap (Segev et al, 2022), which calls for "benchmarking protocols and standards be in place to establish efficiency in all laboratories".

On the positive side, the current rapid market uptake of hydrogen technologies is speeding-up the standardization for guarantee of origin certificates and international market rules. Direct solar fuel technologies can take advantage of this framework as they mature.

2.5.4 Sustainability

The CETO sustainability assessment process framework covers a comprehensive range of environmental, social and economic factors. Given the early stage of development of direct solar fuel as a sector option and with still a very broad set of technology options, it has not been possible to follow this process here.

Nonetheless relevant tools are already available for aspects such energy use and GHG emissions, for instance the Well to Wheels methodology (Prussi et al, 2020) provided by the JEC consortium: JRC, EUCAR (the European council for Automotive Research and development) and Concawe (the scientific body of the European Refiners' Association for environment, health and safety in refining and distribution).

3 Conclusions

- Direct solar fuel or “sunlight-to-X” technologies are an emerging field of advanced alternative fuels (renewable fuels of non-biological origin in EU legislation). These can play a critical role for transport and industry in all net-zero carbon scenarios for the energy system.
- The main routes are photochemical/photobiological and thermochemical, using solar heat at moderate and/or high temperatures followed by an endothermic thermochemical process. The latter is most advanced and 2022 saw demonstrations of pilot plants at the 50 kWt scale or larger in Germany and Spain. These developments have benefited directly and indirectly from EU framework programme funding. Also this year the EIC Fuel from the Sun Artificial Photosynthesis Prize concluded with a successful demonstration event, and detailed results will be available towards the end of 2022.
- A barrier for solar fuels from the thermochemical water splitting concerns the need high solar irradiance and the corresponding geographical constraints, as well as potential competition with land use for PV and for solar thermal technologies used to directly produce low-enthalpy heat. As regards the photochemical/biological pathways, low conversion yields and uncertainties on the scale up of such technologies need to be considered for the long-term market prospects.
- With increasing performance testing of solar fuel processes, there is also a growing need for benchmarking protocols and technical performance and reliability standards. The EU can play a prominent role in such developments.
- From the JRC’s bibliometric analysis, EU organisations have a strong but not leading role in solar fuel science. The EU has been increasing its budget in this area, from EUR 30 million in FP6/7 to EUR 62.5 million in H2020. Continued support is foreseen for Horizon Europe. Although global R&I investment data is not available, internationally the leading countries include USA, China and Japan. In Europe, outside of the EU, the UK and Switzerland are prominent in solar fuel R&D and in many cases are clustered with organisations in EU member states.
- A 2016 Commission study on artificial photosynthesis highlighted the need to improve networking and cooperation within Europe and possibly at a wider international level. In the meantime, the main European universities, research organisations and industry have worked together to produce the 2019 Sunrise Roadmap for “Solar Energy for a Circular Economy” and the Energy-X consortium roadmap on “sustainable production of fuels and chemicals”. These groups now work together in the SUNERGY initiative for fossil-free fuels and chemicals for a climate-neutral Europe. SUNERGY brings together 300+ stakeholders across academia, industry, public institutions and civil society. The recently launched SUNER-C CSA project (2022 to 2025) will support this and plan for future large scale European R&I initiatives. In parallel, the inclusion of solar fuels in the strategic plan of the new Clean Energy Transition Partnership CETP can reinforce their strategic role in the medium-to-long term for achieving the EU energy transition.

References

Buffi, M., Hurtig, O., Mottola, v., Scarlat, N, 2022a, CETO Renewable Fuels of Non-Biological Origin 2022 Status Report on Technology, Trends, Value Chains and Markets, EUR, European Commission, 2022, JRC13073.

Buffi, M., Prussi, M., Scarlat, . N., 2022b, Energy and environmental assessment of hydrogen from biomass sources: Challenges and perspectives,, Biomass and Bioenergy, Volume 165, 2022, 106556, ISSN 0961-9534, https://doi.org/10.1016/j.biombioe.2022.106556.

Chartier. O. et al, Artificial Photosynthesis: Potential and Reality, Report for the Directorate-General for Directorate-General for Research & Innovation, 2016 EUR 27987 EN, DOI 10.2777/410231

Clean Energy Transition Partnership Strategic Research and Innovation Agenda v1.0, November 2020 https://cetpartnership.eu/sites/default/files/documentation/cetp_sria_1.0.pdf

European Commission, 2018, 2050 long-term strategy climate-neutral Europe, and support document: In-depth analysis in support of the commission communication COM(2018)773.

European Commission, 2021, Study on 'Solar Fuels Research & Invest: Defining and developing the global solar fuel value chain: techno-economic analysis and pathways for sustainable implementation', doi:10.2777/508905, KI-01-20-398-EN-N

Faber, C. et al, SUNRISE - Solar Energy for a Circular Economy - Technological Roadmap, November 2019

Ganesh, I., Solar fuels vis-à-vis electricity generation from sunlight: The current state-of-the-art (a review), Renewable and Sustainable Energy Reviews, 44(2015), 904–932

Gideon, S. et al, The 2022 solar fuels roadmap, 2022 J. Phys. D: Appl. Phys. 55 323003

Hammarström, L. & James Durrant, J.,. IC5 2nd Draft 190307, Mission Innovation Challenge "Converting Sunlight" Action Plan Details Cambridge Report, http://www.mission-innovation.net/wp-content/uploads/2019/11/IC5-Cambridge-2019-Draft-1.pdf

IEA, Net Zero by 2050 A Roadmap for the Global Energy Sector, 2021

Kapetaki, Z., Eulaerts O., Georgakaki, A., Gonzalez Sanchez, R., Grabowska, M., Ince, E., Joanny, G., Kuokkanen, A., Letout, S., Mountraki, A., Shtjefni, D., Carbon capture utilisation and storage 2022 Status Report on Technology, Trends, Value Chains and Markets, EUR, European Commission, 2022, doi:10.2760/268143, JRC130663

Norskov J.K, Latimer A & Dickens CF (ed). Research needs towards sustainable production of fuels and chemicals. 2019, https://www.energy-x.eu/research-needs-report/.

Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R. and Lonza, L., JEC Well-to-Tank report v5, European Commission, 2020, doi:10.2760/959137, JRC119036.

Schäppi, R., Rutz, D., Dähler, F. et al. Drop-in fuels from sunlight and air. Nature 601, 63–68 (2022). https://doi.org/10.1038/s41586-021-04174-y

Synhelion press release, Jülich, Germany, August 18, 2022 https://synhelion.com/news/paving-the-way-for-solar-fuels-synhelion-produces-solar-syngas-on-an-industrial-scale-for-the-first-time

Warren, K.J., and Weimer, A.W., Solar thermochemical fuels: Present status and future prospects, Solar Compass 1 (2022) 100010

Zoller, S. et al, A solar tower fuel plant for the thermochemical production of kerosene from H2O and CO2, Joule 6, 1606–1616, 2022 https://doi.org/10.1016/j.joule.2022.06.012

List of abbreviations and definitions

AEC	Alkaline Electrolysis Cell
AP	Artificial Photosynthesis
CAPEX	Capital expenditures
CPC	common patent category
CSA	Coordination and Support Action
DAC	Direct air capture
DSSC	Dye Sensitive Solar Cell
FiT	feed-in tariff
FOAK	First–of-a-Kind
GHG	Greenhouse Gas
IA	Innovation Action
IEA	International Energy Agency
IP	Implementation Plan
IRENA	International Renewables Energy Agency
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCoE	levelised cost of electricity
MI	Mission Innovation
MSCA	Marie Skłodowska-Curie Action
O&M	Operation and Maintenance
PC	Photocatalysis
PEC	Photoelectrochemical cell
PEMEC	Proton exchange membrane electrolyser cell
PPA	power purchase agreement
PV	Photovoltaic
RES	Renewable Energy Source
RFNBO	Renewable fuel of non-biological origin
RIA	Research and Innovation Action
SET	Strategic Energy Technology
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
SWOT	Strengths, Weaknesses, Opportunities, Threats
ToR	Terms of Reference
TRL	Technology Readiness Level

List of figures

List of tables

Annexes

Annex 1 Listing of H2020 projects addressing solar fuels (in alphabetic order)

Acronym	Title	Call	Cost	Start Date	End Date
2D-4-CO2	Designing 2d Nanosheets For Co2 Reduction And Integration Into Vdw Heterostructures For Artificial Photosynthesis	ERC-2018-STG	1,499,931	01-01-2019	31-12-2023
ADVANCEFUEL	Facilitating market roll-out of RESfuels in the transport sector to 2030 and beyond	H2020-EU.3.3.2.,H2020-EU.3.3.7.,H2020-EU.3.3.3.	263,000	01/09/2017	31/08/2020
A-LEAF	An Artificial Leaf: a photo-electro-catalytic cell from earth-abundant materials for sustainable solar production of CO2-based chemicals and fuels	FETPROACT-2016	7,980,861	01-01-2017	30-06-2021
BioInspired_ SolarH2	Engineering Bio-Inspired Systems for the Conversion of Solar Energy to Hydrogen	H2020-EU.1.1.	1,500,000	01/04/2019	30/09/2024
C[Au]PSULE	Crystal phase engineering of Au nanoparticles for enhanced solar fuel generation	H2020-MSCA-IF-2019	166,320	01-04-2020	31-03-2022
CALSOL	Carbon based Artificial Leaf for SOLar fuel production	H2020-MSCA-IF-2017	125,423	01-10-2018	30-09-2020
CO2 Intermediates	From CO2, Water and Sunlight to Valuable Solar Fuels: Tracking Reaction Intermediates in Solar Fuel Generation with Ultrafast Spectroscopy for More Efficient Catalysis	H2020-MSCA-IF-2016	183,455	01-05-2017	30-04-2019

Acronym	Title	Call	Cost	Start Date	End Date
CO2SPLITTING	Carbon dioxide splitting into higher-value chemicals with hybrid photocatalyst sheets	H2020-EU.1.3.2.	184,000	01/09/2018	31/08/2020
DoubleCat	Operando study of double activated catalytic processes by light and heat: catalytic conversion of CO2 into solar fuels	H2020-MSCA-IF-2019	160,932		
ECLIPSE	Towards Efficient Production of Sustainable Solar Fuels	H2020-MSCA-IF-2018	191,149	01-09-2019	31-08-2021
ENERGY-X	Technological solutions to sustainably produce energy and chemicals		976,115	01/03/2019	29/02/2020
EpiAnodes	Heteroepitaxial α-Fe2O3 photoanodes for solar water splitting	H2020-EU.1.3.2.	171,000	01/10/2015	30/09/2017
FANOEC	Fundamentals and Applications of Inorganic Oxygen Evolution Catalysts	H2020-EU.1.1.	2,200,000	01/07/2016	30/06/2021
FENCES	Ferroelectric Nanocomposites for Enhanced Solar Energy Efficiency	H2020-EU.1.1.	2,000,000	01/06/2021	31/05/2026
FLEXCHX	FLEXIBLE COMBINED PRODUCTION OF POWER, HEAT AND TRANSPORT FUELS FROM RENEWABLE ENERGY SOURCES	H2020-EU.3.3.,H2020-EU.3.3.2.	4,490,000	01/03/2018	30/04/2021
FotoH2	Innovative Photoelectrochemical Cells for Solar Hydrogen Production	H2020-EU.2.1.3.,H2020-EU.2.1.2.	2,580,000	01/01/2018	31/12/2021
HYDROSOL-beyond	Thermochemical HYDROgen production in a SOLar structured reactor:facing the	H2020-EU.3.3.8.2.,H2020-EU.3.3.	3,000,000	01/01/2019	31/12/2023

Acronym	Title	Call	Cost	Start Date	End Date
	challenges and beyond				
HyMAP	Hybrid Materials for Artificial Photosynthesis	ERC-2014-CoG	2,506,738	01-07-2015	31-12-2022
InVivoRuBisCO	In vivo Directed Evolution of Ribulose-1,5-Bisphosphate Carboxylase/Oxygenase in Saccharomyces cerevisiae Using an Orthogonal DNA Replication System	H2020-EU.1.3.,H2020-EU.1.3.2.	178,000	01/12/2020	30/11/2022
LICROX	Light assisted solar fuel production by artificial CO2 Reduction and water Oxidation	H2020-EIC-FETPROACT-2019	3,199,603	01-09-2020	31-08-2023
LuSH Art	Luminescent Solar Heterostructures for Artificial photosynthesis	H2020-MSCA-IF-2018	171,473	16-03-2020	30-05-2022
MatEnSAP	Semi-Artificial Photosynthesis with Wired Enzymes	ERC-2015-CoG	1,960,289	01-10-2016	31-03-2023
NEFERTITI	Innovative photocatalysts integrated in flow photoreactor systems for direct CO2 and H2O conversion into solar fuels	H2020-LC-SC3-2020-NZE-RES-CC	4,569,128	01-07-2021	30-06-2025
PEC_Flow	Continuous-flow Photoelectrochemical Cells for Carbon Dioxide Valorization	H2020-EU.1.1.	150,000	01/02/2020	31/07/2021
PECSYS	Technology demonstration of large-scale photo-electrochemical system for solar hydrogen production	H2020-EU.3.3.8.2.	2,500,000	01/01/2017	31/12/2020
PhotoCatRed	Visible-light-driven Photocatalytic CO2 Reduction to Solar fuels by multinary N-	H2020-MSCA-IF-2018	162,040	01-08-2019	31-07-2021

Acronym	**Title**	**Call**	**Cost**	**Start Date**	**End Date**
	Graphene based Heterostructure Composites				
Photofuel	Biocatalytic solar fuels for sustainable mobility in Europe	H2020-LCE-2014-1	5,998,252	01-05-2015	30-06-2020
PhotSol	Towards the Photonic Solar Cell - In-Situ Defect Characterization in Metal-Halide Perovskites	H2020-EU.1.3.2.	160,000	01/07/2019	30/06/2021
PolyNanoCat	Polymer Nanoparticle for Hydrogen Evolution	H2020-EU.1.3.2.	225,000	01/01/2021	31/12/2022
QuantumSolarFuels	Photoelectrochemical Solar Light Conversion into Fuels on Colloidal Quantum Dots Based Photoanodes	H2020-MSCA-IF-2018	237,768	01-11-2019	31-10-2022
SoFiA	Soap Film based Artificial Photosynthesis	H2020-FETOPEN-2018-2019-2020-01 (05/18)	3,235,280	01-01-2019	30-06-2023
Solarfuels	Engineering Silicon Carbide Nanowires for Solar Fuels Production	H2020-MSCA-IF-2014	195,455	28-08-2015	27-08-2017
SolTIME	Solar Fuel Generation through Photoelectrochemical Reduction of CO2 Using Copper Porphyrins in Molecularly Designed Reaction Environments	H2020-MSCA-IF-2020	172,932	01-09-2021	31-08-2023
SUNRISE	Solar Energy for a Circular Economy	H2020-EU.1.2.3.	1,085,000	01/03/2019	30/04/2020
SUN-to-LIQUID	SUNlight-to-LIQUID: Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels	H2020-EU.3.3.,H2020-EU.3.3.3.1.,H2020-EU.3.3.3.3.	6,150,000	01/01/2016	31/12/2019

Acronym	Title	Call	Cost	Start Date	End Date
Sun-To-X	Solar Energy for Carbon-Free Liquid Fuel	H2020-LC-SC3-2019-NZE-RES-CC	3,096,644	01-09-2020	29-02-2024
WO for solar fuels	Integrating molecular water oxidation catalysts with semiconductors for solar fuels generation	H2020-MSCA-IF-2014	183,455	01-05-2015	30-04-2017

).

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

— at the following standard number: +32 22999696,

— via the following form: european-union.europa.eu/contact-eu/write-us_en.

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

Open data from the EU

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
joint-research-centre.ec.europa.eu

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

EU Science

Publications Office of the European Union