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SOLAR FUELS IN THE EUROPEAN UNION

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

2023

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Contents

Abstract

Solar fuel technologies convert solar radiation directly into chemical energy in the form of hydrogen (or potentially other chemicals), that are then converted into liquid or gaseous fuels. They are distinct from e-fuels, which are produced from renewable electricity. Solar fuels have the potential to contribute to replacing fossil fuels and serve as feedstock and commodity chemicals for industrial processes. The main routes considered are direct photochemical/photobiological processes and indirect solar thermochemical processes. Challenges include stability, scale-up, efficiency, and continuous operation. Benchmarking protocols and standards are needed, and the EU can play a prominent role in their development. The EU has increased its budget for solar fuel research and development in Horizon Europe, but leading countries globally include the USA, China, and Japan. In Europe the SUNERGY initiative brings together stakeholders to provide strategies and coordination for research and innovation activities.

Foreword

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan SETIS online platform

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis.
- Clean Energy Outlooks: Analysis and Critical Review.
- System Modelling for Clean Energy Technology Scenarios.
- Overall Strategic Analysis of Clean Energy Technology Sector.

More details are available on the CETO web pages.

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Executive Summary

Solar fuels, and more generally “sunlight-to-X” technologies, are an emerging class of sustainable alternative fuels and chemicals that are set to play an important long-term role in all net-zero carbon scenarios for the energy system. They are distinct from e-fuels, which are produced from renewable electricity. Solar fuels offer potential for distributed production and more citizen engagement, compared to present centralised approaches. Solar fuels categorised under renewable fuels of non-biological origin in EU legislation and can contribute to the related energy targets.

The main routes considered in this report are direct photochemical/photobiological processes and indirect solar thermochemical processes. For the photochemical/biological pathways, low stabilities and uncertainties on the future scale-up of such technologies need to be overcome. The EIC Fuel from the Sun Artificial Photosynthesis Prize in 2022 was a landmark, with three concepts demonstrating operation in field conditions over a three day period. For the solar thermochemical pathway, pilot plants at the 50 kW scale have been set up in Germany and Spain. These developments have benefited in part from EU framework programme funding. Nonetheless significant technical challenges remain to achieving sufficient efficiency and continuous operation.

Bibliometric analysis shows that EU organisations have a strong but not leading role in solar fuel science. 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 SUNER-C project (2022 to 2025) supports this and plan for future large-scale European R&I initiatives. The EU has been increasing its budget in this area, from EUR 30 million in FP6/7 to EUR 62.5 million in H2020 and already over EUR 70 million in the first two years of Horizon Europe. At global level 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.

Future cost competitiveness is a concern for solar fuels. Energy system modelling such as the POLES-JRC CETO global 2°C scenario provide useful indications of the future market for hydrogen and synfuels and chemicals, of which solar fuels can be a part. The projects overnight investment costs to decrease significantly in the coming decade (Figure 7). By 2035, a decrease of around 60% is foreseen for gaseous synfuels and around 65% for liquid synfuels compared to 2020.

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 of photovoltaics benefited from the timely adoption of such measures. This regards, in particular, direct solar to hydrogen conversion but can also be relevant to integrated concepts for syngas and drop-in fuels. Equally, harmonised approaches to sustainability assessments are important, taking advantage of tools already available for aspects such as energy use and GHG emissions of renewable fuels of non-biological origin, for instance, the Well –to-Wheels methodology.

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

– Strengths – Exploits integrated conversion processes for a range of products – Energy storage as fuel, chemical and long-lasting materials – Sustainable materials and processes – Use existing fuel transport and delivery infrastructure –	– Weaknesses – No industrialisation – Current low conversion efficiencies – Lack of performance standards – Long-time scales for cost reductions
– Opportunities – Large future demands for RFNBOs and fossil-free feedstock 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) – Local production possibilities – Contribution to energy security	– Threats – Long-term stability of processes – Public perception of promising technology, but with still too long timespan until delivery (dreamers technology) – Lack of clear scenarios on decentrlaized production systems

Source: *JRC, 2023*

1 Introduction

1.1 Scope and context

This report looks at solar fuel technologies and is one of an annual series of reports from the Clean Energy Technology Observatory (CETO) that assess technology maturity status, development and trends; the value chain analysis and the global market and EU positioning of a range of technologies. It updates the 2022 CETO direct solar fuels report (Taylor et al. 2022). It also builds on previous Commission studies in this field (Chartier et al, 2016; European Commission, 2021) and the on-going work of the SUNERGY initiative.

To clarify the scope the report, we note the following

- Here solar fuels are fuels produced using solar photonic or thermal energy; e-fuels from water electrolysis using photovoltaic electricity are not included.
- The technologies covered are those used to produce hydrogen (or other chemical products) from a process driven by solar radiation, in particular photochemical and photobiological processes. The term artificial photosynthesis is also commonly used to describe the synthesis in this way of solar fuels from carbon dioxide (CO2)/nitrogen and water. Solar-thermochemical processes for thermal water splitting or reforming, powered by concentrated solar radiation, are also included.
- Solar fuels are acknowledged to be part of the broader field of sunlight to x conversion pathways, in which solar fuels are combined with technologies for renewable fuels of non-biological origin (RFNBOs) with the aim to upgrade H2 and CO2 to more refined products such as ammonia, hydrocarbons and alcohols).

CETO also produces annual reports on water electrolysis (Bolard et al, 2023), RFNBOs (Motola et al., 2023) and on CO2 capture, usage and storage (Itul et al, 2023). It is also noted that biomass-to-hydrogen processes also include photochemical and solar thermochemical pathways – these are not specifically considered here. Readers are referred to the recent review by (Buffi et al., 2022) for details.

From an EU renewables policy perspective, the current Renewable Energy Directive (EU) 2018/2001 (REDII) treats solar fuels as RFNBOs, so long as they meet a GHG emission reduction of 70% compared to the fossil fuel comparator for liquid fuels (94 gCO2e/MJ). Recently, the REDII has been re-cast as part of the Fit-for-55 policy. RED-III will increasing the overall 2030 RES target from 30 to 42.5%, and the transport target is updated to 5.5% of advanced biofuels and RFNBOs (with the latter not less than 1% absolute). A RED-II' delegated regulation[1] provides In order to calculate the GHG emissions of RFNBOs and is applicable to solar fuel conversion pathways.

1.2 Methodology and Data Sources

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

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

The data sources include: Existing studies and reviews published by the European Commission, Information from EU-funded research projects and JRC review and data compilation.

[1] Commission Delegated Regulation (EU) 2023/1185, establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels

2 Technology Status

2.1 Technology readiness level

Solar fuel technologies are still at a relatively early stage of development and there are no commercially available systems. Laboratory solar-to-hydrogen (STH) efficiency of solar-to-hydrogen photoelectrochemical devices are in the range 10 to 15% (Segev et al, 2022, see Figure 5b), who also note that for economic viability, this value would need to increase to near the 22% theoretical limit.

For solar-thermo-chemical systems, a recent review (Warren & Weimer, 2022) notes progress with demonstrators at laboratory and field levels for syngas processes, and the need to a) improve overall performance, towards a solar-to-fuel efficiency of 10% and b) develop ways to mitigate the effects of solar intermittency and provide a continuous feed for downstream product processing. Similarly Budama et al's review of solar thermochemical water splitting cycles (Budama et al, 2023) confirm that the STH cycle efficiency is currently 5 to 10%. They draw attention to several technical challenges, such as the need to optimise the redox material for two-step cycles, reduce energy consumption for oxygen pumping from the reduction chamber, improve heat recovery and improve overall cycle efficiency.

SUNERGY's assessment (Faber et al, 2023) of the technology readiness level of solar-to-x and processes is summarised in **Table 2**. It is organised in terms of four product groups: H2, ammonia, chemicals and fuels and CO2 sourcing. Box 1 provides background to the methodology applied.

Table 2. SUNERGY assessment of technology readiness level for sustainable solar hydrogen, ammonia, carbon-based chemicals and fuels.

Product	**Process/route**	**Specific Technology**	**TRL end 2019**	**TRL end 2023**	**TRL target 2030**
Sustainable H_2	Advanced electrolysis	Alkaline PEM SOEC AEM	4-6 (PV, directly coupled)	Alkaline 9 (PV, directly coupled) PEM 9 (GW range) (PV, directly coupled) SOEC 7-8 (100 kW range) AEM: 6 (kW range) AEM: 4 (PV, directly coupled)	9
	Photosynthetic devices	Photo-electrochemical devices	2-4	4	7-8
		Particulate systems	3-4	5	7-8
		Biohybrid devices (electrodes functionalized with living cells)	3	3	5

Product	**Process/route**	**Specific Technology**	**TRL end 2019**	**TRL end 2023**	**TRL target 2030**
	Solar microbial cell factories (biological conversion, precision fermentation)		3-4	4	5
	Solar-thermochemical conversion			4-5 (100 kW range)	7
Sustainable ammonia	Low-emission Haber-Bosch (Green H2 production directly integrated with Haber-Bosch thermochemical conversion)		5-6	6	9
	Electrochemical and plasma-assisted ammonia synthesis		1-2	Electrochemical: 3 (Lithium-mediated) Plasma-assisted: 2	4-5
	Solar microbial cell factories (for direct fertilizer production)		1-2	3	4
Sustainable chemicals and fuels	Electrochemical water splitting and thermocatalytic conversion of CO_2 (two stage process)		6	Methanol: 7 (commercial pilot, with commercial fuel quality) Methane: 6-7 (commercial pilot) Aviation fuel: 6 (Fischer-Tropsch)	9

Product	Process/route	Specific Technology	TRL end 2019	TRL end 2023	TRL target 2030
	Direct electro-reduction of CO_2		3	Syngas (H_2, CO), formic acid: 4 (scale is still major issue) C2 hydrocarbons: 3 (stability still major issue) C3-4 hydrocarbons: 2 (overall device performances still major issue)	7-8
	Direct solar-thermochemical conversion of water and CO_2		4-5	Syngas (H_2, CO), CO: 4-5 (100kW range)	7
	Photosynthetic devices	Photo-electrochemical devices	1-3	Syngas: 3	5-6
		Particulate systems		Syngas: 3	5-6
		Biohybrid devices (electrodes functionalized with living cells)	1	Hydrocarbons: 3	5
	Solar microbial cell factories (biological conversion, precision fermentation)		1-6 (strongly depends on end product and can quickly rise thanks to synthetic biology tools) Lactic acid: 4 Ethylene: 1	Lactic acid: 5-6 Ethylene: 3	Lactic acid: 8 Ethylene: 5-6
Sustainable CO_2 sourcing	Direct air capture		4	5-6 (Scale and system integration still major issues)	8-9

Product	Process/route	Specific Technology	TRL end 2019	TRL end 2023	TRL target 2030
	Direct Ocean capture		2	3	4-5
	Oxy-combustion carbon capture		6	6-7 (depending on the feedstock gas)	8-9
	Amine Capture		8-9	8-9 (for large-scale applications) 7-8 (for small scale applications, economics main issue)	9
	Adsorption (e.g., zeolites)		9 for [CO2] > 50%	9 for [CO2] > 50% 7 for [CO2] = 20-50%	9
	Membrane capture		9 for [CO2] > 50%	9 for [CO2] > 50% 4-5 for [CO2] < 50%	9 6 (for lower CO_2 concentrations)
	Cryogenic capture		9 for [CO2] > 50%	9 for [CO2] > 50% 5-6 for [CO2] < 50%	8-9 7 (for lower CO_2 concentrations)

Source: *SUNERGY 2023*

Box1 SUNERGY note on TRL Evaluation (SUNERGY, 2023)

Evaluating the readiness state of a technology and its future development is a challenging task with high uncertainties. It is particularly challenging to compare technologies that may strongly differ in terms of basic underlying principles and targeted future scale based on a single metric (electricity-driven and directly solar-driven technologies).* Here, for the comparison of the current maturity of various technologies related to the production of fossil-free fuels and chemicals, the Technology Readiness Level as defined by the European Commission, in particular the one for "Alternative fuels" (Technology Readiness Level: Guidance Principles for Renewable Energy technologies, DG RTD 2017), has been used as common metric. It is by no means a comprehensive technology assessment, which would require a holistic approach with multiple criteria, but rather a high-level comparison of the current state of development. For a final large-scale deployment, also overall sustainability, achievable scale and economics will be decisive but are not considered here. SUNERGY Roadmapping efforts are deliberately based on the intuition of leading experts in the field of renewable fuels and chemicals – putting in a broader context current research results, market developments and input from various stakeholders from academia, industry and policy. The given TRL values are based on their technical expertise and market understanding, and on open discussions within the working groups.

Concerning relatively mature technologies, in SUNERGY's roadmapping discussions, experts tend to be more severe in their evaluation than for emerging technologies. These technologies must already withstand direct competition with conventional fossil-based technologies and demonstrate the necessary scales and economics. For 2030 estimations, TRL 8 has been estimated with respect to the fuel market, i.e., the "technology has to be in its final form" and "the system has to be certified for market application" following the European Commission's guidance (Technology Readiness Level: Guidance Principles for Renewable Energy technologies, DG RTD 2017). SUNERGY's experts directly related these criteria to the amount of produced fuel. TRL 8 is hence equivalent to a fuel production capacity in the range of 500MW and a technology may be rated lower if it does not match this scale. Consequently, technologies specifically designed for future small-scale, decentralized applications are rated with TRLs lower than 8. However, this rating is specific for the fuel market and neglects other markets such as the chemical one, where needed capacities and thus such a scale-sensitive TRL evaluation may strongly vary. Concerning emerging technologies, TRL 4 is a decisive step where technologies start their transition from the laboratory into first innovation. It has been attributed by the SUNERGY experts to "integrated small-scale prototypes with auxiliary systems validated in the lab" if "the process/fuel has been tested at the laboratory scale", according to the European Commission's guidance. Here, the past EIC Horizon Prize on Artificial Photosynthesis has been used as a benchmark where small-scale prototypes had to produce sufficient quantities of fuel under outside conditions for three days.

2.2 R&I funding

At global level there is little information available on R&I spending for solar fuels. Concerning the EU research programmes, approximately EUR 30 million of grants were awarded in FP6 and FP7 (Chartier et al, 2016). For Horizon 2020, the funding amounted to EUR 63.6 million, based on a listing of funded projects extracted from the CORDIS and Compass databases (see Annex 1 of Taylor, 2022). An additional EUR 5 million was allocated to the EIC Fuel from the Sun Artificial Photosynthesis Prize.

In Horizon Europe (2021-2027), EU funding for solar fuels continues, with a range of projects as shown in **Table 3** and an estimated EUR 70 million of grants. This includes several solar fuel-related projects funded European Innovation Council Pathfinder Challenge on novel routes to green hydrogen production.

Table 3. Summary of the Horizon projects on solar fuels and artificial photosynthesis.

Project acronym	Title	ID	Programmes	Project start date	Project end date
CHALCON	Chalcogenide-Silicon tandem PEC for CO2 reduction	101067667	HORIZON.1.2	01/09/2022	31/08/2024
Circular Fuels	Production of sustainable aviation fuels from waste biomass by coupling of fast pyrolysis with solar energy	101118239	HORIZON.2.5.2, HORIZON.2.5	01/07/2023	30/06/2027
COFPOR-4-fuels	Fuel forming electrocatalysis: Devising multifunctional covalent organic frameworks with vinylenic linkage for electrocatalytic CO2 reduction and water oxidation	101105393	HORIZON.1.2	01/01/2024	31/12/2025
CONFETI	Green valorization of CO2 and Nitrogen compounds for making fertilizers	101115182	HORIZON-EIC-2022-PATHFINDER CHALLENGES-05	01/11/2023	31/10/2026

Project acronym	Title	ID	Programmes	Project start date	Project end date
DynNano	Understanding Dynamic Processes at Nanoscale Working Interfaces for Solar Energy Conversion	101076858	HORIZON.1.1	01/10/2023	30/09/2028
ECOLEFINS	Nano-Engineered Co-Ionic Ceramic Reactors for CO2/H2O Electro-conversion to Light Olefins	101099717	HORIZON.3.1	01/10/2023	30/09/2026
FastTrack	Photons and Electrons on the Move	101054846	HORIZON.1.1	01/11/2022	31/10/2027
GH2	GreenH2 production from water and bioalcohols by full solar spectrum in a flow reactor	101070721	HORIZON-EIC-2022-PATHFINDER CHALLENGES-02	01/10/2022	30/09/2025
HyPhoCO	Organic/Inorganic Hybrid Photoelectrodes for sustainable CO2 reduction	101030782	H2020-EU.1.3, H2020-EU.1.3.2.	01/01/2022	31/12/2023
MacGhyver	Microfluidic wAstewater treatment and Creation of Green HYdrogen Via Electrochemical Reactions	101069981	HORIZON-EIC-2022-PATHFINDER CHALLENGES-04	01/09/2022	31/08/2026
MolPPS	Molecular Catalyst Immobilized into Porous Photocathode for production of Solar fuel	101104639	HORIZON.1.2	01/01/2024	31/12/2025
OMATSOLFUEL	Valence band engineering of oxidation materials for cheap and sustainable solar fuel production	101105640	HORIZON.1.2	01/09/2023	31/08/2025
OPHERA	Optimised Halide Perovskite nanocrystalline based Electrolyser for clean, robust, efficient and decentralised pRoduction of H2	101071010	HORIZON-EIC-2022-PATHFINDER CHALLENGES-03	01/10/2022	31/03/2026
PECSolFuel	Bias-free high-performance solar NH3 production by perovskite-based photocathode and in-situ valorisation of glycerol	101107294	HORIZON.1.2	01/04/2024	31/03/2026
Photo2Fuel	Artificial PHOTOsynthesis to produce FUELs and chemicals: hybrid systems with microorganisms for improved light harvesting and CO2 reduction	101069357	HORIZON.2.5, HORIZON.2.5.1	01/09/2022	31/08/2025

Project acronym	Title	ID	Programmes	Project start date	Project end date
PHOTOSINT	PHOTOelectrocatalytic systems for Solar fuels energy INTegration into the industry with local resources	101118129	HORIZON.2.5.2, HORIZON.2.5	01/09/2023	31/08/2027
PhotoSynH2	Photosynthetic electron focusing technology for direct efficient biohydrogen production from solar energy	101070948	HORIZON-EIC-2022-PATHFINDER CHALLENGES-01	01/10/2022	30/09/2027
PLANKT-ON	Plankton-like Protocells for Artificial Photosynthesis Targeting Carbon-neutral Energy Vectors	101099192	HORIZON.3.1	01/04/2023	31/03/2026
POMASAC	Photoelectrochemical Oxidation of Methane using Single Atom Catalysts	101105451	HORIZON.1.2	01/12/2023	30/11/2025
PYSOLO	PYrolysis of biomass by concentrated SOLar pOwer	101118270	HORIZON.2.5.2 ,HORIZON.2.5	01/07/2023	30/06/2027
PZschemeCO2Red	Understanding the Science and Identifying the Issues Behind the Low Performance of Z Scheme Photocatalysts for CO2 Reduction	101108387	HORIZON.1.2	01/07/2024	30/06/2026
REFINE	From solar energy to fuel: A holistic artificial photosynthesis platform for the production of viable solar fuels	101122323	HORIZON.2.5.2, HORIZON.2.5	01/11/2023	31/10/2027
SOLAR-CAT	Solar driven CO2 reduction and alcohol oxidation without sacrificial reagent.	101064765	HORIZON.1.2	01/10/2022	30/09/2024
STED	Real Space-Time imaging and control of Electron Dynamics	101108851	HORIZON.1.2	01/08/2023	31/07/2025
SULPHURREAL	An innovative thermochemical cycle based on solid sulphur for integrated long-term storage of solar thermal energy	101115538	HORIZON.3.1	01/10/2023	30/09/2026
SUNER-C	SUNER-C: SUNERGY Community and eco-system for accelerating the development of solar fuels and chemicals.	101058481	HORIZON.2.4, HORIZON.2.4.4	01/06/2022	31/05/2025

Project acronym	Title	ID	Programmes	Project start date	Project end date
SUNGATE	SUnlight-driven Next Generation Artificial photosynthesis bio-hybrid TEchnology platform for highly efficient carbon neutral production of solar fuels	101122061	HORIZON.2.5.2, HORIZON.2.5	01/10/2023	30/09/2027
SUN-to-LIQUID II	SUNlight-to-LIQUID - Efficient solar thermochemical synthesis of liquid hydrocarbon fuels using tailored porous-structured materials and heat recuperation	101122206	HORIZON.2.5.2, HORIZON.2.5	01/11/2023	31/10/2027
WEPOF	Watching Excitons in Photoactive Organic Frameworks	101039746	HORIZON.1.1	01/09/2022	31/08/2027

Source: JRC elaboration of CORDIS data

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
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
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
Solar 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"))

Source: JRC analysis

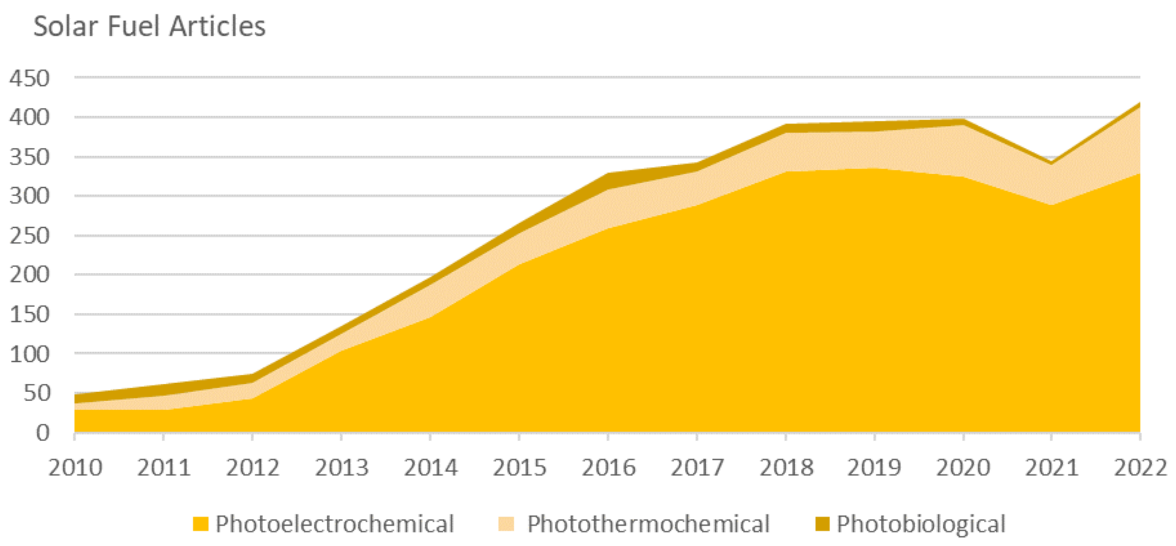
2.3 Scientific Publishing and Patenting trends

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 main solar fuel pathways considered in this report: photobiological, photoelectrochemical and thermochemical as shown in **Table 4**. A large majority address the photoelectrochemical pathway, followed by thermochemical and photobiological processes (**Figure 1**). shows the time trend for publications on all pathways the EU and leading countries and regions. China, Rest-of-World[2], EU and USA are most prolific. **Figure 3** shows the total articles and % of highly cited articles for

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

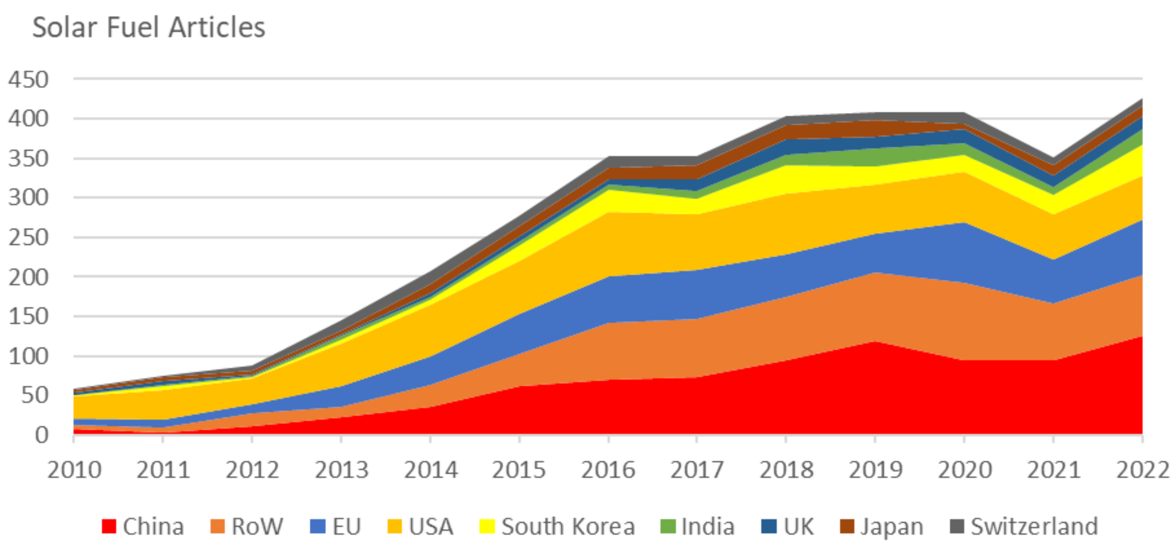
each country/region from the same data set. China leads on total numbers, but Switzerland, USA and UK lead in terms of % highly cited articles. **Figure 4** looks at the publications of the individual EU countries for 2022, for which German organisations are clearly lead, followed by France, Finland and Spain.

Figure 1. Trend in main subject areas for global scientific publications on solar fuels.



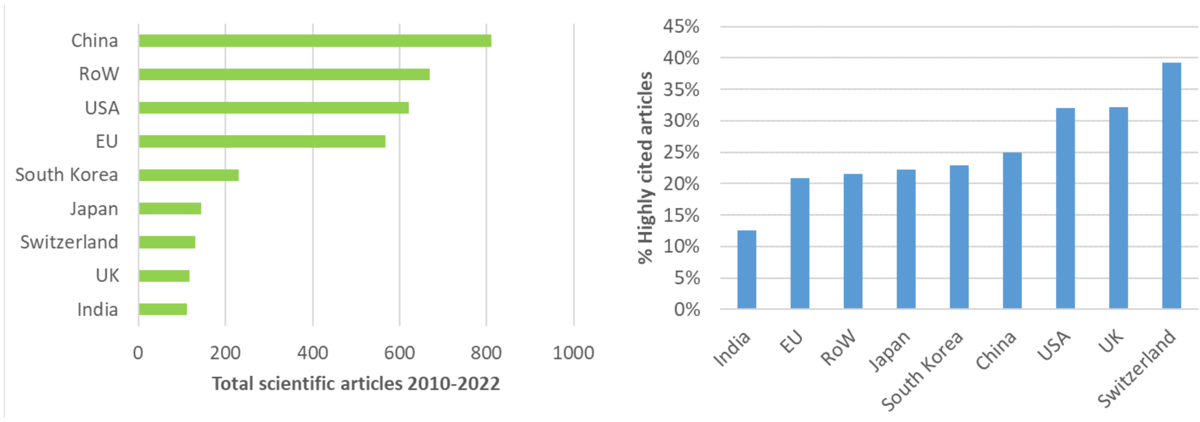
Source: JRC TIM data and elaboration

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



Source: JRC TIM data and elaboration

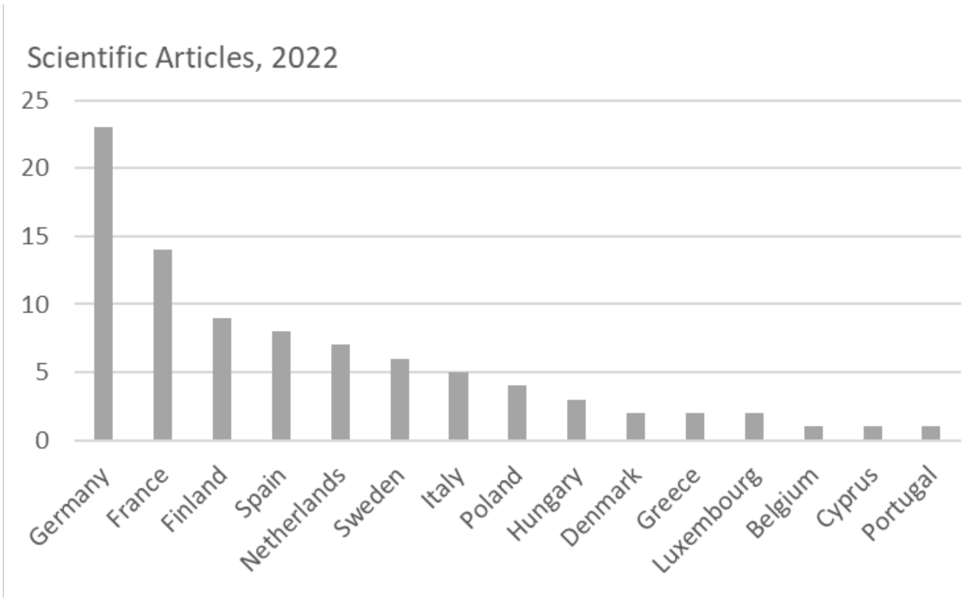
Figure 3. Breakdown of leading countries and regions for a) total scientific articles and b) by % of highly cited articles from all publications on solar fuels in the period 2010 to 2022.



a) Total articles b) % Highly cited

Source: JRC TIM data and elaboration

Figure 4. Ranking of EU countries for publications on solar fuels in 2022. Other EU countries that have published on solar fuels since 20210 includes Austria, Croatia, Czechia, Estonia, Ireland, Latvia, Lithuania, Romania, Slovakia and Slovenia.



Source: *JRC TIM data and elaboration*

2.4 Impact and Trends of EU-supported Research and Innovation

2.4.1 EIC Horizon Prize 'Fuel from the Sun: Artificial Photosynthesis'

The Prize challenged teams from around the world to build a fully functional, bench-scale prototype of an artificial photosynthesis system able to produce a useable synthetic fuel. 22 applications were received, from which 3 finalists were selected by a Jury of 6 independent experts to test their concept in real life conditions during 72h non-stop operation at JRC, Ispra, Italy.

The winner was the University of Tokyo with their partner INPEX Corporation for their application "UTIAPS – Artificial Photosynthesis Driven by Water-Splitting Particulate Photocatalyst". The key technological developments in their concept involve efficient photocatalytic modules, gas separation devices, green fuel synthesis reactors, storage systems, and equipment for safety (Yamada et al, 2023).

The other finalist teams were:

- Commissariat a L'Energie Atomique Et Aux Energies Alternatives (CEA), France, for their application EASI-Fuel, - European Autonomous Solar Integrated Fuel Station. EASI-fuel provides the proof of concept for fuel production by coupling photo-electrolysis of water with continuous H2 and CO2 conversion into biomethane.
- Cambridge University for their application CamSolarFuel, - Hybrid Perovskite Photoelectrochemical Leaf for Autonomous Syngas Product. Their approach stood out for combining unassisted aqueous CO2 reduction with water splitting to produce a hydrogen and carbon monoxide mixture called syngas in a single device

2.4.2 Solar thermochemical demonstrators

There have been several recent demonstrations of pilot processes using the solar thermochemical pathway. In 2022, Synhelion (Germany) announced that the production of syngas at an industrial scale had been demonstrated on the solar tower of the German Aerospace Centre (DLR) in Jülich. In this system concentrated solar heat at over 1 000°C is used to react methane and carbon dioxide of biowaste origin with water to produce syngas, a mixture of H2 and CO. The syngas is then processed by standard gas-to-liquid technology into a solar fuel. The system is reported to have a production capacity of 100 standard cubic meters of syngas per hour when commissioned in 2023, which would potentially yield 150 000 litres of liquid fuel per year. No public information on the GHG emissions value has been found so far. This plant is part of the SolarFuels project funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). The company also raised €14.74M of Early Stage VC (Series B) in a deal led by Swiss KMU Partners in September 2021. In 2023 Synhelion also announced projects for solar hydrogen production with the University of Florida. A restriction to exploiting thermochemical water splitting of this type in the EU is the need high solar irradiance for economic operation (above 1 800 kWh/m2/y according to Synhelion, which is reached only in the most southern areas of the EU).

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.

2.4.3 R&I coordination

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. SUNERGY produced a strategic research agenda in 2022 (Kargul, Faber et al, 2022). It is about to release a roadmap on solar fuels and chemicals (Faber et al, 2023), which is intended to provide a series of concrete technological milestones for a) pilot and demonstration project development, b) technology industrialisation and scale-up, and c) first-of-a-kind project development.

Sunergy has its roots in the EU-funded Sunrise project (2019-2020) that initially brought together the key European actors on solar fuels and led to the Sunrise Roadmap. This group subsequently merged with the Energy-X consortium that produced a roadmap on sustainable production of fuels and chemicals in 2019 (Norskov et al, 2019).

Solar fuels have not been explicitly addressed under the EU's Strategic Energy Technology Plan (SET-Plan[3]), but are addressed thematically in the key actions on renewable fuels and bioenergy and carbon capture and storage/use. The proposed SET-Plan joint solar strategic research and innovation agenda will also include solar fuels in its scope. The 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 strategic agenda

[3] https://energy.ec.europa.eu/topics/research-and-technology/strategic-energy-technology-plan_en

(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 (see Mission Innovation, 2021). Under Mission Innovation 2.0, launched in June 2021, this work continues and a “Sunlight-to-X” collaborative innovation platform was approved at the end of 2022. It is co-led by the EC, USA and China and has support from Australia, Austria, France, Germany, Italy, Japan, Republic of Korea and the United Kingdom.

2.4.4 Standards

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”. A step forward on this was the publication of protocol for “Best Practices in PEC Water Splitting: How to Reliably Measure Solar-to-Hydrogen Efficiency of Photoelectrodes” by authors from USA, China and Germany (Alley et al, 2022).

In the future, solar fuel technologies can also take advantage of the framework being developed for green hydrogen, including standardisation of guarantee of origin certificates and international market rules.

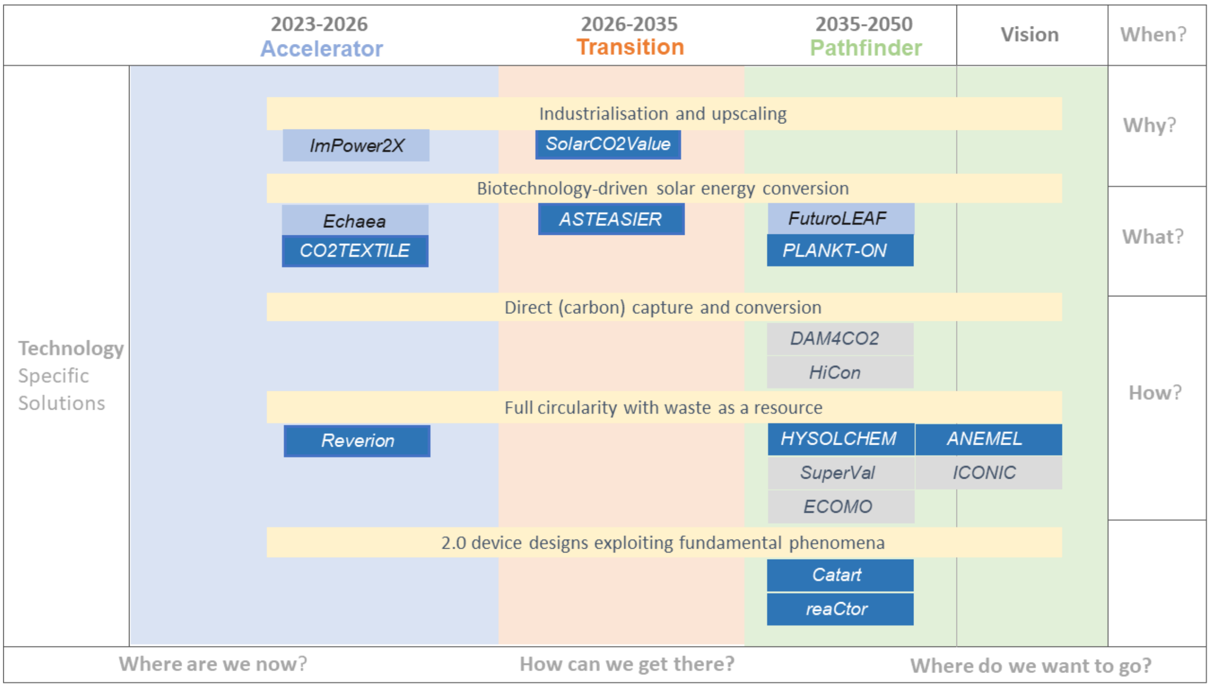
2.4.5 Emerging trends

In March 2023, the European Innovation Council, together with the JRC, held a Horizon Scanning Workshop on Solar Fuels and Chemicals. The invited experts considered over 100 signals. These had been submitted by experts or identified by data and text mining of scientific publications and research project proposals previously submitted to the EIC. The results overview (Javier et al., 2023) identifies the following thematic clusters:

- Interface engineering
- Challenge of scalability and application
- CirculAIR fuels – this refers to using renewable energy and DAC-CCU to produce e-molecules, which can be completely circular with respect to water and heat requirements.
- Stability of CO2 reduction processes:
- Cyanobacteria, as an example of research into harnessing microbiological processes to generate a variety of products based on organisms’ interactions with sunlight and abundant materials.

The EIC is also carrying out a landscaping exercise on its funded projects (**Figure 5**). It notes the use of biotechnology at all maturity levels, where microorganisms significantly facilitate the synthesis of diverse chemical compounds. On the fundamental research level, the capture and direct conversion of carbon dioxide in a single device promises large energy savings compared to using separate steps. Full circularity, where waste becomes a resource, is another emerging trend, as is the development of novel device designs, for instance exploiting quantum phenomena (C. Faber, 2023).

Figure 5 EIC landscaping of the EIC Pathfinder (fundamental research), Transition (TRL 4-6) and Accelerator (high risk, high impact, scale-up) projects (the colour code is ended = light blue, running = dark blue and starting = grey).



Source C. Faber, European Innovation Council

3 Techno-Economic Aspects and Sustainability

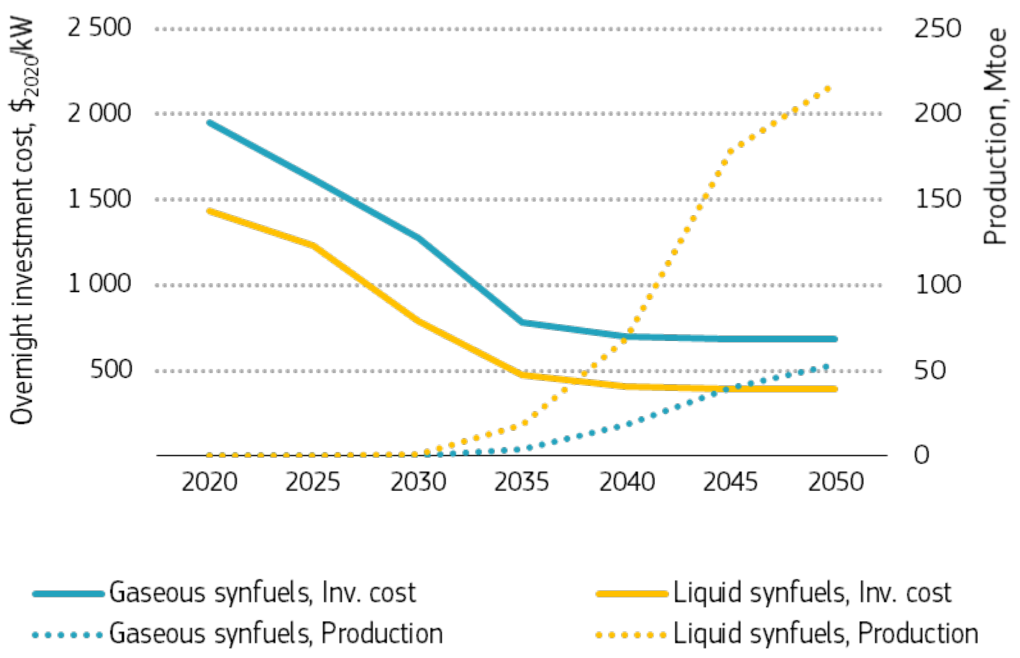
3.1 Prospective Markets

Energy system modelling provide useful scenarios for the possible future market for non-fossils fuels. The 2023 IEA revised Net Zero Energy scenario (IEA, 2023) foresees that by 2050 hydrogen-based fuels (i.e., hydrogen itself, together with synthetic or e-fuels) would account for approximately 14% (239 Mtoe) of transport energy consumption[4] (this declined from 20% in the 2021 NZE analysis). 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 scales, and in distributed and off-grid systems can offer a range of different market.

The CETO energy system scenario analyses at global level (POLES-JRC) and EU level (POTEnCIA) consider synthetic fuels in detail, but not solar specifically (see the overall description in Annex 1). For the global scenario, liquid and gaseous synfuels begin to develop significantly around 2035 and reach 218 Mtoe and 53 Mtoe respectively in 2050. This is comparable to the revised IEA NZE results. **Figure 7** shows the projected uptake of synthetic fuels in the EU according to the POTEnCIA Climate Neutrality Scenario POTEnCIA. Also at EU level, these fuels begin to develop around 2035 and total production reaches 41 Mtoe in 2050. This is significantly lower than values in the Commission's 2050 longer-term strategy (EC, 2018) for the below 1.5 degree compliant scenarios (1.5TECH and 1.5LIFE), with annual requirements of 150 Mtoe and 140 Mtoe by 2050 respectively.

Solar fuels can contribute significantly to these future markets. Cost competitiveness remains however a concern. 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 the 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. Indeed, the SUNRISE roadmap (Faber et al, 2019) provided considerable data on the product costs needed for the specific pathways to become cost-competitive with current products. As a general indication, regarding synfuels, the POLES-JRC CETO global 2°C scenario projects overnight investment costs to decrease significantly in the coming decade (Figure 7). By 2035, a decrease of around 60% is foreseen for gaseous synfuels and around 65% for liquid synfuels compared to 2020. Of course, as already said, these numbers do not consider solar fuels specifically but synthetic fuels in general, and, in this sense, they are provided as a general guide.

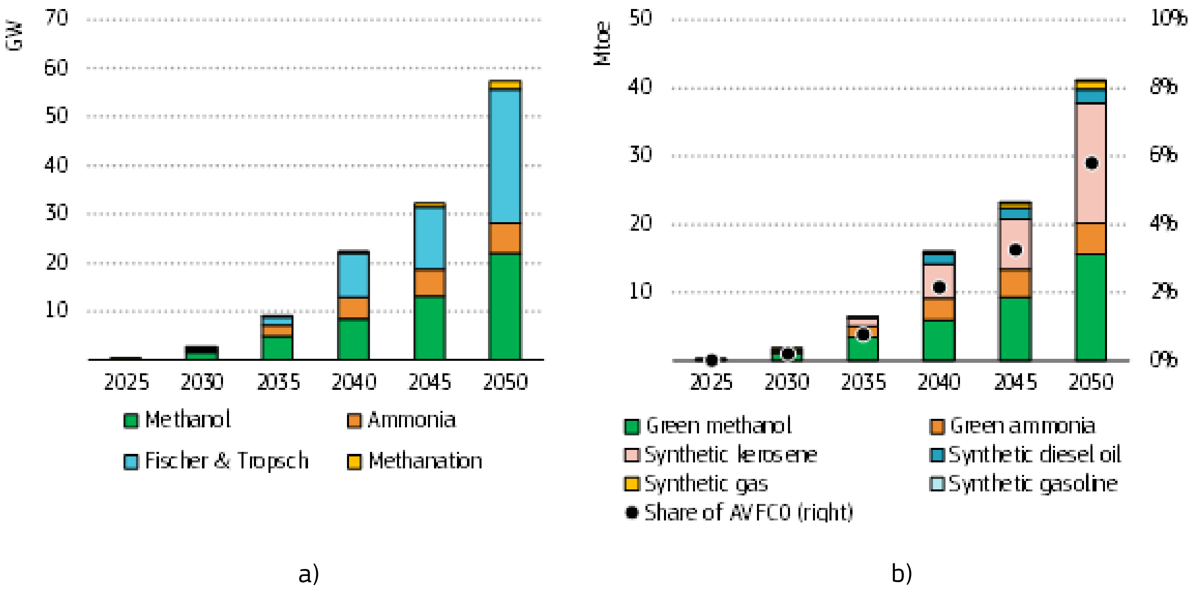
Figure 6 Global energy system scenario for synfuels - overnight investment cost and production.



Source: POLES-JRC (see Annex 1)

[4] the other sources are electricity, bioenergy and fossil fuels

Figure 7 Projected synfuels installed capacity (left) and production (right) in the EU according to POTEnCIA CETO Climate Neutrality Scenario.



Source: JRC POTEnCIA (see Annex 1)

Notes: AVFCO = available energy for final consumption and energy consumed in international aviation and shipping.

3.2 Value chains

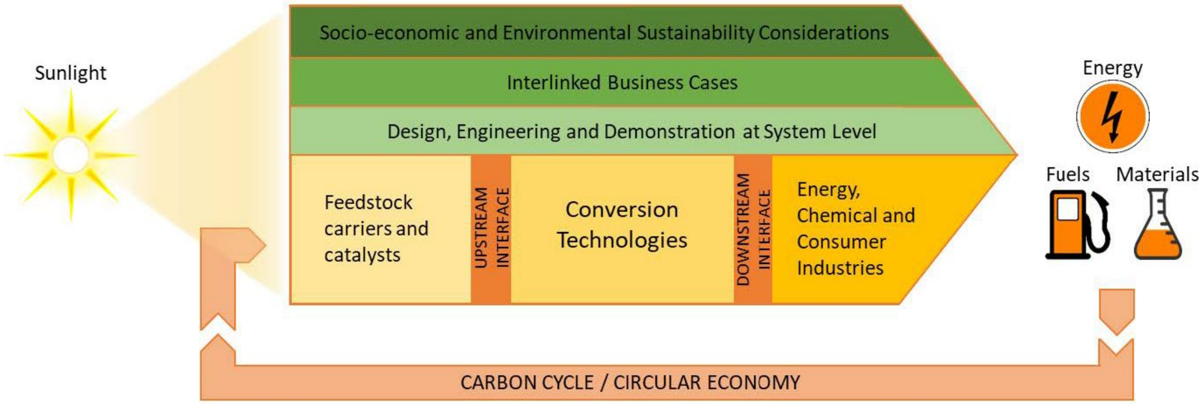
The Mission Innovation IC5 report provides a useful visualisation of how the solar-to-x value chain can look like in the future (**Figure 8**). While the focus of this report is very much on the core conversion processes, it highlights the role of upstream feedstock providers as well the downstream industries and consumer of the product.

3.3 Sustainability

As shown in **Figure 8**, socio-economic and environmental considerations need to be considered at all stages of the value chain for solar fuels. 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).

The CETO sustainability assessment 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.

Figure 8 Converting sunlight value chain



Source: Mission Innovation IC5 report, 2021

4 Conclusions

- Solar fuels, and more generally "sunlight-to-X" technologies, are an emerging class of sustainable alternative fuels and chemicals that are set to play an important long-term role in all net-zero carbon scenarios for the energy system. They also offer potential for distributed production and more citizen engagement, compared to present centralised approaches. Solar fuels categorised under renewable fuels of non-biological origin in EU legislation and can contribute to the related energy targets.
- The main routes considered in this report are direct photochemical/photobiological processes and indirect solar thermochemical processes. The SUNERGY technology readiness level assessment provides a useful update the development of solar-to-x options for a range of products: hydrogen, ammonia and any carbon-based synthetic fuels (e.g. hydrocarbons and alcohols) and chemicals.
- For the photochemical/biological pathways, low stabilities and uncertainties on the future scale-up of such technologies need to be overcome. The EIC Fuel from the Sun Artificial Photosynthesis Prize in 2022 was a landmark, with three concepts demonstrating operation in field conditions over a three day period.
- For the solar thermochemical pathway, pilot plants at the 50 kW scale have been set up in Germany and Spain. These developments have benefited in part from EU framework programme funding. Nonetheless significant technical challenges remain to achieving sufficient efficiency and continuous operation.
- There is a growing need for benchmarking protocols and technical performance, reliability and sustainability standards. The EU can play a prominent role in such developments.
- Bibliometric analysis shows that 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 and already over EUR 70 million in the first two years of Horizon Europe. At global level 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.
- Future cost competitiveness is a concern for solar fuels. Energy system modelling such as the POLES-JRC CETO global 2°C scenario provide useful indications of the future market for hydrogen and synfuels and chemicals, of which solar fuels can be a part. The projects overnight investment costs to decrease significantly in the coming decade (Figure 7). By 2035, a decrease of around 60% is foreseen for gaseous synfuels and around 65% for liquid synfuels compared to 2020.
- The SUNERGY initiative on fossil-free fuels and chemicals brings together 300+ stakeholders from academia, industry, public institutions and civil society in Europe and is providing a strategic lead on planning research and innovation activities. It receives funding from Horizon Europe through the SUNER-C Coordination and support action (2022 to 2025). In parallel, the inclusion of solar fuels in the strategic plan of the Clean Energy Transition Partnership CETP and in the proposed SET-Plan joint solar strategic research and innovation agenda can help realise the potential of these technologies to help achieve a sustainable future energy system.

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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

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Annexes

Annex 1 Energy system models and scenarios used in CETO

A1.1 POTEnCIA Model Overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

- By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;
- By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;
- By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

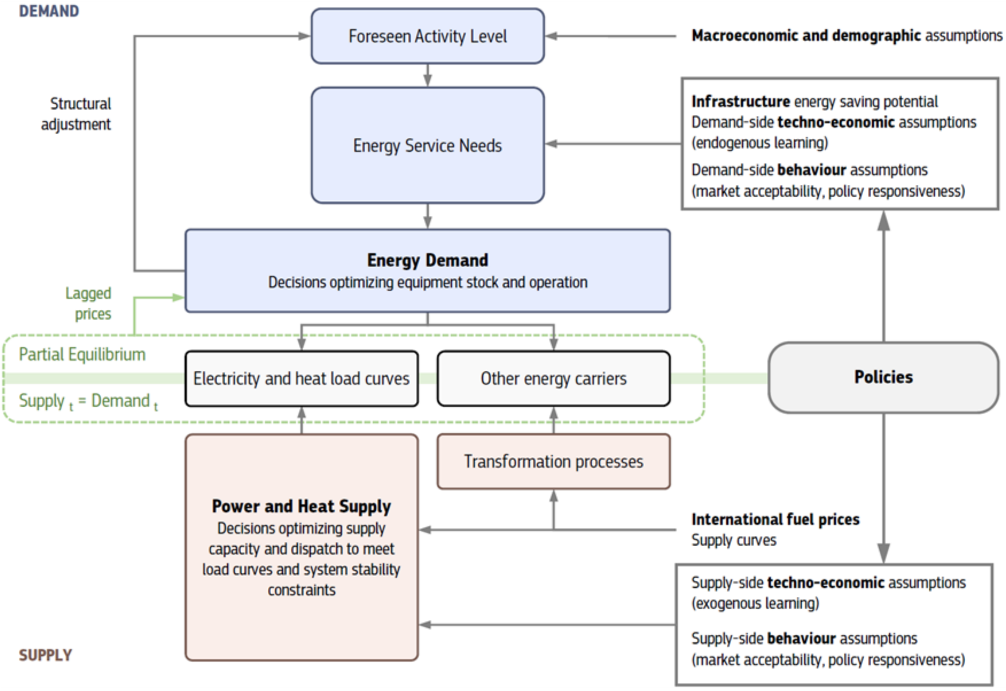
The core modelling approach of POTEnCIA (Figure A3-1; detailed in the POTEnCIA model description and in the POTEnCIA Central Scenario report) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies. This core modelling approach is tailored to each sector, for instance to represent different planning horizons and expectations about future technologies under imperfect foresight. In particular, power dispatch modelling uses a high time resolution with full-year hourly dispatch to suitably depict the increasing need for flexibility from storage and demand response, and the changing role of thermal generation in a power system dominated by variable renewable energy sources. Within this sector modelling framework, investment decisions of the representative agents are simulated with discrete-choice modelling. The model then finds an overall equilibrium across different sectors using price signals for resources such as traditional and renewable energy carriers while accounting for efficiency and environmental costs.

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (JRC-IDEES). JRC-IDEES has been developed in parallel to POTEnCIA, and an updated release is planned in 2024 to ensure the transparency of POTEnCIA's base-year conditions and to support further research by external stakeholders.

A1.2 POTEnCIA CETO Climate Neutrality Scenario overview

The technology projections provided by the POTEnCIA model are obtained under a Climate Neutrality Scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU27 GHG emissions by 55% by 2030 versus 1990, and reaches the EU27´s climate neutrality by 2050 under general assumptions summarized in Table A3-1. To suitably model technology projections under these overarching GHG targets, the scenario includes a representation of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the deployment of bioenergy and renewable power generation technologies to 2030 is consistent with the EU's Renewable Energy Directive target (42.5% share of renewables in gross final energy consumption by 2030, according to the REDII' recast). Similarly, the adoption of alternative powertrains and fuels in transport is also promoted by a representation of updated CO2 emission standards in road transport and by targets of the ReFuelEU Aviation and FuelEU Maritime proposals.

Figure A3-1. The POTEnCIA model at a glance



Source: Adapted from the POTEnCIA Central scenario report

Table A3-1. General assumptions of the POTEnCIA CETO Climate Neutrality Scenario

General scenario assumptions	Modelled scenario and policy assumptions
GDP growth by Member State	GDP projections based on EU Reference Scenario 2020, with updates to 2024 from DG ECFIN Autumn Forecast 2022
Population by Member State	Population projections based on EU Reference Scenario 2020, with updates to 2032 from EUROPOP 2019
International energy markets	Natural gas import projections consistent with REPowerEU targets for supply diversification and demand reduction. International fuel price projections to 2050 aligned with REPowerEU

Source: JRC

A1.3 POLES-JRC Model

POLES-JRC (Prospective Outlook for the Long term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. POLES-JRC is hosted at the JRC and is particularly adapted to assess climate and energy policies.

POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables etc.) to transformation (power, biofuels, hydrogen) and final sectoral demand (Figure A3-2). International markets and prices of energy fuels are simulated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global framework:

access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2050 and is updated yearly with recent data and model updates.

The POLES-JRC model is used to assess the impact of European and international energy and climate policies on energy markets and GHG emissions, by DG CLIMA in the context of international climate policy negotiations and by DG ENER in the context of the EU Energy Union.

POLES-JRC has also been applied for the analyses of various Impact Assessments in the field of climate change and energy, among them: the “Proposal for a revised energy efficiency Directive” (COM(2016)0761 final) and “The Paris Protocol – A blueprint for tackling global climate change beyond 2020” (COM(2015) 81 final/2).

Moreover, POLES-JRC provided the global context to the EU Long-Term Strategy (COM(2018) 773) and formed the energy/GHG basis for the baseline to the CGE model JRC-GEM-E3.

POLES-JRC forms part of the Integrated Assessment Modelling Consortium (IAMC) and participates in inter-model comparison exercises with scenarios that feed into the IPCC Assessment Reports process.

POLES-JRC results are published within the series of yearly publications "Global Climate and Energy Outlooks – GECO". The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at: https://ec.europa.eu/jrc/en/geco

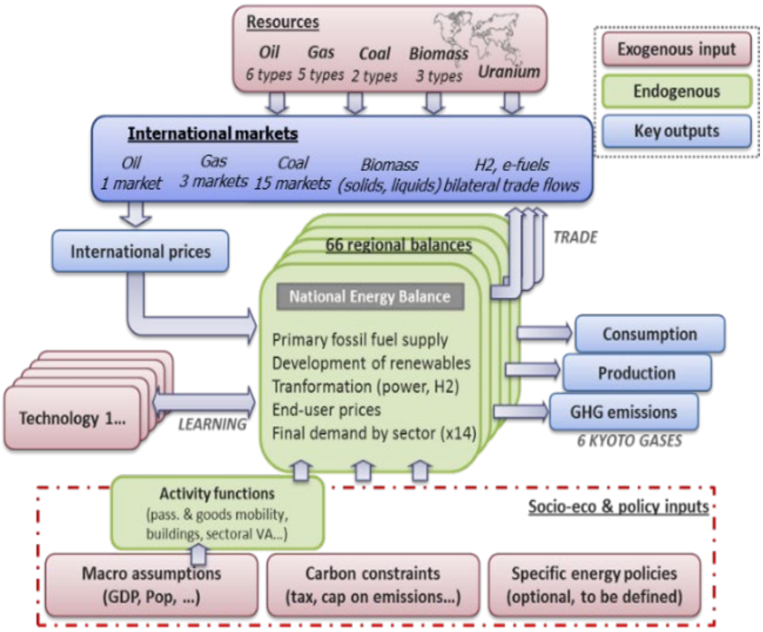
A1.3.1 Power system

POLES-JRC considers 37 power generating technologies, covering existing technologies as well as emerging technologies. Each technology is characterised by its installed capacity, cost parameters (overnight investment cost, variable & fixed operating and maintenance cost), learning rate and other techno-economic parameters (e.g. efficiencies). The cost evolution over time is taken into account by technology learning driven by accumulated capacity.

For renewable technologies maximum resource potentials are taken into account. Similarly, the deployment of carbon capture and storage (CCS) technologies is linked to region-specific geological storage potential. In addition to these technical and economic characteristics, non-cost factors are applied to capture the historical relative attractiveness of each technology, in terms of investments and of operational dispatch.

With regard to the clean energy technologies covered by CETO, the model includes power generation using photovoltaics (utility and residential), concentrated solar power (CSP), on-shore and off-shore wind , ocean energy, biomass gasification and steam turbines fuelled by biomass, geothermal energy as well as hydropower. CCS-equipped combustion power technologies are considered as well. Moreover, electricity storage technologies such as pumped hydropower storage and batteries are also included.

Figure A3-2. Schematic representation of the POLES-JRC model architecture



Source: JRC

A1.3.2 Electricity demand

The total electricity demand is computed by adding the electricity demand from each sector (i.e. residential, services, transport, industry and agriculture). The evolution over time of the sectoral electricity demand is driven by the activity of each sector and competition between prices for electricity and other fuels.

POLES-JRC uses a set of representative days with an hourly time-step in order to capture load variations as well as to take into account the intermittency of solar and wind generation. The usage of representative days also allows to capture hourly profiles by sector and end-uses.

With a view to other CETO technologies influencing electricity consumption, the model includes heat pumps in the residential and service sector, batteries for electric vehicles and electrolysers.

A1.3.3 Power system operation and planning

The power system operation assigns the generation by technology to each hour of each representative day. The supplying technologies and storage technologies must meet the overall demand.

The capacity planning considers the existing structure of the power mix (vintage technology), the expected evolution of the demand, and the production cost of technologies.

A1.3.4 Hydrogen

POLES-JRC takes into account several hydrogen production routes: (i) low temperature electrolysers using power from the grid or power from solar and wind, (ii) steam reforming of natural gas (with and without CCS), (iii) gasification of coal and biomass (with and without CCS), (iv) pyrolysis of coal and biomass as well as high temperature electrolysis using nuclear power.

Hydrogen can used as fuel in all sectors. Moreover, hydrogen is used to produce fertilisers as well as to produce fuels used in the transport sector (i.e. gaseous and liquid synfuels and ammonia). POLES-JRC models global hydrogen trade and considers various means of hydrogen transport (pipeline, ship, truck, refuelling station).

A1.3.5 Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM model[5]. This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass potential, production cost and carbon value. Moreover, the emissions from land use and forestry (CO_2) as well as agriculture (CH_4 and N_2O) are derived from GLOBIOM.

Power generating technologies using biomass are biomass gasification (with and without CCS) and biomass fuelled steam turbines.

Hydrogen can be produced from biomass via gasification and pyrolysis. Moreover, the production of 1st and 2nd generation biofuels for gasoline and diesel is considered.

A1.3.6 Carbon Capture Utilization and Storage (CCUS)

POLES-JRC takes into account CCUS technologies for:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS;
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and coal and biomass pyrolysis;
- Direct air capture (DAC) where the CO_2 is stored or used to produce synfuels (gaseous or liquid);
- CO_2 storage in geological sites.

A1.3.7 Model documentation and publications

A detailed documentation of the POLES-JRC model and publications can be found at:

- https://publications.jrc.ec.europa.eu/repository/handle/JRC113757
- https://ec.europa.eu/jrc/en/poles

[5] Global Biosphere Management Model (GLOBIOM) model description. International Institute for Applied Statistical Analysis, Luxenburg, Austria. http://www.globiom.org

A1.4 POLES-JRC CETO Global 2°C Scenario

The global scenario data presented in this CETO technology report refers to a 2°C scenario modelled with the POLES-JRC model. The 2°C scenario assumes a global GHG trajectory consistent with a likely chance of meeting the long-term goal of limiting the temperature rise over pre-industrial period to 2°C in 2100.

The 2°C scenario was designed with a global carbon budget over 2023-2100 (cumulated net CO_2 emissions) of approximately 1150 $GtCO_2$, resulting in a 50% probability of not exceeding the 2.0°C temperature limit in 2100. A single global carbon price for all regions is used in this scenario, starting immediately (2023) and strongly increasing. The 2°C scenario is therefore a stylised representation of an economically-efficient pathway to the temperature targets, as the uniform global carbon price ensures that emissions are reduced where abatement costs are lowest. This scenario does not consider financial transfers between countries to implement mitigation measures.

The POLES-JRC model has been updated with the latest technologies costs from recent literature. Most of the historic data used in the 2°C scenario refers to data used in the GECO 2022 scenarios (energy balances, energy prices, capacities).

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