



Study on

'Solar Fuels Research & Invest: Defining and developing the global solar fuel value chain: techno-economic analysis and pathways for sustainable implementation'

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Final Report

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List of abbreviations

Abbreviation	Definition
AP	Artificial Photosynthesis
AEC	Alkaline Electrolysis Cell
CAPEX	Capital expenditures
CEPS	Centre for European Policy Studies
COP21	2015 United Nations Climate Change Conference in Paris
CCU	Carbon capture and utilisation
CHP	Combined heat and power
DAC	Direct air capture
DG	Directorate-General
DG RTD	Directorate-General for Research and Innovation
DPCI	Derwent Patent Citation Index
DSSC	Dye Sensitive Solar Cell
DWPI	Derwent Word Patent Index
GECO	Global Energy and Climate Outlook
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GMO	Genetic Modified Microorganism
ICE	Internal combustion engine
INPADOC	International Patent Documentation
IPC	International Patent Classification
IPCC	Intergovernmental Panel on Climate Change
ISFF	International Solar Fuel Forum
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCOE	Levelized cost of energy
MI	Mission Innovation
O&M	Operation and Maintenance
PCT	Patent Cooperation Treaty
PC	Photocatalysis
PEC	Photoelectrochemical cell
PEM	Proton Exchange Membrane
PEMEC	Proton exchange membrane electrolyser cell
PPP	Purchasing Power Parity
PV	Photovoltaic
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
SDG	Sustainable Development Goals
SSP	Shared Socioeconomic Pathways
STCH reactor	Solar Thermochemical Hydrogen reactor
SWOT	Strengths, Weaknesses, Opportunities, Threats
ToR	Terms of Reference
TRL	Technology Readiness Level
UN	United Nations
US	United States

Executive summary of key study results

Using sunlight as energy source, solar fuels offer great potential to meet worldwide future energy demands. As depicted in Figure 1 below, they result from the conversion of sunlight into fuels such as methanol or hydrogen. They can be easily stored to respond to fluctuating energy needs and can be used for different applications in the transport, building and industrial sectors. Solar fuels can be produced through different technological pathways, namely Electrochemical, Chemical, Thermochemical and Biochemical processes. The market for solar fuels is nevertheless still at an early development stage. Reaching large-scale production of solar fuels will necessitate a coordinated approach relying on experts from diverse fields and integrating knowledge regarding technological developments, industrial scale-up and market acceptance.

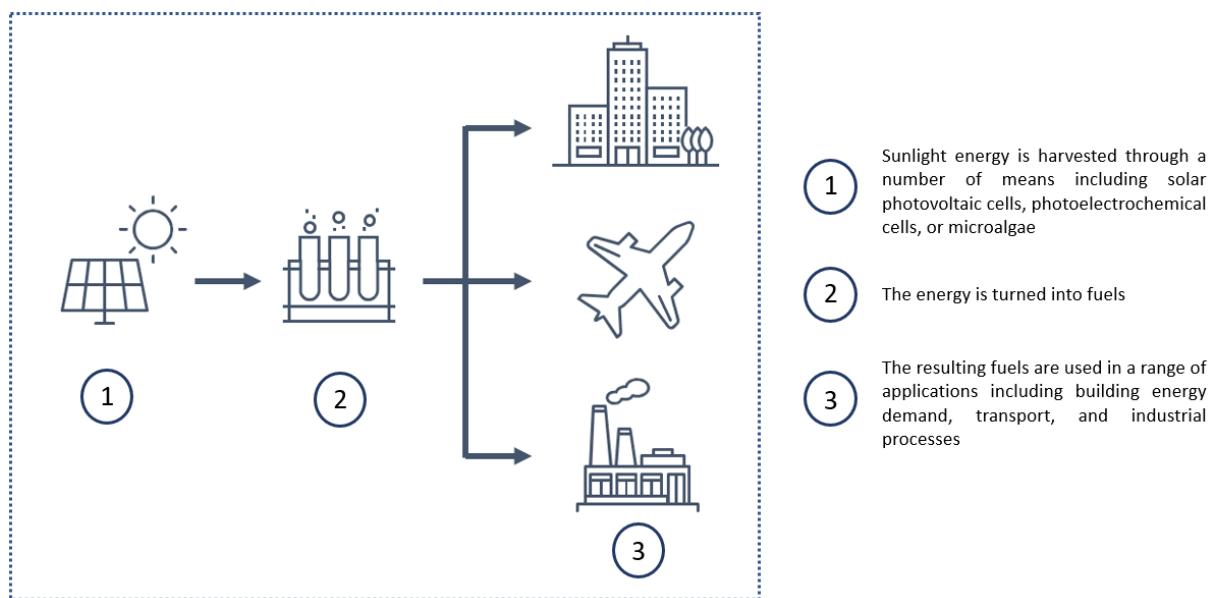


Figure 1 – Solar Fuel Value Chain

In this perspective, the European Union has at COP21 joined Mission Innovation with the aim of reinvigorating and accelerating global clean energy innovation, notably looking at the potential of solar fuels produced through different technological approaches and pathways. This was part of the European Union's overarching pledge to decarbonise its society and economy and commitment to the role of worldwide champion in renewable technologies. Considering solar fuels as a potential "game changer", the European Commission, co-chairing the Converting Sunlight Innovation Challenge, launched a qualitative and quantitative assessment of solar fuels' value chains and the development of a forward-looking techno-economic international roadmap.

This sets the context of this European Commission funded study on 'Solar Fuels Research & Invest: Defining and developing the global solar fuel value chain: techno-economic analysis and pathways for sustainable implementation', conducted by a Consortium composed of EY, IMEC, RINA and CEPS.

1.1. *Definition of solar fuels value chains*

The study has analysed key solar fuel value chains through four specific production pathways: Chemical, Electrochemical, Thermochemical and Biochemical. For each technological pathway, the main technological components associated with their fuel production processes were outlined in a qualitative manner, identifying the various raw materials and resources needed for each technology to produce a specific solar fuel. This categorisation was conducted for the following pathways and technologies:

- Electrochemical pathway: Alkaline Electrolysis ("AE"), Proton Exchange Membrane electrolyser ("PEMFC"), Photo-electrochemical electrolyser cell ("PEC")

- Thermochemical pathway: Solid Oxide Electrolyser Cell ("SOEC")
- Chemical pathway: Artificial Photosynthesis ("Artificial Leaf")
- Biochemical pathway: Biohybrid system ("Bionic Leaf"), Microalgae

The aim of this qualitative analysis and selection was to focus on the most relevant value chains in terms of their potential for technological and economic improvements. It provided the basis for the economic and quantitative analysis of the technologies' value chains. The quantitative analysis included additional promising technologies which were covered under the Hydrogenation and Methanation pathways. The value chain analysis was performed based on a Levelized Cost of Energy ("LCOE") economic modelling exercise, decomposing the LCOE variables into a set of value chain components including capital expenditures ("CAPEX"), overhead and maintenance, production costs including labour and energy input costs, and considering the valorisation of certain by-products. The analysis was carried out for the year 2020 and per fuel, for example looking at all relevant technologies producing hydrogen, and allowed for the comparison of green solar technologies against their fossil-based counterparts.

The analysis revealed that production costs, comprising primarily energy input costs, are the key driver of technologies' current LCOE in most pathways, namely Electrochemical, Thermochemical, Hydrogenation and Methanation. The energy inputs to the Electrochemical and Thermochemical pathways consist in electricity derived from solar PV, whose costs themselves are primarily driven by CAPEX. The capital expenditures for solar PV are therefore embodied in the costs of green hydrogen produced through the Electrochemical and Thermochemical pathways, and end up determining a substantial portion, up to 60 percent, of the costs of green hydrogen. The costs of green hydrogen represent 87 percent and 93 percent of the LCOE for fuels produced through the Hydrogenation and Methanation pathways in 2020, respectively, thereby implying that the capital expenditures for solar PV are indirectly responsible for over half of the LCOE for solar fuels produced through the Hydrogenation and Methanation pathways.

CAPEX is the highest cost component for SOEC and mainly for microalgae, reflecting the low maturity level of both technologies. In this context, microalgae also experiences high overhead and maintenance costs, reflecting its experimental nature.

One clear observation emanating from the value chain and LCOE analysis is the cost advantage that fossil fuel technologies, including steam methane reforming and the methanol process, benefit from compared to their green counterparts. Another key takeaway is that the current cost of solar fuels is mostly driven by the high CAPEX associated with solar PV, despite significant cost reductions in the past decade. Therefore, achieving low cost solar PV is a key objective for making solar fuels competitive.

This analysis therefore provides a snapshot of the current state of the studied technologies' value chains, in the form of a decomposed LCOE. The LCOE model also allows for a forward-looking time-series analysis through 2100, estimating performance of the technologies over time and assessing at which point in time the green technologies could overcome the cost competitiveness of their fossil counterweights. This analysis is presented in the next section of this study, drawing a technological roadmap (for 2030 and 2060) and economic roadmap (through 2100) for all studied technologies.

1.2. *Roadmap for Solar Fuels and Market Outlook*

1.2.1. Technology and economic roadmap for solar fuels

The study provides a technological roadmap for solar fuel technologies for 2030 and 2050 as well as an economic roadmap for solar fuels through 2100. The technological roadmap for 2030 and 2050 aimed at assessing the main technological challenges and bottlenecks that must be overcome to reach the production of solar fuels at commercial scale.

Starting with the identification of key technologies under the chemical, electrochemical, thermochemical and biochemical pathways, the analysis determines the current Technology Readiness Level ("TRL") of the components of each technology. The study then focuses on identifying the main challenges linked to each component and to the system as a whole: this phase entails a SWOT analysis and a patent analysis, where possible. The main outcomes of the technological roadmap present the estimated TRL advancements towards 2030 and 2050, including the major actions to be carried out in order to move forward to the commercial scale of the technologies.

The economic roadmap, building on the technological roadmap, accounts for the results of technological improvements in the solar fuel pathways by modelling the expected LCOE for each technology. Two scenarios for the development of solar fuels are contemplated: the first models relatively stable levels of investment in solar fuel pathways, whereas the second foresees a significant investment push, thereby accelerating the time to market for solar fuels. The latter scenario, which we have labelled as "scale", foresees significant investments in solar fuel technologies, even prior to solar fuels becoming cost-competitive with fossil fuels.

Technology roadmap

- *Electrochemical pathway*

The Proton Exchange Membrane electrolyser ("PEMEC") technology is used in the electrochemical pathway of solar fuels in combination with photovoltaics. The state of the art TRL of PEMEC has been identified to be between 7 and 8. The advantages of PEMEC are the fast response time, that makes it very attractive to work with intermittent renewable electricity sources and the high purity of the product gases. This technology has the potential to reach full market availability within 5 years. Upscaling to GW production requires the strong reduction or substitution of noble metal catalysts like PGM. There are two ways to address this bottleneck. One is the mitigation from proton exchange membrane to hydroxyl exchange membranes and thus operations in alkaline instead of acidic electrolytes. This will reduce the pressure on the electrode/catalyst material because more abundant metals could be applied. On the other hand, it shifts the development effort towards the membrane, because hydroxyl exchange membranes are not commercially available with the same TRL than proton exchange membranes. The other possibility to accelerate the PEMEC technology would be the strong reduction of Platinum Group Metals ("PGM") catalysts by novel material technologies like core shell nanoparticles or novel thin film process technologies where only a fraction of the noble metal catalysts is needed.

The SOEC technology is used in the electrochemical pathway of solar fuels in combination with photovoltaics. The state-of-the-art TRL of the SOEC technology is determined to be between 6 and 7. This means that prototypes have been tested in the field and in compliance with intended working conditions. Due to the high system temperature, co-electrolysis with CO₂ is possible. As a product, syngas (CO+H₂) could be utilised in combination with a Fischer-Tropsch process directly into higher hydrocarbons like synthetic kerosene or synthetic diesel. Key bottlenecks towards market implementation are mainly the stability of the solid oxide membrane and the high operation temperature. Long ramp up time due to the high operation temperature prevents the direct coupling with highly intermittent renewable electricity sources like solar and wind. In the future, when battery cost further drops, low cost batteries can be used to buffer and provide a constant electricity supply. Material development and reactor design effort is needed to make this technology available for the market within the next 10 years. Market availability will also depend on the integration of low-cost batteries to keep the system in operation for low renewable power generated at night, with clouds or low wind.

The state of the art of the PEC technology within the electrochemical pathway of solar fuels is determined to be between 3 and 4. This means that small-scale prototype of the system or sub-systems are developed in laboratory. The bottlenecks/critical issues to overcome to obtain a stable system and provide prototype operations is corrosion, which occurs with all materials over long periods of time, and catalyst poisoning. This is caused by the

introduction of solution impurities, and it has been shown that low concentrations of impurities can have a huge impact on electrode efficiency and changes to the composition and morphology (structure/structural features) of the electrode can decrease their efficiency. Within the next 10 years this technology will successfully demonstrate prototyping. But then the challenge will come with the upscaling of the technology to proof operations in the field under real conditions. For that, large-scale processing methods are required like roll to roll production and high-volume deposition techniques. This technology will be applied in stand-alone systems for households or local energy communities. We expect a market introduction of this technology in the 2040s.

- *Chemical pathway*

The state of the art TRL of the Photocatalytic particulate or colloidal systems technology is determined to be between 2 and 3. This means the technical analysis of the concept is investigated and partially the technological concept is experimented and validated at laboratory scale. The first bottlenecks/critical issues to overcome towards a proof of concept system are the development of a gas separation membranes, ionic charge carrier mediators and materials that provide process stability, high catalyst efficiency and high photosensitivity. A breakthrough for this technology will be the development of self-assembled and self-repairing nanomaterials. After the prototyping is demonstrated the upscaling challenge needs to be addressed. The same constraints to the materials apply like in the PEC upscaling challenge. For that, large-scale processing methods are required like roll to roll production and high-volume deposition techniques. This technology will be applied in standalone systems for households or local energy communities. We expect market introduction of these systems in the 2050s.

- *Thermochemical pathway*

Solar thermochemical hydrogen production systems are based on two-step processes at high-temperature ($>1000^{\circ}\text{C}$) involving thermal decomposition and subsequent re-oxidation of metal oxides. They are composed of a concentrated solar system and a reactor for thermochemical reactions, the former being available at high maturity (TRL 7-9) and the latter (redox materials and reactor absorber) at pilot scale only (TRL 5-7). The overall TRL of the system results therefore in the range 5-7, with main technological issues related to materials suitable for high-temperature, durability and hydrogen yield, and to reduction of temperatures and production costs. The developed technological roadmap foresees by 2025 the identification of suitable materials, achieving demonstration at TRL 6, improvement of competitiveness and demonstration at TRL 7 by 2030 and full-scale demonstration around 2035, with commercial deployment in years up to 2050.

- *Biochemical pathway*

In the biohybrid systems a photoelectrochemical cell provides reducing equivalents in the form of e.g. hydrogen molecules or electrons to engineered bacteria, which are able to use them to produce targeted chemicals through metabolic pathways. Although similar devices aiming to produce e.g. fine chemicals have been developed, this technology for solar fuels production is currently deployed at very low TRL (TRL 2-3): several improvements are thus needed, especially concerning reactor design and configuration, durability of materials employed in the photoelectrochemical section, metabolic efficiencies and integration of the different components within the overall system.

Although microalgae-based systems have already reached a commercial-scale production of added-value compounds such as nutraceuticals, cosmetics, pigments, food ingredients, an effective market deployment of microalgae-based solar fuels still entails several challenges, especially from an economic perspective due the high production costs. In this context, further technical improvements are needed (e.g. in the cultivation systems, in the harvesting processes, in the biofuels production), with the specific target to investigate system's configurations enabling to valorise side-streams in a circular economy approach as well as to co-produce high-value compounds along with biofuels (e.g. bioethanol, biodiesel, biogas/biomethane).

Economic Roadmap

An economic roadmap for solar fuels was developed, as a continuation to the technology roadmap which analysed the key challenges, bottlenecks and opportunities that could pace solar fuel technologies' development over time.

In this context, the economic roadmap aimed at analysing the economic and cost-competitiveness of the different pathways for solar fuel production. The objective was to study the cost performance of the technologies over time, and to assess at which point in time they could become cost competitive with their fossil counterparts. The economic roadmap analysis was carried out through a time series LCOE analysis through 2100, looking at the competitiveness of the different technologies in producing different fuels, namely hydrogen, methanol, ethanol and methane. The analysis looked at the technologies' developments under two investment scenarios: a stable scenario characterised by normal investment levels, and a scale scenario foreseeing an investment push in the studied technologies.

Looking at the hydrogen technologies, the analysis demonstrated that while AEC currently benefits from a cost-advantage amongst the green hydrogen technologies, PEMEC stands out as the most promising technology due to its cost competitiveness over time, under the two scenarios. PEMEC is expected to surpass its fossil benchmark, SMR, as early as 2039 under a scale scenario. Regarding methanol production, CO₂ hydrogenation could reach cost parity with its fossil benchmark, motor gasoline, in 2053 under a stable scenario. With rapidly rising gasoline prices, CO₂ hydrogenation could become market competitive as of 2042 with an investment push. Against this, microalgae for ethanol production remains less affordable than motor gasoline through 2100, reflecting the low maturity and relative inefficiency of the technology. Power-to-methane also comes out as a promising technology expected to reach cost parity with natural gas in 2060 under a scale scenario.

Our analysis therefore identified PEMEC, CO₂ hydrogenation and power-to-methane as key solar fuel technologies which are expected to reach market competitiveness with their fossil benchmarks to 2060. This analysis is complemented by our market outlook for solar fuels and solar fuel technologies through 2100. The analysis foresees the future potential demand for solar fuels and required investments in the PEMEC, CO₂ hydrogenation and power-to-methane technologies necessary to meet this forecasted demand.

1.2.1. Market outlook for solar fuels for 2050 and 2100

A market outlook for solar fuels was developed to assess the potential contribution of solar fuels to worldwide decarbonised energy systems in 2050 and 2100. The analysis comprised a forecast of final energy consumption, broken down by region (Africa, Asia, Australia and New Zealand, Europe, North America, and South America), by sector (industry, transport, buildings, and other) and by fuel type (biomass, coal, e-fuels, electricity, gas, heat, hydrogen, and oil). Both hydrogen and E-fuels, i.e. synthetic fuels manufactured from green hydrogen and CO₂, were considered to be solar fuels for the purpose of the analysis.

The analysis considered three scenarios for the development of worldwide energy systems: a Reference scenario, assuming a baseline level of effort toward decarbonisation corresponding to current efforts; a 2°C scenario, where efforts are made to limit global temperature rises to 2100, relative to pre-industrial levels, by no more than 2°C, and a 1.5°C scenario.

In the 2°C scenario, solar fuels would be expected to contribute to 3.8 percent of our energy needs worldwide in 2050, and 5.8 percent in 2100. Looking at individual sectors, for the 2°C scenario, we foresee solar fuels contributing to just 0.8 percent of energy needs in industry in 2050, and 1.5 percent in 2100. In transport, our analysis expects solar fuels to contribute to 11 percent of energy demand in 2050, rising to 15.2 percent in 2100. Finally, in buildings, solar fuels can be expected to contribute to 3.1 percent of final consumption in 2050, and 4.7 percent in 2100.

Evidence gathered through stakeholder workshops held as part of this study, and through literature review, reveals a number of factors that could impact the uptake of solar fuels worldwide, including:

- Costs of solar fuels, which are primarily driven by the price of solar electricity at first vs. costs of comparable fossil fuels,
- Costs of adapting end-use systems to solar fuels, such as changing from coal to hydrogen in steel manufacturing,
- Infrastructure costs,
- Demand for carbon-neutral industrial products, vehicles and transportation services, and heating and cooling technologies in buildings, and
- Supportive regulations and policies such as those implementing carbon pricing mechanisms.

Industry, in particular, could potentially become early adopters of solar fuel technologies in certain applications. As industries are increasingly considering carbon capture and storage schemes, CO₂ may become more readily available, and could serve as an input to solar fuel production. These solar fuels could be produced and used on-site to power the same CO₂-emitting industrial processes, thereby closing the carbon loop. Such schemes, with the right incentives, could prove attractive to industries, driving them to invest in early-stage technologies.

The analysis provides a detailed outlook for Africa in particular, for which a slightly lower contribution from solar fuels is expected. Some of the reasons for this include a high cost of capital in Africa as well as high costs for utilizing solar fuels in end-use applications. This is especially true for hydrogen—even though it is expected to reach market maturity sooner than other solar fuels, the cost to businesses, developers, and vehicle owners and operators to adapt their industrial processes, buildings and vehicles to run on hydrogen remain very high. Nevertheless, the lack of legacy infrastructure in many parts of Africa, coupled with its high solar irradiance factor, make it an ideal target for investment in solar fuels. The development of local solar fuel supply chains could spark greater local demand, and contribute to increasing the contribution of solar fuels to Africa's energy needs at a greater pace than originally expected.

1.3. *Creation of an International Solar Fuel Forum*

The International Solar Fuel Forum is focused on developing a strong worldwide communication network to stimulate expert awareness and information exchange on solar fuels, in support to the research and findings of the study. The International Solar Fuel Forum created for this purpose brought together international stakeholders of scientific experts, authorities, industry stakeholders and civil society actors to discuss research and investment in solar fuels.

The Solar Fuel engagement and communication strategy created is composed of many different elements which reflect the project scope and specifications. It details the various tools, methods and actions taken to successfully build and engage with a solar fuel communication network, while accounting for contextual factors during the implementation.

Building the Solar Fuel Communication Network required three main foundational elements. Attention to privacy and data protection was vital, to ensure that the network had the appropriate data protection measures in place. The privacy policy created for the project and the way of contacting stakeholders guaranteed the privacy and confidentiality of the data collected from stakeholders. A detailed communication action plan was developed to map relevant stakeholders and contact them about the project. This facilitated the creation of the network and encouraged multipliers to share the information about the project with their own networks. Lastly having a central visual identity was crucial for project visibility and recognition among stakeholders.

To these three elements were added the key tools to build the network: the Webex technical solution to host the activities of the network, and the project landing page. The EY project landing page was the central point for registration to the project, with information on the study and the privacy policy considerations to collect the details of those interested. Furthermore, the technical platform of Webex Meetings and Webex Teams hosted the International Solar Fuel Forum and the virtual workshops. With multiple useful features for hosting international videoconferences and virtual chat spaces, Webex provided the user-friendly accessible environment needed to start discussions.

Contextual factors played a role in further shaping the communication network. The global outbreak of the COVID-19 virus and the national confinement measures taken to curb the spread of the virus changed the communication environment. To respect physical distancing, more communication moved to the digital realm, resulting in a busier and more crowded environment. In addition, the participants who joined the project were from international locations around the world, which was factored into the scheduling of the workshops by varying the start times for the different time-zones.

Engaging with the Solar Fuel Communication Network was done through four main activities. The email network was the main point of contact with the stakeholders to disseminate updates about the project and invitations for the activities. The Forum on Webex Teams was the central discussion area available for stakeholders and served as a source of information on the project activities. The Solar Fuel Survey created direct stakeholder participation in the study methodology, input data and pathways, which also fed into the discussions at the workshops. Lastly, the virtual workshops were the main stakeholder engagement point, consisting of presentations and discussions via virtual videoconferencing.

The Solar Fuel Communication Network created exists on Webex Teams as the International Solar Fuel Forum, and as a database of 70 registered stakeholders. These stakeholders could still be contacted in the context of the project by the European Commission, if there is a desire to continue with the Network.

Introduction to the project

Background

The main share of worldwide energy demand is currently met by utilizing fossil fuels, a situation which has largely led and is leading to climate change. With rising population and energy demands, increased importance and investments are directed towards renewable energy sources to guarantee our future energy supply. Amongst them, solar energy is our most important renewable energy source. Yet, given land constraints and restricted usability of electricity to meet energy needs with existing technologies, we are not able to exploit solar energy to its full potential. Using sunlight as energy source, solar fuels offer great potential to meet worldwide future energy demands. They result from the conversion of sunlight into synthetic fuels such as hydrogen or methanol amongst other and can be easily stored to respond to fluctuating energy needs. Solar fuels can be produced through different technological pathways, namely Electrochemical, Chemical, Thermochemical and Biochemical processes. The market for solar fuels is nevertheless still at an early development stage. Reaching large-scale production of solar fuels will necessitate a coordinated approach relying on experts from diverse fields and integrating knowledge regarding technological developments, industrial scale-up and market acceptance.

In this perspective, the European Union has at COP21 joined Mission Innovation with the aim of reinvigorating and accelerating global clean energy innovation, notably looking at the potential of solar fuels produced through different technological approaches and pathways. This was part of the European Union's overarching pledge to decarbonise its society and economy and commitment to the role of worldwide champion in renewable technologies. Considering solar fuels as a potential "game changer", the European Commission co-chairing the Converting Sunlight Innovation Challenge, launched a qualitative and quantitative assessment of solar fuels' value chains and the development of a forward-looking techno-economic international roadmap.

This sets the context of this European Commission funded study on 'Solar Fuels Research & Invest: Defining and developing the global solar fuel value chain: techno-economic analysis and pathways for sustainable implementation', conducted by a Consortium composed of EY, IMEC, RINA and CEPS.

This study builds on the latest technology results in the field of solar fuels and provides a complementary analysis to those produced by the SUNRISE and Energy X consortia (merged to SUNergy in 2019), the 2020 roadmaps published by the Hydrogen Europe consortium and, finally, the 2017 DG RTD study on Artificial Photosynthesis. It is worth mentioning in this context the EIC Horizon prize: "Fuel from the Sun: Artificial Photosynthesis" which will reward the best technology that produces sustainable fuel by combining sunlight, water and carbon via artificial photosynthesis.

Objectives and scope

The scope of this project is to perform a techno-economic analysis and sustainability forecast of solar fuels, with the direct analysis of primary data, and to assess the potential contribution of solar fuel to worldwide energy demands. The specific objectives of this study are to analyse the value chains of the identified solar fuels, as well as their market potential and to inform long-term policy supporting the development of solar fuel technology and to engage with global experts on the topic of solar fuels technology.

The project was articulated around the following four main Tasks:

- Task 1: Definition of Solar Fuel Value Chains**
- Task 2: Roadmap for Solar Fuels and Market Outlook**
- Task 3: Creation of an International Solar Fuel Forum**
- Task 4: Outreach and Dissemination**

The output resulting from these Tasks are presented in this report as follows:

Section 0: Methodology used to conduct the study

Section 1: A techno-economic analysis of worldwide solar fuel value chains;

Section 2: A technology development roadmap for 2030 and 2050 and economic roadmap to 2100; a Market Outlook mapping the full potential of solar fuels for 2050 and 2100;

Section 3: A presentation of the activities undertaken for the creation of the International Solar Fuels Forum;

Section 4: An outline of the activities undertaken to disseminate the study results.

0. Methodology

This chapter will present the methodologies that were used to conduct the analysis of solar fuel value chains, the technology and economic roadmaps as well as the market outlook for solar fuels.

0.1. Solar Fuel Value Chain Analysis and Economic roadmap

0.1.1. LCOE model

The value chain analysis and economic roadmaps aim at analysing each technological pathway covered in the study from an economic perspective, looking at the different cost components of the technologies and their competitiveness over time. This analysis was achieved through the development of a Levelized Cost of Energy ("LCOE") economic model, specifically designed for the purpose of this study. The LCOE model was used as basis for the solar fuel value chain analysis as well as for the development of the solar fuel economic roadmap.

Modelling the LCOE of energy technologies is a widely applied way of benchmarking their production costs against one another on a comparable basis per unit of energy produced. The cost categories typically included in LCOE modelling include capital costs, overhead and maintenance costs, and operating costs such as labour and energy input costs. The costs included in our LCOE model, and additional details regarding how they were derived, will be summarily discussed below as well as in Annex I: LCOE model methodology.

Our methodology (Annex I: LCOE model methodology), regional assumptions (Annex II: Regional assumptions) and time-based assumptions (Annex III: Time-based assumptions) were presented to relevant stakeholders and experts in the field of solar fuels through a survey and three consultation workshops (one general and two pathway specific) for input and validation. Additional inputs and feedback from stakeholders, received through correspondence as follow up to the stakeholder consultation workshops, were considered as well. All our data was refined and validated taking into consideration the comments and feedback received through our stakeholder consultation process.

0.1.1.1. Model structure and pathways modelled

The LCOE model we developed considers solar fuel and comparable fossil fuel technologies in three different process nodes, ranging from electricity generation or fossil fuel extraction at the base, through hydrogen production, to the production of synthetic hydrocarbon fuels. Two of the later-stage pathways included—i.e. CO₂ hydrogenation and power-to-methane rely on hydrogen produced through electrolysis or through PEC.

Figure 1 below shows an overview of this structure, showing primary energy technologies at the left, followed by electrolysis technologies as well as the photoelectrochemical cell producing hydrogen, and three different pathways—i.e. CO₂ hydrogenation, microalgal ethanol, and power-to-methane—for synthetic hydrocarbon production. At the bottom of the figure, we see fossil fuel-based technologies included in the LCOE model as a benchmark.

Energy input costs to the electrolysis technologies included—i.e. AEC, PEMEC and SOEC—are a significant cost driver for these technologies, and the cost of the hydrogen that they produce is in turn a significant driver of the costs for CO₂ hydrogenation and power-to-methane. We have therefore paid significant attention to modelling costs for solar PV by examining benchmarks in the literature, and validating our inputs with stakeholders, including through the stakeholder workshops held for the purpose of this study.

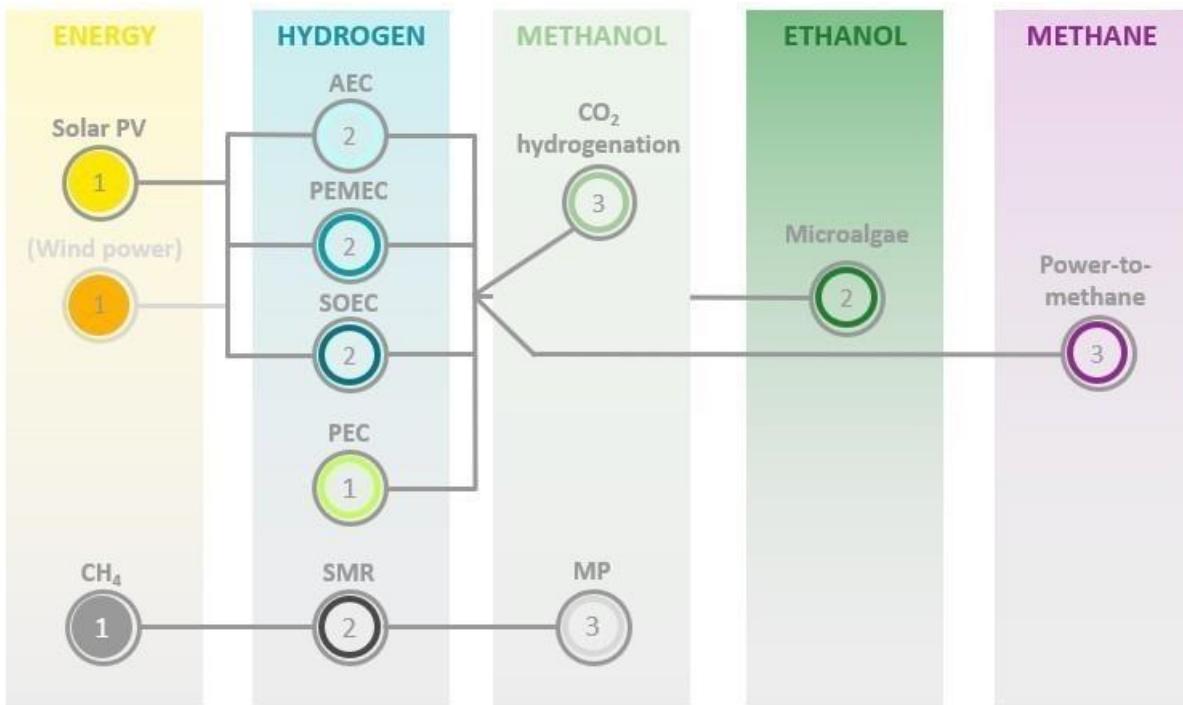


Figure 1 – Model structure

The energy technologies and solar fuel pathways modelled include:

- Solar PV,
- Wind power,
- Alkaline Electrolyser Cell (AEC),
- Proton Exchange Membrane Electrolyser (PEMEC),
- Solid-Oxide Electrolyser Cell (SOEC),
- Photo-Electrochemical Cell (PEC),
- Steam methane reforming ("SMR"),
- CO₂ hydrogenation,
- Methanol process,
- Microalgae, and
- Power-to-methane.

A number of very low-TRL technologies, including the bionic leaf and thermochemical pathway for solar fuels, have not been included in the LCOE model due to a lack of data. The PEC technology, while being in the early stages of development as well, has however been the subject of a number of techno-economic analyses. Because of this, were able to include it in the model although with a delayed start in 2050, based on conversations with experts, including those held during the project's dedicated stakeholder workshops.

Technical information regarding the process and components involved in each pathway are discussed in section 0, on the identification of solar fuel pathways. Nevertheless, this section does not include solar PV, wind power, SMR, CO₂ hydrogenation, the methanol process, and power-to-methane. These pathways have been included in the LCOE model for a number of reasons. Solar PV and wind power provide the primary energy required for the electrolysis and microalgae pathways. CO₂ hydrogenation and power-to-methane are

promising technologies for the production of synthetic hydrocarbons required to fulfil a number of energy uses for which hydrogen is not suitable. Finally, SMR and the methanol process provide fossil fuel-based benchmarks to assess the competitiveness of solar fuels in the market. An overview of each of these technologies is provided below.

Solar PV

Solar PV is, among mainstream energy technologies, the one which has seen the greatest cost reductions in the past decade—the cost of solar PV modules has declined by a factor of 10, in as many years, according to some sources¹. Solar PV is competitive with fossil fuels for electricity generation and is currently the most affordable technology for new power plants in many jurisdictions. It is expected to become the most affordable technology overall within ten years. As discussed above, solar PV is a key input to many solar fuel technologies, and an accurate forecast of its costs is therefore crucial to predicting the future costs of solar fuels.

Wind power

Wind power remains, in many jurisdictions with low solar irradiance, more affordable than solar PV. We modelled the costs of wind power, as an alternative scenario option other than solar PV, in order to examine the future potential of fuels derived from renewable energy in general.

Power-to-methane

Power-to-methane is an attractive energy technology, in that it allows for the production of fully carbon-neutral hydrocarbon fuels. The entire value chain comprises hydrogen production from renewable energy through water electrolysis, coupled with a reaction, in a second step, of the hydrogen produced earlier with CO₂, forming methane and water. In order for the resulting fuel to be fully carbon neutral, the CO₂ used in the process must be obtained through direct air capture, as it will later be released in the atmosphere with fuel combustion.

Its main advantages are that the methane produced is compatible with existing natural gas infrastructure and with a wide range of energy end-use cases, and that natural gas is easier to store than hydrogen. Its disadvantages are that it adds a layer of costs to the solar fuel value chain, relative to using just hydrogen, and that methane is an aggressive greenhouse gas. Although it is unclear what level of leakages could come from power-to-methane relative to natural gas extraction, they are expected to be approximately similar², therefore requiring caution with regards to the technology.

CO₂ hydrogenation

CO₂ hydrogenation, similarly to power-to-methane, involves using captured CO₂ and hydrogen to produce methanol. Methanol is nearly a drop-in replacement for motor gasoline and is therefore expected to contribute substantially to phasing out fossil fuels in road transport for the share of remaining internal combustion engine ("ICE") vehicles.

¹ International Renewable Energy Agency, 2019, Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects, Available at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf

² The International Council on Clean Transportation, 2018, What is the role for methane in European decarbonization?, Available at https://theicct.org/sites/default/files/publications/Role_Renewable_Methane_EU_20181016.pdf

Steam Methane Reforming (SMR)

SMR is a technology for the production of syngas, which comprises hydrogen and carbon monoxide, using natural gas as a feedstock and steam. Over 95 percent of hydrogen produced worldwide comes from fossil fuels, chief among which is SMR³. We have modelled the cost of SMR, based on assumptions on the rising cost of natural gas, coupled with a carbon price, as well as the cost of SMR technology, to provide a benchmark against which to assess the competitiveness of the hydrogen-producing solar fuel pathways, i.e. AEC, PEMEC, SOEC and PEC. The hydrogen produced through SMR is often called “grey” hydrogen, to be contrasted with “green” hydrogen produced through the solar fuel pathways.

Methanol process

The methanol process is equivalent to CO₂ hydrogenation, albeit with the use of grey hydrogen, instead of green hydrogen. It has been included in the model to provide a benchmark against which to assess the competitiveness of CO₂ hydrogenation.

Figure 2 below presents an overview of the types of costs included in the model, including how they are derived. Each of these will be discussed individually in the sections below.

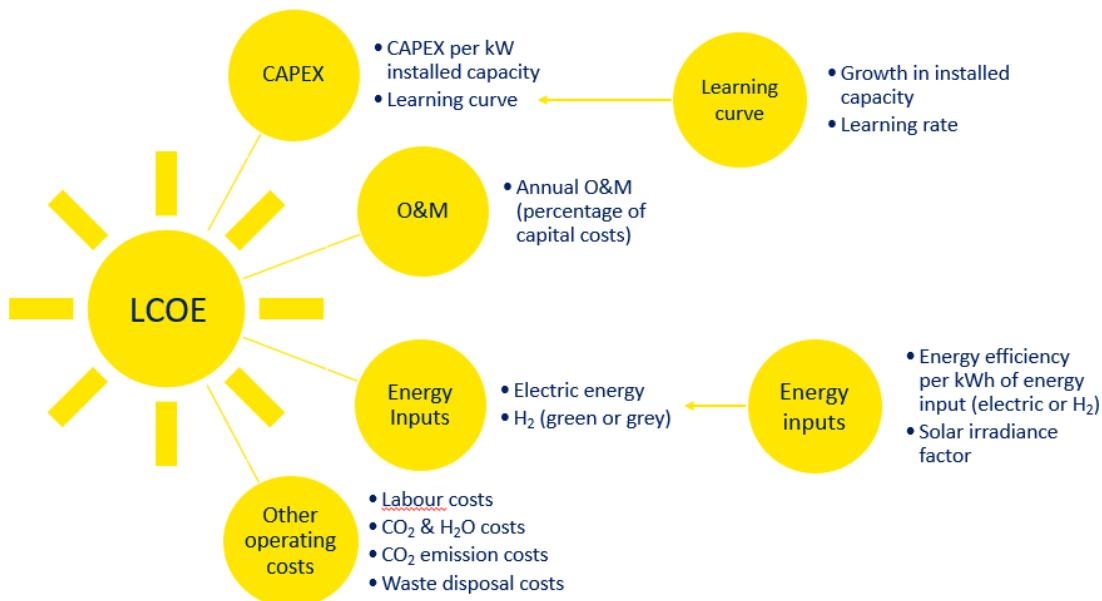


Figure 2 – Model mechanics

0.1.1.2. Capital expenditure costs

Capital expenditures (CAPEX): CAPEX or capital costs are the costs incurred in the value chain of building the manufacturing plant together with all the required equipment to produce the solar fuel. They are modelled for each technology, expressed per kW of installed capacity. In order to derive estimates of the CAPEX required per kWh of fuel produced, we apply a capital recovery factor, based on a number of factors including the discount rate, the estimated lifetime of a typical plant, and the capacity factor for the production process—see Annex I: LCOE model methodology for additional details on how the capital recovery factor is derived.

³ The other main fossil fuel-based hydrogen production technology is coal gasification.

The LCOE model begins with estimates of capital expenditures, in 2020, for each technology. These initial estimates are provided in Annex III: Time-based assumptions. The CAPEX estimates are then modelled through 2100, based on the learning curve concept.

Learning curve: The learning curve is a concept relating the decrease in the cost of a given technology to the growth in cumulative installed capacity of that technology, where the cumulative installed capacity is defined as the sum of the nameplate output capacity of all plants that have been installed since the inception of the technology. Conceptually, the learning curve posits that the more a technology is deployed, the more opportunities for cost reductions are found throughout the entire technology value chain.

A key variable in the learning curve is the learning rate, which determines the level of cost reductions achieved with each doubling of installed capacity. The learning rates applied for each technology were derived from estimates in the literature, and validated through discussions with experts, including as a part of the stakeholder workshops held for the purpose of this study. Our assumptions regarding the learning rates for each technology are presented in Annex III: Time-based assumptions.

0.1.1.3. Overhead & maintenance costs

Overhead and maintenance ("O&M") costs are included in the model to account for a number of expenditures. Overhead expenditures include legal and administrative costs, insurance expenditures, and rent or mortgage payments. Maintenance costs are also included in our LCOE model to account for the regularly scheduled replacement of plant equipment. O&M costs scale up according to plant size, and can therefore be estimated as a percentage of capital costs. Our assumptions regarding the O&M costs for each technology modelled are presented in Annex III: Time-based assumptions.

0.1.1.4. Operating costs

The third category of costs accounts for a number of operating costs, including labour costs, resource input costs, and, in particular, energy and hydrogen input costs. The LCOE model also accounts for operating revenues from the sale of oxygen, a by-product of electrolysis, for the PEMEC, AEC and SOEC technologies. Labour costs are assumed to be proportional to plant size, and are therefore included as a ratio of installed capacity. The resource inputs to the model and associated components include:

- Water—water is a key input to electrolysis, and its costs are estimated with different assumptions per region,
- CO₂ as a resource—the synthetic hydrocarbon solar fuels modelled in the LCOE analysis require a source of CO₂, on top of hydrogen, and the cost of carbon capture and utilisation ("CCU") is included, with a forecast to 2100, to account for these costs,
- CO₂ emission costs—hydrogen production through SMR emits CO₂, and the costs associated with these carbon emissions are modelled through a direct carbon price presented in Annex II: , and
- Waste disposal costs.

Energy input costs can represent a significant share of the LCOE for some solar fuel technologies, as will be presented in section 1.2 below. Energy input costs are included for electrolysis technologies, i.e. AEC, PEMEC, and SOEC, as well as for microalgal ethanol production, where electricity is needed for pumps, motors, driers and other equipment. The LCOE model accounts for the energy consumption of solar fuel technologies by including a variable for their energy efficiency. Energy input costs are endogenously modelled, consisting of the modelled LCOE of solar PV. While some mature technologies are assumed to have reached near maximum theoretical energy efficiency, we have included expectations with regards to future expected energy efficiencies for some technologies. These assumptions are presented in Annex III: Time-based assumptions.

Similarly to energy input costs, the costs of hydrogen inputs represent a significant share of the LCOE for CO₂ hydrogenation and power-to-methane. These costs are accounted for through a variable for the efficiency of production of fuel outputs, per unit of hydrogen inputs.

0.1.2. Identification of Value Chain technology and economic components

0.1.2.1. Identification of data sources and data collection with regards to CAPEX and OPEX

The data collection for the model development was based on relevant academic research papers. However, to face the issue of data scarcity for low TRL emerging technologies, in addition to academic research, external databases were also consulted in order to retrieve the necessary variables and assumptions. The data is drawn from databases such as Oxford Economics, Eurostat, the European Commission, the World Bank, our proprietary EY Countdown Clock model, BP outlook reports, BMI research and the International Monetary Fund (IMF). A list of references is provided in the respective section at the end of the document.

Most of the literature on solar fuels is covered in this study. Nonetheless, a complete and individual analysis of all existing literature exceeds the defined scope of the project. We list these hereinafter.

- SOEC: (EGUCHI, 1996; Hauch et al., 2008; Kim-Lohsoontorn & Bae, 2011; KUSUNOKI, 1995)
- PEMEC: (Khatib et al., 2019; Chang Liu et al., 2018)
- PEC: (U.S. Department of Energy, 2009)
- Bionic Leaf: (Khajuria & Kotwal, 2018; Chong Liu et al., 2017)
- Microalgae: (A.K. Mishra, 2019; Fasaei et al., 2018; Meena & Naik, 2019; Scarlat et al., 2018)

0.1.2.2. Main assumptions included in the model

Regional assumptions

For most cases, the non-time-based assumptions are regional assumptions, varying across the following regions: Europe, Asia, North-America, South-America, Africa and Australia. To analyse the competitiveness of solar fuel value chains thoroughly, we consider their performance across these different regions. These non-time-based assumptions apply regardless of the different pathways and technologies.

The data that is being used here is drawn from the databases presented in chapter 0.1.2.1. A number of additional variables, including the annual rate of change in the price of resources included in the model, have not been taken from these database, but have been determined through stakeholder consultation, including in the form of a stakeholder survey, and conversations held with experts through stakeholder workshops. They are more subjective and susceptible to changes in the economic environment. Therefore, ranges are being used to take the volatility of these figure into account. An overview of the regional assumptions (technology agnostic) can be found in Annex II: Regional assumptions.

Time based assumptions

Time-based assumptions are the input parameters that vary over time and across technologies. While the value chain analysis consists in looking at the current status of the studied technologies, the model allows for forecasted analysis over 3 focus periods and 1 terminal period. The periods in question are 2020-2029, 2030-2039, 2040-2049 and 2050-2100, respectively. All variables required for calculating the LCOE originate from these assumptions. Some variables do not require an assumption past the 2020 focus periods

because they are endogenously modelled. An overview of the time based assumptions (technology specific) can be found in the Annex III: Time-based assumptions.

After having extracted all the useful data from research papers and databases, the analysis can be performed based on a specific set of scenarios. Below, an overview can be found of which scenarios were taken into consideration.

Table 1 - Model scenarios

	Scenario	Notes/ Assumptions
Range	Normal High Low	The ranges set three levels of optimism: low, average, and high; providing lower and upper bounds for LCOE values
Growth	Scale Stable	The cost improvements can occur if supported by adequate research and development, i.e. funding. The model takes these funding ratios into account by imposing a 2-sided wig in the growth rate of installed capacity of the relevant technology: Scale and non-scale growth (referred to as stable). Whether we assume the total installed capacity of the technology to grow more quickly.
Energy Source	Solar PV Wind power	Solar will be used as the main energy source to produce solar fuels. Nevertheless, given the differing levels of solar irradiance per region, wind energy will also be included within the analysis of the European region which experiences lower levels of solar irradiance.
Year	2020-2100	
Region	Africa Asia Australia Europe North America South America	

The LCOE for each of the technologies included was calculated for each combination of scenarios above, for every year in scope, and for each of the six regions. The resulting dataset was then loaded into an interactive visualization software program called Power BI, allowing for an interactive visualisation and analysis of results at global or regional level, throughout the entire forecasting period, and according to specific scenario combinations⁴.

⁴ The Power BI file was made available as an appendix to the submission of this report.

0.1.2.3. Time series model development up to 2100

The model allows to conduct a time-series analysis to assess the performance of the solar fuel value chains over time through 2100. The comparison between the grey and solar technologies is the major point of attention, as it defines the key fuel tipping point: the moment when solar fuels have a cost advantage over their fossil counterparts.

0.2. Technology roadmap for solar fuels

The technological roadmap for 2030 and 2050 aims at assessing the main technological challenges and bottlenecks that must be overcome to reach the production of solar fuels at commercial scale.

Starting with identification of key technologies determined under the chemical, electrochemical, thermochemical and biochemical pathways, the analysis determines the current TRL of the components of each technology. The study then focuses on identifying the main challenges linked to each component and to the system as a whole: this phase entails a SWOT analysis and a patent analysis, where possible.

After presenting the methodology used for the technological roadmap, each technology will be assessed in detail. The technologies and pathways covered in the analysis are as follows:

- Electrochemical pathway: Proton Exchange Membrane electrolyser ("PEMEC"), Photo-electrochemical electrolyser cell ("PEC"), Solid Oxide Electrolyser Cell ("SOEC")
- Chemical pathway: Photocatalytic particulate or colloidal systems
- Thermochemical pathway: Solar thermochemical hydrogen production systems
- Biochemical pathway: Biohybrid system ("Bionic Leaf"), Microalgae

Starting from the information retrieved in the identification of solar fuel value chains, the four technological pathways (chemical, electrochemical, thermochemical and biochemical) with the related value chains previously defined are studied to identify and understand the main bottlenecks and technical barriers to be overcome, as well as to set the objectives to be met, towards a full-scale implementation of the targeted value chains. The following Figure 3 roughly summarizes the methodological approach followed within the present technology roadmap.

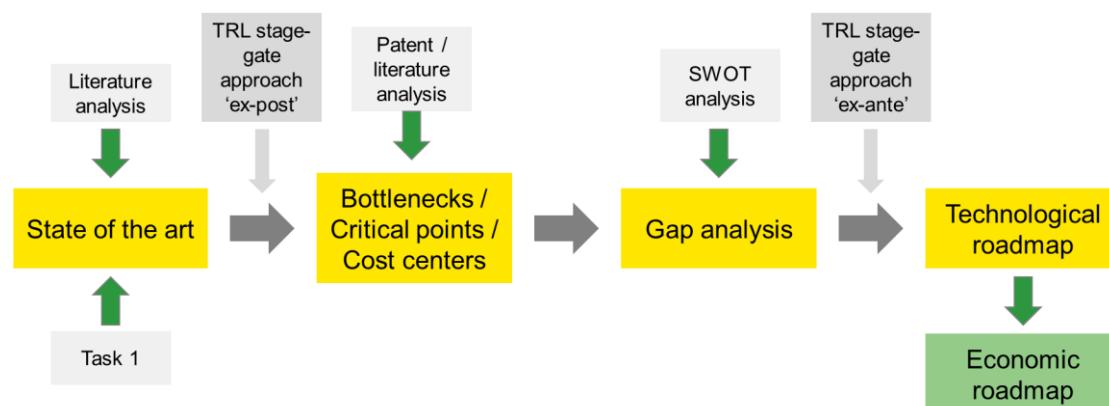


Figure 3 - Summary of the methodological approach followed towards the Technological Roadmap

Firstly, the state of the art of each technology and related components (identified within the value chain analysis in Section 1) is assessed. This phase is mainly based on a literature analysis, partly already conducted in the value chain analysis, and on the consultation of

stakeholders carried out through a specific survey and dedicated workshops: this approach allows identifying the current TRL of each component of the value chains.

To do this and to verify 'the actual TRL', a specific approach ('stage-gate approach') has been developed in the framework of the technical support provided to the European Commission – DG Research and Innovation on the topic of "Technology Readiness Level: Guidance Principles for Renewable Energy technologies" (hereinafter referred to as 'TRL Tender').

In order to efficiently exploit the outcomes of such 'TRL Tender', the stage-gate approach and the related checkpoints to be tackled for each TRL have been partly revised (see the following subchapter 'TRL assessment through the state-gate approach') and adapted to fit the object of the present work, i.e. solar fuels technologies. In this context, the stage-gate approach can be exploited 'ex-post', by applying this innovative approach to the targeted solar fuels pathways.

Starting from the list of checkpoints reported in Table 2, for each TRL identified per each technological component, the 'main checkpoints' are defined and set: these checkpoints are mostly a summary of the ones reported in Table 2 and are intended to be a more straightforward indication of what that specific Technology Readiness Level means.

After this preliminary step, 'the core' of the methodology is deployed. In particular, two main steps can be identified: patent analysis and SWOT analysis.

The purpose of these steps is to identify the main technological challenges and the main research trends dealing with the technologies identified per each pathway.

This approach also allows extending the analysis on TRLs, trying to identify the highest level that each technology can reach in terms of readiness. Indeed, considering the TRL examination as a roadmap backbone, the study intends to estimate the development of the technology finding bottlenecks, critical points, gaps and possible solutions over time. In this sense, a graphical representation showing the evolution of the TRL (y-axes) over time (x-axis) is targeted. This chart describes the events expected to speed up the progress (at the current knowledge stage), where the TRL advancements can be commented with the technology improvements identified in the previous phases of the analysis.

In the following subchapters the main steps of the roadmap are briefly described.

0.2.1. Patent analysis

This step focuses on the research of possible technical solutions and the respective provider, thanks to a **patent analysis**. This phase aims also to identify the major 'research trends' related to a technological pathway, i.e. the technological hotspots that still prevent a full-scale deployment of the targeted solar fuels value chains.

Patent search is performed exploiting the hierarchy classification attached to each patent application by its examiners. More in details, the International Patent Classification (IPC) is a structured, standardized, classification scheme that classifies each patent filed worldwide by a (series of) code(s) related to its technology area(s). The IPC is subdivided into sections, classes, subgroups. It currently divides technology into around 50,000 subareas and is thus a very precise tool allowing identification of technologies satisfying specific needs. From the analysis of IPC, it is possible **to identify involved technology families and relevant technology providers**.

- Patenting trends are useful to understand the dynamics of a sector, in particular:
- the number of patents submitted per year gives an indication of the sector's liveliness;
- the number of applicants gives an indication of the sector's level of crowding;

- the slope of the patenting curve helps identifying the average position of the sector's technology families along the curve of technology evolution.

After the first and second step of the present methodology it is already possible to identify, for each assessed value chain, the most relevant critical points and bottlenecks which represent the main obstacles to the further implementation of the systems at upper scales. Such 'hotspots' in the value chain are often not only associated with technological hurdles, but they represent also 'cost centres', i.e. areas requiring technological improvements with high potential to lead to economic benefits for the whole value chain

In the following subchapters the overall approach on which a typical patent analysis is based is presented.

Scenario Analysis

The Scenario Analysis includes the execution of analysis of world's patent databases, in order to identify major trends in technical developments, main areas of research, maturity of products and technologies, emerging and currently under development solutions, providing innovative means to meet the objective of the project.

A patent is an industrial property right that protects a technical invention for a limited period of time (e.g. 15 years), giving the holder an exclusive right to prevent other from selling, making and using the patented invention. An invention to be patentable must fulfil three criteria: being new, innovative and be susceptible of industrial application.

The analysis has been carried out exploiting Derwent Innovation (website: www.derwentinnovation.com) database. Derwent Innovation is an integrated search service launched by Clarivate Analytics that offers cross-content search across patent data, scientific and technical content, and business information. The patent collections covered by Derwent Innovation include the British, Chinese, European, French, German, Japanese, Korean, PCT and US collections as well as bibliographic data from other collections. The collections are underpinned by global, standardized patent data including bibliographic data, full text documents, drawings, Derwent Word Patent Index (DWPI) and Derwent Patent Citation Index (DPCI).

The Scenario Analysis has been carried out following 3 different "strategies":

- **IPC Codes** based analysis
- **Keywords** based analysis
- **IPC Codes and Keywords** based analysis

Each "strategy" is characterized by sequential steps of analysis with the aim to explore and to achieve more information on each topic.

IPC Code

The investigation is based on the identification and use of specific **IPC Codes** related to the technology of interest.

The International Patent Classification (IPC) provides for a hierarchical system of language independent symbols for the classification of patents and utility models according to the different areas of technology to which they pertain. The IPC Classification, is a means for obtaining an internationally uniform classification of patent documents, and has as its primary purpose the establishment of an effective search tool for the retrieval of patent documents by intellectual property offices and other users, in order to establish the novelty and evaluate the inventive step or non-obviousness (including the assessment of technical advance and useful results or utility) of technical disclosures in patent applications. The **IPC code is an alphanumerical code** (Figure 4), composed by:

Section Symbol – Each section is designated by one of the capital letters A through H;

Class Symbol – Each class symbol consists of the section symbol followed by a two-digit number;

Subclass Symbol – Each subclass symbol consists of the class symbol followed by a capital letter;

Group Symbol – Each group symbol consists of the subclass symbol followed by two numbers separated by an oblique stroke.

F	MECHANICAL ENGINEERING; LIGHTING; HEATING; WEAPONS; BLASTING
F24	HEATING; RANGES; VENTILATING
F24F	AIR-CONDITIONING; AIR-HUMIDIFICATION; VENTILATION; USE OF AIR CURRENTS FOR SCREENING
F24F 1/00	Room units for air-conditioning, e.g. separate or self-contained units or units receiving primary air from a central station
F24F 1/02	•Self-contained room units for air-conditioning, i.e. with all apparatus for treatment installed in a common casing

Figure 4 - Example of IPC codes

The patent analysis has been developed according to an increasing level of detail. In particular, successive searches have been performed in order to select solutions specifically addressing the application of interest and, at the same time, exploring research topics and technological development in the target sector, in a comprehensive way.

Keywords

The analysis is based on the use of a series of **Specific Keywords**, defined starting from the key technological factors and from the target functionalities. Keywords allow extracting patents dataset independently from the exact definition of the technological area of interest (no IPC code filters applied).

This approach can help identifying relevant patents that for some reason have not been classified in one of the identified IPC codes, moreover, this analysis can be useful to foster the technology transfer activity.

IPC Codes and Keywords

The investigation is based on the combined use of **IPC Codes and Specific Keywords**.

The use of IPC code allows searching a large number of patents relating to specific categories, such as those identified by every section, class, subclass and group. The additional use of specific keywords helps to further narrow the search by framing more closely specific technologies within a particular framework set by the IPC filter.

0.2.2. SWOT analysis

In this step, the value chains are further studied through a SWOT analysis to identify issues and propose possible directions for solutions. This analysis is mainly the results of literature analysis, patent analysis and stakeholders consultation through surveys and dedicated workshops carried out during the project.

The SWOT analysis is a common tool in decision making, used to provide a qualitative “at a glance” view on Strengths, Weaknesses, Opportunities and Threats of a system, process, solution or strategy. In particular, while Strengths and Weaknesses are inherent properties of the system that can be modified or controlled by the system owner, Opportunities and Threats are external factors that system owner can adapt to, but not control directly.

	Positive	Negative
Internal	Strengths	Weaknesses
External	Opportunities	Threats

Figure 5 - General scheme of the SWOT analysis

A SWOT analysis is useful to:

- highlight the main factors (internal and external) that can affect the success of a strategy;
- analyse critical points and propose alternative solutions;
- make sure that the strategy considers the overall context.

SWOT is typically compiled in brainstorming sessions among technology and market experts: in the framework of this project, workshops with stakeholders can be exploited to efficiently carry out the SWOT analysis.

The main outcomes coming from these three steps will allow depicting an overall scenario of the current situation associated to each technological pathway and the related assessed value chains, along with the future trends and improvements that can most significantly benefit the market deployment of the targeted solar fuels.

By comparing these results with the requirements developed per each technological pathway in the framework of the 'TRL Tender' (thus by applying the stage-gate approach 'ex-ante'), it will be possible to carry out a gap analysis: this will consist in identifying the main critical points (or 'cost centres') still hindering a TRL advancement towards full scale implementation.

Such gap analysis will set the basis for the technological roadmap: the latter will suggest scenarios and milestones to be reached and possible resources to be committed. For this reason, the technological roadmap will run in parallel with the economic one.

0.2.3. TRL assessment through the state-gate approach

The TRL scale is one of the main tools for the assessment of the maturity of a given technology and allows also comparisons between maturities of different types of technologies.

As concerns renewable energy technologies, in 2017 a consortium led by EY and including RINA Consulting and Technofi provided the European Commission – DG Research and Innovation with a technical assistance on the topic of "Technology Readiness Level: Guidance Principles for Renewable Energy technologies".

In this context, guidelines were developed to assign a TRL to renewable energy technologies belonging to ten different categories. The adopted methodology was based on a stage-gate approach: this means that the conditions that need to be met to assign a specific TRL level to a technology are clearly outlined.

For each of the nine TRL levels, the following items are defined:

- **the level of readiness** (ranging from 1 to 9);
- **the statement of the readiness** (i.e. title) covering technology, manufacturing, market and system integration aspects in a short but comprehensive sentence;
- **the detailed description of the readiness** in terms of technology, manufacturing and integration maturity (i.e. integration of the technology within the system environment, which deals with system readiness level);
- **the checkpoints** describing the milestone of the level n, completed with the corresponding achievements, that allows to move to the next readiness level n+1.

The set of checkpoints is to be seen as an ensemble of driving examples allowing the verification of the achievement of the related readiness level.

The following Table 2 provides a TRL guidance document potentially applicable to Solar Fuels, prepared following the principles of the "Guide of Guides" developed in the above-mentioned project.

Table 2 - TRL guidance

RE TECHNOLOGY: SOLAR FUELS	
TRL #1	<p><i>Basic research. Principles postulated and observed but no experimental proof available</i></p> <p>Description</p> <p>A new concept related to solar fuels is proposed. It could consist of a fuel, different from the existing ones, or of an innovative way to produce or to convert a fuel base on solar energy input. Technical options for the concept are identified and relevant literature data reviewed.</p> <p>Examples of results and knowledge qualifying this TRL:</p> <ul style="list-style-type: none"> • Identification of an innovative fuel, in terms of environmental and performance issues; • Identification of a new production process, to increase and optimize the use of solar energy; • Concept on new materials (e.g. feedstocks, catalysts, intermediates, etc.), processes and their characteristics. <p>Evaluation of the potential benefits of the new concept over the existing ones and indication of safety issues should be reported to support a better understanding of the technology.</p> <p>Checkpoints</p> <p>Once readiness level 1 is achieved, the scientific concept is observed and documented. This means:</p> <ul style="list-style-type: none"> • Identification of possible materials, components and systems and relevant risks and hazards; • Preliminary concept design; • Preliminary evaluation of the potential benefits and technological gaps of the new concept over the existing ones.
TRL #2	<p><i>Technology formulation. Concept and application have been defined</i></p> <p>Description</p>

The technology concept, its application and interfaces to other systems are defined.

Preliminary modelling of the intended concept or system is available.

Identification of preliminary proof of concept approach for the realization of systems or sub-systems is performed.

Identification of preliminary solar fuel production or conversion steps is performed at laboratory scale.

Examples of results and knowledge qualifying this TRL:

- Estimation of innovative way to fuel production or conversion from solar input;
- First indication of fuel composition and properties (e.g. lower and higher heating values...);
- Definition of the proof of concept approach in terms of technologies, materials, etc.

Checkpoints

Once readiness level 2 is achieved, the applied technological concept has been defined. This means:

- Technical analysis of the concept is investigated;
- Interactions between components are qualitatively assessed;
- Qualitative assessment of advantages (e.g. environmental, technological, economical) of the new concept, fuel or system is done;
- Proof of concept approach and preliminary technical specifications (e.g. technologies, compositions, limitations) are defined.

TRL
#3

Applied research. First laboratory tests complete; proof of concept

Description

First model completed and preliminarily tested. Development of experimental application is initiated at component, system or sub-system level.

The first proof of concept prototype is developed by laboratory set-up.

Innovative ways to exploit solar energy for fuel production or conversion and its manufacturing approach are tested through bench-scale experiments. Characterization of fundamental properties is made.

Numerical models and simulations (e.g. structural FEM, CFD, control, detailed thermodynamic cycle simulations, etc.) if available should support laboratory testing.

Examples:

- First proof of concept prototype of the innovative fuel and test in a simplified system;
- First proof of concept prototype of the innovative manufacturing approach, at laboratory scale;
- Preliminary validation of the assumption performed so far, with reference to fuel characteristics and performances;
- Evaluation of solar energy to fuel conversion performances.

Checkpoints

Once readiness level 3 has been achieved, the applied technological concept has been defined. This means:

- The concept is tested at laboratory scale;
- Parameters characterizing the fuel or the technology, including solar energy to fuel conversion, are measured/calculated;
- First proof-of-concept prototype is ready and preliminarily tested;
- Verification of the proof of concept through consolidated simulation tools and cross-validation of the numerical models thanks to literature data (if applicable) is done.

	<ul style="list-style-type: none"> Qualitative assessment of advantages (e.g. environmental, technological, economical) of the new concept, fuel or system is demonstrated.
TRL #4	<p><i>Small scale prototype built in a laboratory environment ("ugly" prototype)</i></p> <p>Description</p> <p>Small-scale prototype of the system or sub-systems is developed in laboratory. The prototype can achieve repeatable/stable performance.</p> <p>Integration between the tested technology and the other sub-systems is proven at laboratory level.</p> <p>When a small-scale prototype is not feasible, a validated simulation model is provided, considering the real operating conditions.</p> <p>Examples of results and knowledge qualifying this TRL:</p> <ul style="list-style-type: none"> Parameters and features of fuel production or conversion process from solar input are established; Validation of the assumption performed so far, with reference to fuel characteristics and performances; The range of admissible impurities is quantified. <p>Checkpoints</p> <p>Once readiness level 4 has been achieved, the applied technological concept is experimented and validated. This means:</p> <ul style="list-style-type: none"> The fuel or the process is tested and validated at laboratory scale; The prototype characteristics are defined; Integration with complementing subsystems is done; Quantitative assessment of advantages (e.g. environmental, technological, economical) of the new concept, fuel or system is demonstrated; The hazards associated to the technology should be identified.
TRL #5	<p><i>Large-scale prototype tested in intended environment</i></p> <p>Description</p> <p>A large-scale laboratory prototype is developed and integrated together with other subsystems in intended working environment, including those for the exploitation of solar energy input, if not subject of the technology. It includes testing in different operating conditions.</p> <p>Examples:</p> <ul style="list-style-type: none"> Realization of a large-scale laboratory prototype; Storage and utility connections are included in the prototype. <p>Checkpoints</p> <p>Once readiness level 5 has been achieved, the technology is ready to move forward to pilot-scale. This means:</p> <ul style="list-style-type: none"> A large-scale laboratory prototype is realized and tested in intended working environment; The large-scale prototype can achieve repeatable/stable solar energy to fuel conversion performance; The manufacturing process parameters are defined; Information to perform environmental and socio-economic sustainability assessment is available; Life-cycle analysis could be done.

TRL #6	<p><i>Prototype system tested in intended environment close to expected performance</i></p> <p>Description</p> <p>A pilot-scale prototype is fine-tuned to a variety of operating conditions together with other subsystems and in compliance with intended working conditions (on field) including the exploitation of actually available solar resource.</p> <p>Reliable performances are provided by the pilot-scale prototype in line with the expectations. Interoperability between the tested technology and the other connected technologies is optimized.</p> <p>Examples:</p> <ul style="list-style-type: none"> • Fuel production process from solar energy input demonstrated in real working conditions; • the pilot-system behaviour is analysed under different natural solar irradiation conditions. <p>Checkpoints</p> <p>Once readiness level 6 is achieved, the technology is enlarged to pilot-scale. This means:</p> <ul style="list-style-type: none"> • The technology is demonstrated in working environment conditions; • Fuel characteristics are stable even under variable solar energy availability conditions; • The process is safe and reliable; • Realization of a pilot-scale prototype that could be integrated with other subsystems and fine-tuned on field; • Measurement of pilot-scale prototype performance in different and relevant extreme conditions; • Performance matches the KPIs, especially in terms of solar energy to fuel conversion; • Social acceptance is evaluated.
TRL #7	<p><i>Demonstration system operating in operational environment at pre-commercial stage</i></p> <p>Description</p> <p>A demonstrator is installed to be tested to its final process purpose.</p> <p>All solar fuel qualification steps are completed.</p> <p>Compliance with relevant environment conditions, authorization issues, local / national standards are analysed and guaranteed, at least for the demonstration site. The demonstrator is able to guarantee its functionalities due to a proper control and management strategy and an adequate maintenance approach.</p> <p>When it comes to the systems level, similar concept layouts and plants can be replicated in different operational conditions.</p> <p>Manufacturing processes requiring investments are identified. The manufacturing risks towards prototyping are identified as well as manufacturing cost drivers and KPIs.</p> <p>Needs for tooling, facilities, material and skills are identified.</p> <p>Example:</p> <ul style="list-style-type: none"> • the full-scale system behaviour is analysed under different natural solar irradiation conditions. <p>Checkpoints</p> <p>Once readiness level 7 is achieved, the technology concept is validated at demonstration scale. This means:</p> <ul style="list-style-type: none"> • System/technology demonstrated in field under different working conditions; • Manufacturing approach is demonstrated; • Life-cycle assessment and life-cycle costing are re-evaluated;

	<ul style="list-style-type: none"> • Regulatory aspects are analysed and followed.
TRL #8	<p><i>First of a kind commercial system. Manufacturing issues solved</i></p> <p>Description</p> <p>The technology is experimented in deployment conditions (i.e. real world) and has proven its functioning in its final purposes in working conditions.</p> <p>Manufacturing chain and installation process are stable enough for entering in a low-rate production and all materials are available.</p> <p>Limiting factors are still present to move to commercial scale production.</p> <p>Examples:</p> <ul style="list-style-type: none"> • The new solar fuel has proven performance under potential market conditions; • The production plant has proven performance under potential market conditions; • The complete system is certified for market application. <p>Checkpoints</p> <p>Readiness level 8 is achieved, once:</p> <ul style="list-style-type: none"> • Technology is proven in its final form and under expected conditions; • Production is potentially commercially viable; • Compliance with legal obligations of the technology is in place.
TRL #9	<p><i>Full commercial application, technology available for consumers</i></p> <p>Description</p> <p>Limiting factors are solved. The technology is ready for full operation production.</p> <p>Checkpoints</p> <ul style="list-style-type: none"> • Technology available for the market; • Full rate production readiness; • Business plan is available.

0.3. Market outlook methodology: Solar fuel demand

In general, a country or region's energy demand can be seen as a function of its population and of its Gross Domestic Product ("GDP")⁵. Nevertheless, this relationship has evolved over time, and with advancing economic growth in a number of economies, including Europe and North America, it appears that the energy demand in a given region can become decoupled from its economic growth. In other words, the region's economy can grow, while its energy demand falls simultaneously.

In order to forecast the demand for solar fuels from present times, to 2050 and 2100, we relied on data on the current and expected future energy intensity of economies, on GDP growth forecasts, and on the current and expected future energy mix, for six regions worldwide. The following sections present our methodology for the market outlook.

⁵ Pirlonea, C., Cicea, C., 2012, Econometric perspective of the energy consumption and economic growth relation in European Union. Renewable and Sustainable Energy Reviews

0.3.1. Data sources and region definitions

Three main databases were used for the market outlook exercise. We accessed Oxford Economics' Global Economics databank to access GDP data. More specifically, we used GDP per capita, in real terms and at purchasing power parity ("PPP") exchange rate. In looking at the relationship between GDP and energy demand, it is standard practice to use real (i.e. constant price) GDP measures, as they are corrected for inflation, thereby allowing an assessment of the relationship between energy demand and the real growth of an economy. Furthermore, we used GDP at PPP to account for differences in price levels between the economies in our analysis.

We accessed the International Energy Agency's (the "IEA") Word Energy Balances⁶ for estimates of final energy consumption for a number of countries and country aggregations, broken down by sector and by type of fuel. The end user categories covered by the IEA's final energy consumption data include industry, buildings (including residential, commercial and public), transport, and other⁷.

Finally, we used the Joint Research Centre's (the "JRC") Global Energy and Climate Outlook⁸ ("GECO") for estimates of final energy consumption as well, broken down by type of fuel. The fuel types covered by the GECO include biomass, coal, e-fuels⁹, electricity, gas, heat, hydrogen and oil.. The GECO dataset includes observations from 2000 to 2017, and forecasts at five-year intervals from 2020 to 2050.

The datasets used in the market outlook exercise each have different levels of granularity when it comes to country-level statistics. As our exercise was carried out on a region-by-region basis, the data for individual countries and country aggregations was summed up to arrive at a regional total. The regions considered in this study include Africa, Asia, Australia and New Zealand, Europe, North America, and South America. For more information on the definition of geographical regions, see Annex I.

0.3.2. Forecasting Total Final Consumption to 2050 and 2100

There are two main metrics for the consumption of energy, including fuels, in a given jurisdiction, namely primary energy consumption and final energy consumption.

Final energy consumption is defined as the energy consumed by end users, i.e. households, industry, services, and agriculture. Final energy consumption reflects the market demand for energy by energy users. This can be contrasted with the total primary energy supply, which is defined as the sum of energy production and net imports of energy. Indeed, final energy consumption measures what is actually consumed by end users, without considering transformation or distribution losses. Total primary energy supply considers the total domestic energy supply to a region, prior to any transformation, such as electricity generation from coal.

Therefore, the main difference between primary and final energy consumption is that the former includes the consumption of fuels by the energy sector for the production of electricity, as well as losses in transformation and distribution. Solar fuels are, by definition,

⁶ IEA, World energy balances and statistics, available here: <https://www.iea.org/subscribe-to-data-services/world-energy-balances-and-statistics>

⁷ Other final consumption includes agriculture and forestry, fishing, non-energy use, and non-specified.

⁸ European Commission Joint Research Centre, 2020, Global Energy and Climate Outlook 2019 – Data visualisation, available here: <https://ec.europa.eu/jrc/en/geco/visualisation>

⁹ E-fuels are synthetic fuels, either gaseous or liquid, produced through the use of electricity to produce hydrogen, which is combined with carbon dioxide to produce hydrocarbon fuels.

themselves produced by applying solar energy to drive the production of a fuel. As a result, they are not a primary source of energy, and are logically not considered as a suitable input to the energy sector¹⁰. For the purpose of this analysis, the primary energy supplied to the energy sector is considered to comprise renewable energy sources, in particular solar photovoltaic ("PV").

Our market outlook consists in an assessment of the potential contribution of solar fuels to energy needs worldwide in 2050 and 2100. The IEA's data on total final consumption provides historical insights from 2000 to 2017. We plotted the growth of GDP per capita in each of the six regions against a decline in the energy intensity of GDP, defined as the total final consumption (in thousand tonnes of oil equivalent, "ktoe") per \$ billion USD of GDP. The decline in the energy intensity of GDP has occurred through a gradual shift in the sectoral composition of world economies, through energy efficiency gains in buildings, engines, industrial processes. Further digitalisation of world economies, and automation of operations and processes, as well as innovations in the energy sector, are expected to contribute to continuing the decline in the energy intensity of world economies.

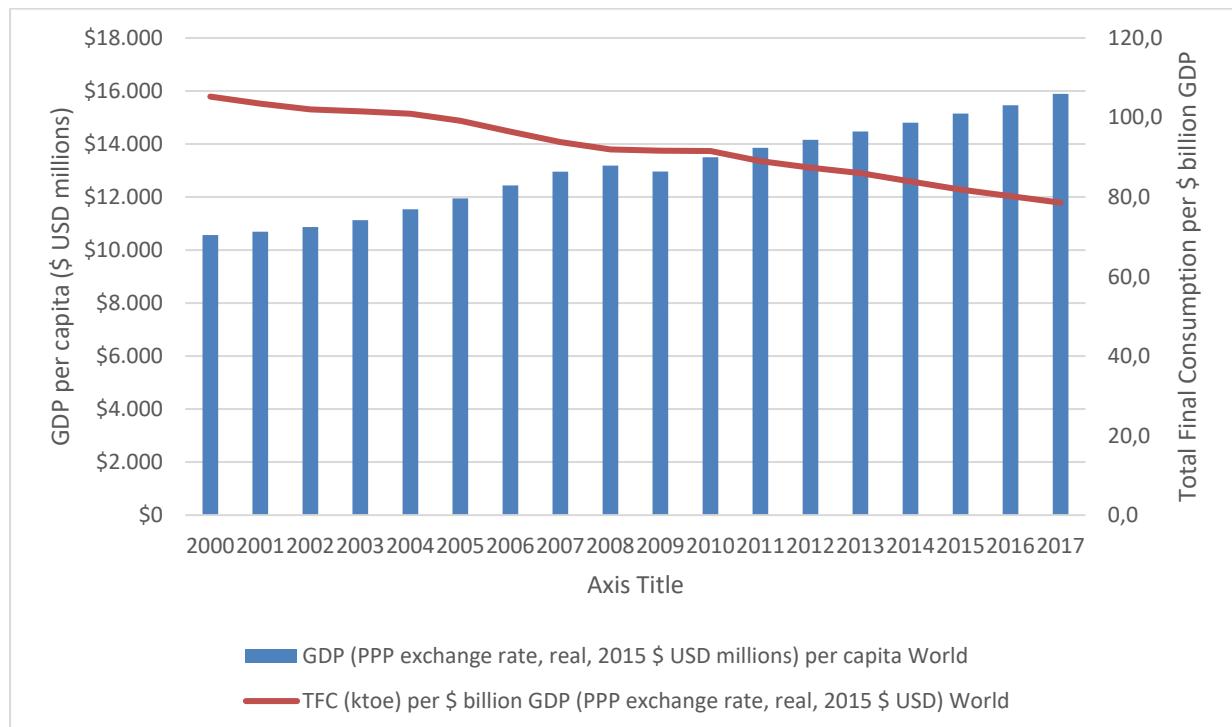


Figure 6 - GDP per capita and Total Final Consumption per \$ billion GDP, World

All six regions show concurrent marked trends towards greater GDP per capita, while the energy intensity of the economy, measured as the total final consumption of energy per \$ billion USD of GDP, declines. This signals a decoupling of economic growth from energy consumption, and foretells scenarios for each region where the total final consumption of energy may rise at a slower rate than economic growth, or even decline.

We forecasted the decline in total final consumption per \$ billion USD of GDP for each region by fitting an exponential curve to the historical data observed from 2000 to 2017. We included forecasted energy consumption data from the GECO as well, providing estimates reflecting three scenarios for the development of future energy systems¹¹, and

¹⁰ Solar fuels can, and are expected to, play a role in the energy sector as a means of storing variable renewable energy production, particularly at inter-seasonal time scales where batteries face challenges. These considerations are discussed in further detail in sector 3.5 below.

¹¹ The scenarios model three levels of investment towards abating climate emissions. The first is a reference scenario, modelling baseline conditions. The second scenario models strong commitments to limiting the global rise in temperatures by 2100, relative to pre-industrial levels,

establishing a benchmark for the forecast. We consulted a number of additional data sources to validate our forecast, including the in-depth analysis in support of the European Commission's "A Clean Planet for All" Communication¹², the European Commission's EU CO scenarios¹³, as well as the IEA's World Energy Outlook¹⁴.

Based on these estimates of total final consumption per \$ billion USD of GDP, from 2018 to 2050, we derived estimates of total final consumption for each region using the GDP figures previously accessed from Oxford Economics, as discussed above. The GDP dataset we used has historical data from 2000 to 2017, provisional data for 2018 and 2019, and forecasted data for 2020 onwards. The forecasted GDP figures, including 2020, do not take into account the impacts of the COVID-19 pandemic on the global economy and energy system. Our results therefore reflect pathways that were expected to arise prior to these impacts. Nevertheless, we believe that as economies worldwide recover from these impacts, the GDP growth trajectories will trend towards the pathways we have modelled. Additionally, the COVID-19 pandemic has highlighted the need for strong commitments to a fair transition towards climate-friendly economies. Pledges made both in the EU and abroad¹⁵ prove that there is broad support for such commitments. The EU's pledge is reflected in the most ambitious decarbonisation scenario, as discussed in section 0.3.3 below.

As a next step, we examined the IEA's data on total final consumption, broken down by sector, from 2000 to 2017, in order to determine broad trends in each region reflecting changes in the makeup of each region's economy. We applied linear regression to observed data from 2000 to 2017 to forecast the share of final consumption in each sector¹⁶ out of total final consumption, for each region, up to 2050 and to 2100. As with our forecasts of total final consumption, we relied on benchmarks from the GECO, as well as the most recent EU CO scenarios, figures reported in the European Commission's "A Clean Planet for All" Communication, and the IEA's World Energy Outlook to validate and further refine our forecasts.

In a further step, we used the GECO's estimates of final consumption by fuel type, within each sector and region, to reflect changes in each the energy mix for each sector and region. The GECO dataset includes the following categories of fuel types¹⁷:

- Biomass,
- Coal,

by 2°C. The third scenario models very strong commitments made to limit this temperature rise to 1.5°C. More information about the scenarios is provided below.

¹² European Commission, 2018, In-depth analysis in support on the COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, Available online at https://ec.europa.eu/knowledge4policy/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en

¹³ More specifically, the EU Reference Scenario 2016, and more importantly the updated EU CO3232.5 scenario.

¹⁴ International Energy Agency, 2019, World Energy Outlook 2018, Available here: https://webstore.iea.org/download/direct/2375?fileName=World_Energy_Outlook_2018.pdf

¹⁵ For instance, Germany's € 9 billion hydrogen strategy, Germany and France's announcement of a € 500 billion green recovery package, and China's pledge to become carbon neutral by 2060.

¹⁶ i.e. industry, transport, buildings and other.

¹⁷ We use "fuel type" here, and throughout this report, to refer to the form of energy consumed at the point of consumption, consistently e.g. Eurostat's usage, such as in table TEN00129 showing final energy consumption in industry by type of fuel.

- E-fuels,
- Electricity,
- Gas,
- Heat,
- Hydrogen, and
- Oil.

We extended the initial forecasting horizon through 2100, to model observed trends toward greater electrification across all sectors. Specifically, we observed the trends in the energy mix by sector and region, and applied linear regression to forecast each fuel type's respective share of energy consumption in each sector and region to 2100.

In a last step before obtaining final results of fuel consumption by sector and region, broken down by fuel type, we extended our forecast to 2100, turning to sources informing on potential trajectories for economic growth in each region to 2100. We applied growth rates in GDP per capita, for each region, observed in a dataset on Shared Socioeconomic Pathways ("SSP") maintained by the International Institute for Applied Systems Analysis. These SSPs include forecasts for socio-economic data and are regularly used in climate change modelling, including by the Intergovernmental Panel on Climate Change ("IPCC"). More specifically, we used SSP2, a "middle-of-the-road" scenario where broad socio-economic trends and technological do not differ significantly from historical patterns.

We then extended our forecast of the exponential decline in the energy intensity of GDP, i.e. the total final consumption of energy per \$ billion USD of GDP, for each region, to 2100. Applying the GDP forecasts described above, we obtained estimates of total final consumption of energy up to 2100.

We then applied the previously derived forecasted shares per fuel type for each sector, in each region, to our estimates of total final consumption in each region through 2100 in order to derive estimates of final consumption for each sector and region.

Based on the results of our levelized cost of energy ("LCOE") analysis to 2100, we expect that hydrogen derived through electrolysis powered by solar PV will be market-competitive, and indeed less expensive than steam methane reforming, before 2050. We therefore assume that in 2050, forecasted demand for hydrogen can be fulfilled by electrolysis powered by solar PV. The GECO's definition of e-fuels covers both e-liquids and e-gases¹⁸. We have used a number of information sources, including conversations with experts in our stakeholder workshops, as well as the European Commission's "A Clean Planet for All" Communication to determine the share of e-fuels and e-gases within final consumption in each sector.

0.3.3. Scenarios: Reference, 2°C of temperature rise and 1.5°C of temperature rise

Our market outlook considers three different scenarios for the development of worldwide energy systems to 2050 and 2100. These are driven by assumptions made by the GECO, which are summarized below.

The Reference scenario models a situation where climate commitments¹⁹ and sectoral policies in place in June 2019 remain as a baseline, and no new commitments are made. Nevertheless, as discussed above, current trends showing a decoupling of economic growth

¹⁸ E-fuels are synthetic fuels, either gaseous or liquid, produced through the use of electricity to produce hydrogen, which is combined with carbon dioxide to produce hydrocarbon fuels.

¹⁹ Albeit only those climate commitments that have been made binding by legislation.

from energy consumption continue, as factors including current policies, civil society and innovation drive market conditions favouring clean energy technologies. Despite being labelled as the reference scenario, it does not necessarily reflect expected pathways in some regions, such as the EU which has committed to full decarbonisation by 2050.

The 2°C scenario models a pathway where the average global temperature rise by 2100, relative to pre-industrial levels, is limited to 1.5°C. The scenario is driven by carbon pricing, differentiated across regions depending on per-capita incomes. This results in a sharp rise in electricity consumption, as a share of total final consumption of energy, across all sectors, and a decline in the consumption of fossil fuels.

The 1.5°C scenario, finally, models a pathway where the average global temperature rise by 2100, relative to pre-industrial levels, is limited to 2°C. This scenario most closely reflects the EU's commitment to reach carbon neutrality by 2050. Compared to the Reference and 2°C scenarios, the 1.5°C scenario assumes even greater efforts worldwide to drastically reduce energy consumption, as well as even greater electrification across all sectors²⁰.

0.3.4. Estimates of required investments

In order to estimate the investments required in solar fuel technologies, to meet the forecasted demand in 2050 and 2100, we extracted the capital expenditures ("CAPEX") modelled and presented in the economic roadmap. Based on our analysis of the levelised cost of energy ("LCOE") of electrolysis technologies, we determined that hydrogen production based on the proton exchange membrane electrolyser cell ("PEMFC") was most likely to be able to meet hydrogen demand. We therefore applied the estimates of CAPEX per unit of energy for PEMFC, to hydrogen demand, in order to obtain estimates of the required annual investments required to meet energy needs in 2050 and 2100.

For the demand for e-fuels, we distinguished between e-gases and e-liquids in each sector based on expert opinion derived from stakeholder workshops held in the course of the project, and on benchmarks from reports including the European Commission's "Clean Planet for All" Communication. Given the set of technologies included in our LCOE model, we made some assumptions regarding which technology would best fit the demand for e-gases and e-liquids. Specifically, we assumed that the power-to-methane technology would fulfil the modelled demand for e-gas, whereas CO₂ hydrogenation, producing methanol, could fulfil the demand for e-liquids.

²⁰ DG JRC, 2020, GECO 2019 Visualisation, Available here:
<https://ec.europa.eu/jrc/en/geco/visualisation>

1. Definition of solar fuel value chains

This chapter will present our study results aiming at defining and analysing solar fuel value chains produced through different technological pathways. The first section will in a qualitative manner present the technologies covered in our analysis while the second section will look at the current composition of these solar fuel technologies' value chains through a Levelised Cost of Energy (LCOE) economic modelling exercise.

1.1. Identification of Solar Fuels by pathways

Four technological pathways to produce solar fuels are analysed in this study:

- ▶ *Chemical including artificial photosynthesis*
- ▶ *Electrochemical*
- ▶ *Thermochemical*
- ▶ *Biochemical*

The main objective of this section is the identification of the solar fuel technologies within each of the four pathways, the specific technology components that compose their respective value chains together with their associated Technology Readiness Level (TRL). To achieve this goal, an analysis of the TRL of each technological component was produced, in line with the description of the solar fuel value chains and the evaluation of the technological solutions that can add value to each production pathway.

Due to the diversity and the complexity of the sector, the first step of the analysis was the identification of the main solar fuels that can be developed through the pathways. Within each technological pathway, a specific value chain is identified and selected for the study: the aim of this selection is to focus on the most relevant value chains in terms of potential for technological and economic improvements.

With the view to provide pragmatic examples for each of the technological pathways, specific 'case studies' have been selected for a more detailed analysis. Then, the TRL of each component is assessed through a literature analysis: this phase paves the way for the following techno-economic analysis of the value chains performed in section two of this report.

The information and data gathered (including the assessed TRL of the technologies) were discussed and validated by stakeholders of the solar fuels research community, through a set of workshops and a survey that were launched as part of the project.

1.1.1. Chemical and Electrochemical pathway

The chemical and electrochemical pathways are discussed together in this section and could be subclassified into two technology routes, a direct route using photo-electrochemical cells and an indirect route using the combined approach of photovoltaic and electrolysis cell (Figure 7). The direct route where solar energy is directly converted into fuels via photo-electrocatalytic reactions could be broken down further in area devices (Photo-Electrochemical Cell, PEC) and particle devices (Photo Catalyst particles, PC). The indirect route develops three major applications: Proton Exchange Membrane Electrolyser (PEM), Alkaline Electrolyser (AE) and Solid-Oxide Electrolyser Cell (SOEC). The approaches in the direct route are still in research phase and thus at low TRL 1-3. The indirect route benefits from the mature PV technology and large-scale electrolyzers. PEM and AE are developed at TRL 7-9 and are commercially available. SOEC is under development and in prototyping phase, thus at TRL 6-7. For PEM, AE and SOEC, solar fuels are produced in combination with photo-voltaic devices. These can be large solar farms in the direct neighbourhood of the electrolyser benefiting from the cheapest electricity generation cost. In parallel, more decentralized approaches are under investigation where capital expenditures are reduced by converter- and cable-less direct integration of PV and electrolyser.

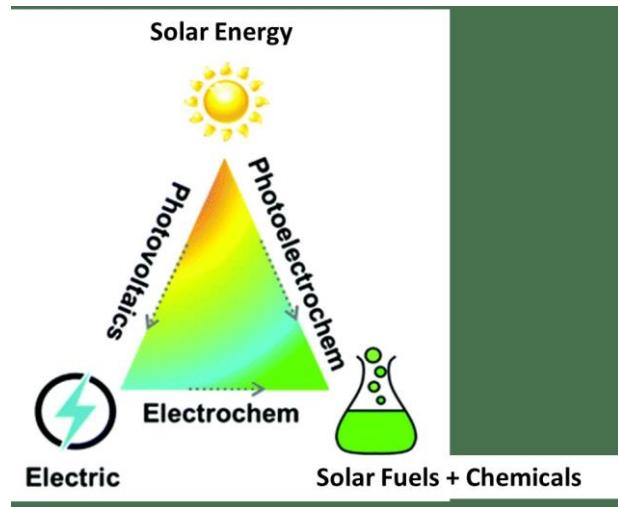


Figure 7 - Two different approaches to electro(chemical) solarfuels: indirect photovoltaic+electrolysis and direct photoelectrochemical including photocatalysis and artificial photosynthesis.

Direct Route PEC and PC

1.1.1.1. Photoelectrochemical PEC Electrolysis

Photoelectrochemical (PEC) water splitting is a promising solar-to-hydrogen pathway for hydrogen production at [semi-central and central scales²¹](#), offering the potential for high conversion efficiency at low operating temperatures using cost-effective thin-film and/or particle semiconductor materials. The PEC cell is the most compact embodiment of this approach where photogenerated electrons are utilized to reduce CO₂ directly at a semiconductor/electrolyte interface. Fujishima and Honda first achieved an electrochemical photocatalysis of water at a semiconductor electrode in 1972. These approaches suffer under low solar to fuel or solar to hydrogen efficiencies (typically StH% <10%). The choice of electrolyte for PEC systems is dictated by the nature of the photoelectrode material. Generally, [alkaline electrolytes](#) are used with TiO₂ and Fe₂O₃ photoanodes, while WO₃ is used with neutral and acidic electrolytes because it is only stable in such media. Finally, NaHCO₃ and Na₂SO₄ are employed as electrolytes for BiVO₄ photoanodes.

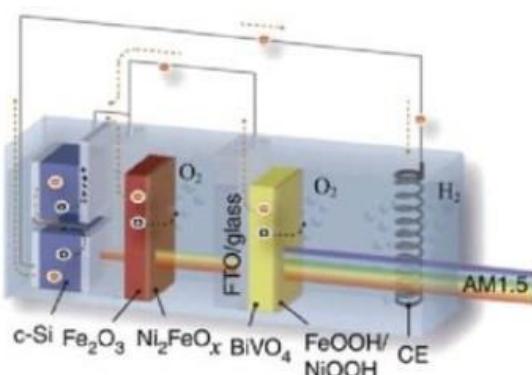


Figure 8 - Schematic illustration of a full PEC cell CB: Conduction Band; VB: Valance Band; F: Fermi Energy Level

The solar to hydrogen efficiency could be enhanced by adding a PV cell in the stack and creating a PV/PEC tandem cell.

²¹ <https://www.energy.gov/eere/fuelcells/central-versus-distributed-hydrogen-production>

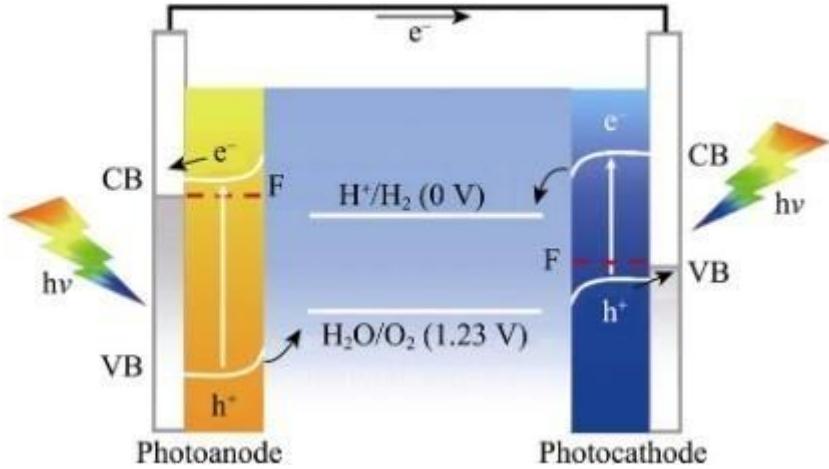


Figure 9 - Scheme of a PEC/PV tandem cell with modified BiVO₄ /-Fe₂O₃ dual photoanodes and two parallel-connected c-Si cells (Song-Can et al., 2018)

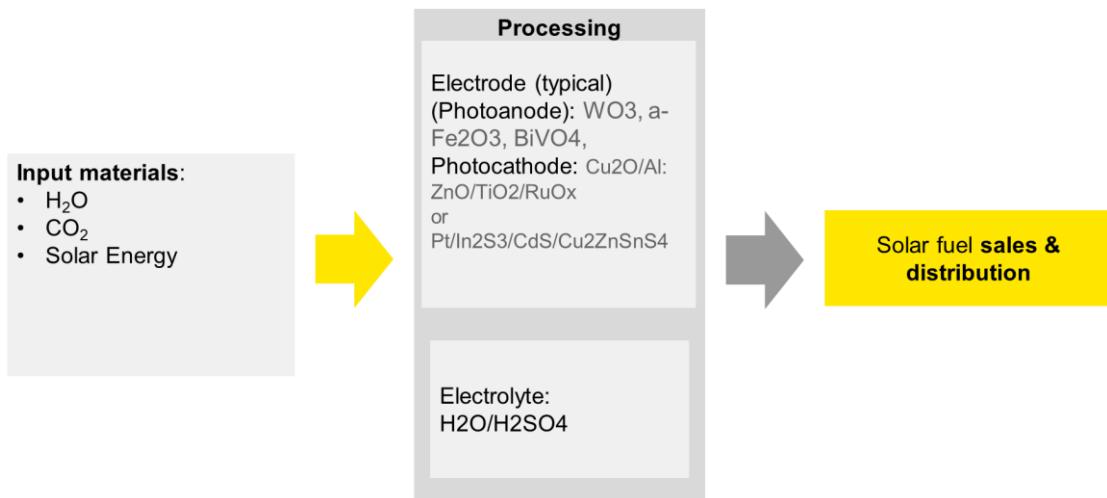


Figure 10 - Simplified scheme of value chain for Photovoltaic Electrolysis Cell (PEC) to produce solar fuels

In the Photoelectrochemical Cell (PEC) technology the sunlight is directly converted into chemical products.

In the **upstream** phase of the PEC value chain, solar radiation as primary energy source, water for Hydrogen generation and CO₂ for higher synthetic hydrocarbon fuels are identified. The required materials and their processes into electrolyser components like electrodes and electrolytes are under development in TRL 3-4. The encapsulation material for this technology is identified with technology readiness level 5. The land use needs for this technology is rather limited because of the compact design of the electrodes which act as electricity source and electrolyser material in once. For this reason, the PEC technology is predicted to find its application in decentralized approaches, because it is highly independent from primary energy sources others than direct sunlight.

In the **intermediate** phase of the PEC value chain, differentiation need to be made between Hydrogen and hydrocarbon solar fuels. For the case of PEC generating hydrogen, this chemical can be used directly as fuel in hydrogen fuel cells for traffic applications (e.g. cars, busses, trucks, folk lifter, etc), mixed to a certain percentage into the existing gas grid (the exact injection amount is still under discussion and can vary between different countries), act as seasonal storage for gas turbines (re-electrification), be converted into NH₃ using the Haber-Bosch process or liquified for transport in ships or pipelines. If hydrogen is used as an energy vector it can be used to react with CO₂ using the Fischer-Tropsch process to generate hydrocarbon solar fuels.

In a **downstream** phase of the PEC value chain the end-users of the produced solar fuels are either distributed in a localised grid to act for industrial and private sectors as chemical feedstock or for residential use (heating, cooling, electricity) or feeding refuelling stations and fuel cells for application in transport like personal cars, heavy commercial vehicles or trains.

Table 3 – Electrochemical pathway - Photoelectrochemical (PEC) - Estimated TRL for each technology components

Pathway/Technology	Technology component	TRL
Electrochemical (Photoelectrochemical, PEC)	Electrodes	3-4
	Electrolyte	3-4
	Encapsulation	5

Continued improvements in efficiency, durability, and cost are still needed for market viability. Ongoing research and development of PEC materials, devices and systems is making important strides, benefiting from strong synergies with contemporary research efforts in photovoltaics, nanotechnologies, and computational materials, notably:

- Efficiencies are being improved through enhanced sunlight absorption and better surface catalysis;
- Durability and lifetime are being improved with more rugged materials and protective surface coatings;
- Hydrogen production costs are being lowered through reduced materials and materials processing costs.

1.1.1.2. Chemical Photocatalysis particles and artificial Photosynthesis

Photocatalysis is the activity occurring when a light source interacts with the surface of semiconductor materials, the so called photocatalysts. During this process, there must be at least two simultaneous reactions occurring, oxidation from photogenerated holes, and reduction from photogenerated electrons. The photocatalyst itself should not undergo change and therefore a precise synchronisation of the two processes needs to take place. Later it was discovered that TiO₂ aids in decomposing cyanide in water, rising interest towards the material's environmental applications. TiO₂ is suitable for photocatalysis for several reasons, some of which are its common availability, relatively low cost, and high chemical stability.

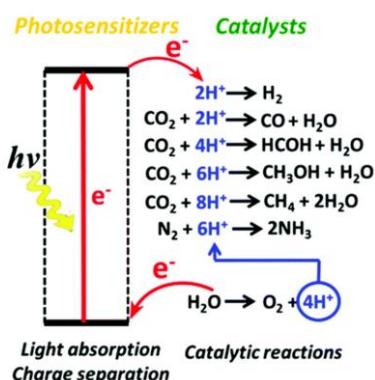


Figure 11 - Schematic drawing of direct conversion of solar energy to chemicals: photocatalysis

Photocatalysis on photocatalyst particles involves three sequential steps: (i) absorption of photons with higher energies than the bandgap of the photocatalysts, leading to the excitation of electron–hole pairs in the particles, (ii) charge separation and migration of these photoexcited carriers, and (iii) surface chemical reactions based on these carriers. This is depicted in Figure 12.

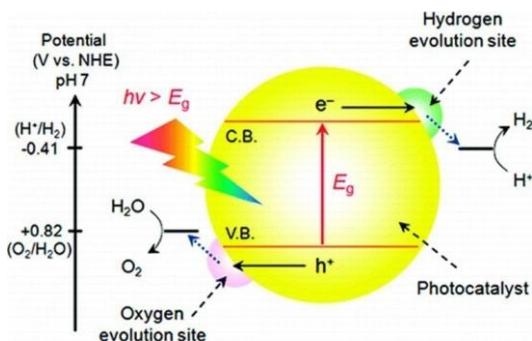


Figure 12 - Schematic picture of Photo catalysis (PC) (Source: Maeda and Domen, 2010)

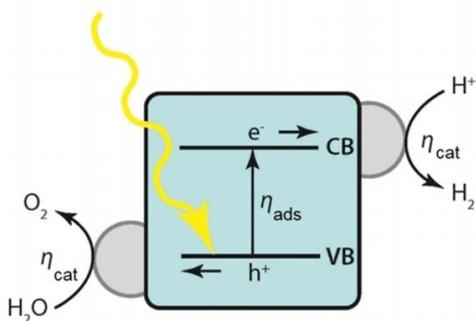


Figure 13 - Core shell particles, Two compound system: Semiconductor+ dual co-catalysts (B. Mei et al, ACS Catal. 2018, 8, 9154–9164)

- Metal co-catalyst like Pt, Au, etc
- Sensitizer Dye
- Composite semiconductor

Illumination of a semiconductor with the efficiency, η_{ads} , is followed by charge carrier separation η_{sep} and the surface redox reaction occurring at the surface of the cocatalyst particles, η_{cat} . Here, dual co-catalyst functionalization (e.g. hydrogen and oxygen evolution) are driven by different co-catalysts. (Right) Co-catalysts can be dynamic in nature, and a few examples of feasible changes of the cocatalyst are sketched.

Challenges:

The deactivation of a co-catalyst/semiconductor composite might occur because of:

- (1) changes of the light absorbing semiconductor material (e.g. by corrosion);
- (2) changes/rearrangement of the applied cocatalysts, in particular modification of the physiochemical properties of a cocatalyst, such as oxidation state, phase composition, particle size and atomic structure.

Artificial photosynthesis using Dye Sensitive Solar Cells (DSSC)

One of the latest developments in the framework of artificial photosynthesis is represented by the so-called 'artificial leaf'. This technology has been implemented at very low TRL so far (TRL 4-5) and is based on die sensitive solar cell material (DSSC).

The parts that mimic the biological leaf are the following:

The sensitizer S replaces chlorophyll;

The semiconducting membrane replaces the biological membrane;

- 1 Dye sensitizer: Rubinium based complex;
- 2 Semiconducting membrane: ceramic like TiO₂;
- 3 Iodine based mediator.

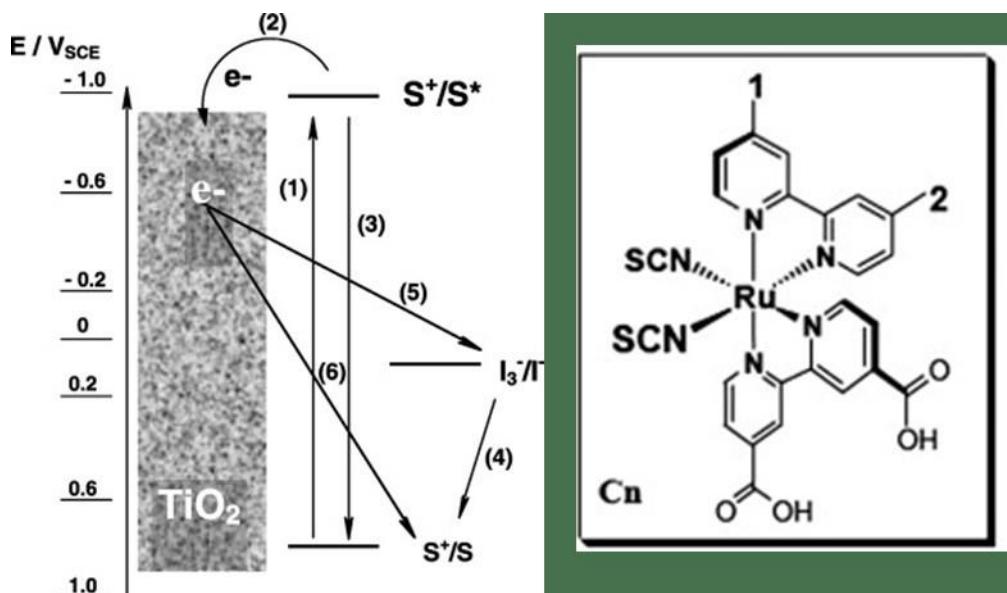


Figure 14 - Schematic of an artificial photosynthesis cell (Grätzel, Coordination Chemistry Reviews, 111 (1991) 167-174)

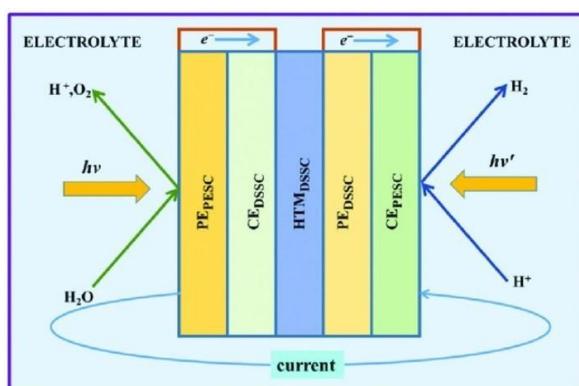


Figure 15 - Artificial leaf-type compact Photoelectrosynthetic/Dye sensitive solar (n-PESC/DSSC) tandem cell.

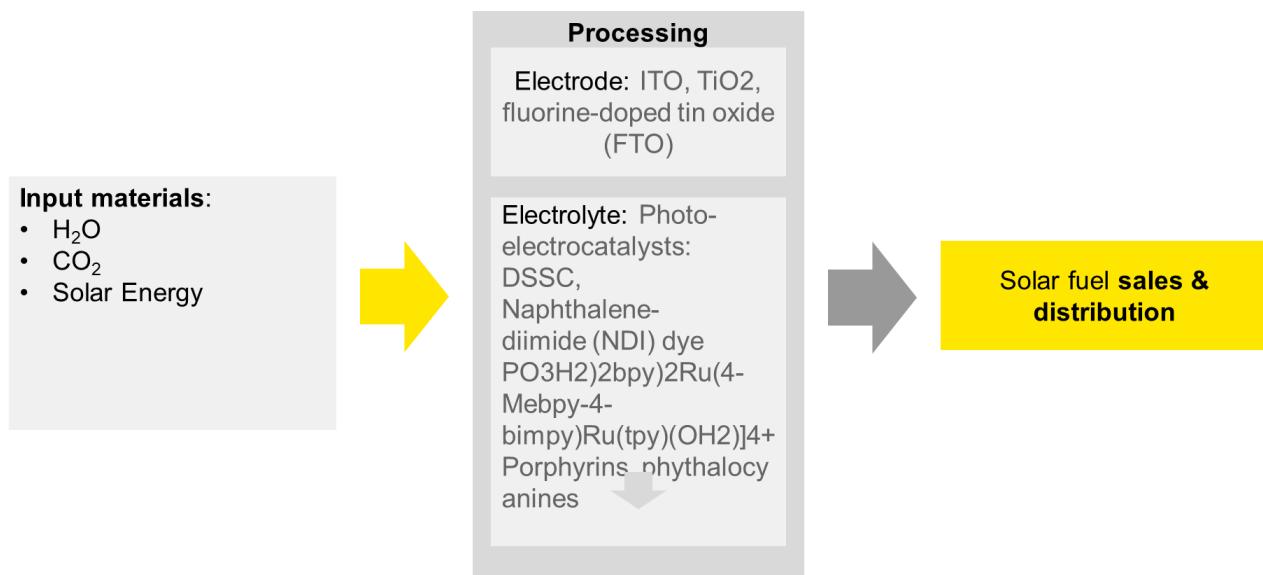


Figure 16 - Simplified scheme of a photocatalyst value chain (Artificial Leaf using DSSC) to produce solar fuels

In the Photocatalysis on photocatalyst particles or colloids (PC) technology the sunlight is directly converted into chemical products.

In the upstream phase of the PC value chain, solar radiation as primary energy source, water for Hydrogen generation and CO₂ for higher synthetic hydrocarbon fuels are identified. The required materials and their processes into electrolyser components like electrodes and catalysts are under development in TRL 2-3. The electrolytes material for this technology is identified with technology readiness level 3.

In the upstream phase of the Photoelectrosynthetic/Dye Sensitive Solar Cell (Artificial leaf) value chain, solar radiation as primary energy source, water for Hydrogen generation and CO₂ for higher synthetic hydrocarbon fuels are identified. Electrode and electrolyte material are under development in TRL 4-5. Encapsulation of this materials has an TRL of 5.

The land use needs for this technology is rather limited because of the compact design of the electrodes which act as electricity source and electrolyser material in once. For this reason, the PC technology is predicted to find its application in decentralized approaches, because it is highly independent from primary energy sources others than direct sunlight. In the intermediate phase of the PC value chain, differentiation need to be made between Hydrogen and hydrocarbon solar fuels. For the case of PEC generating hydrogen, this chemical can be used directly as fuel in hydrogen fuel cells for traffic applications (e.g. cars, busses, trucks, folk lifter, etc), mixed to a certain percentage into the existing gas grid (the exact injection amount is still under discussion and can vary between different countries), act as seasonal storage for gas turbines (re-electrification), be converted into NH₃ using the Haber-Bosch process or liquified for transport in ships or pipelines. If hydrogen is used as an energy vector it can be used to react with CO₂ using the Fischer-Tropsch process to generate hydrocarbon solar fuels.

In a downstream phase of the PC value chain the end-users of the produced solar fuels are either distributed in a localised grid to act for industrial and private sectors as chemical feedstock or for residential use (heating, cooling, electricity) or feeding refuelling stations and fuel cells for application in transport like personal cars, heavy commercial vehicles or trains.

The porous TiO₂ is analogous to the chloroplast in leaves, in that it increases the amount of pigment molecules per volume, allowing more light to be absorbed. After a dye molecule transfers an electron to the TiO₂, it is positively charged and needs an electron to become neutral. However most of the dye molecules are not in physical contact with the counter electrode. To solve this problem we use materials which can "ferry" electrons between the counter electrode and the dye molecules.

Table 4 – Chemical pathway - Artificial Leaf - Estimated TRL for each technology components

Pathway/Technology	Technology component	TRL
Chemical (artificial leaf)	Electrodes	4-5
	Electrolyte	4-5
	Encapsulation	5

In order to operate the practical application, we need overcome some drawbacks of the dye-sensitized cells:

- Improve the transformation rate; recently, dye-sensitized cells can reach about 11%, but the normal traditional silicon cell is more than 15%;
- Solve the problem: the bigger in size, the efficiency will weaken;
- Improve the lifetime.

Indirect route PV+EC

1.1.1.3. Alkaline Electrolysis Cell (AEC)

AEC devices are the most commonly used hydrogen generators in the industry. The hydrogen production becomes pure with 99%. After certain purification processes, it is possible to reach the high purity rates required for hydrogen fuel cells. The efficiency of the hydrogen production is approximately 80%. Potassium hydroxide is used in the rate of 25%-30% as electrolyte for the electrolysis. They become more effective when operated at low current densities (0.3 A/cm^2). In commercial alkaline electrolyzers, the current density range is $100\text{--}400 \text{ mA/cm}^2$. The disadvantages are also high corrosive effect of liquid electrolyte used in high-temperature values. For this reason, they have a very short lifetime.

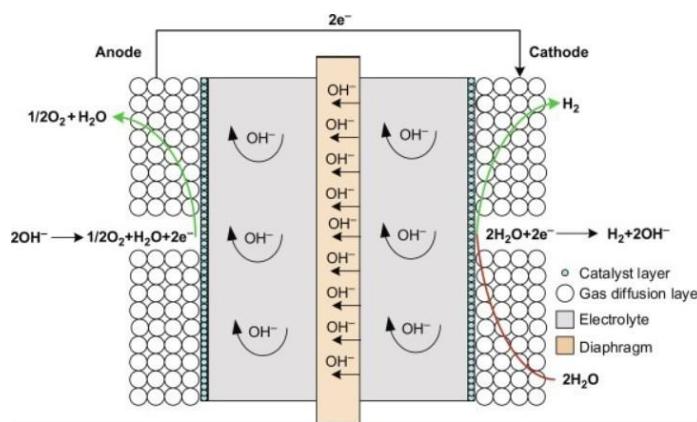


Figure 17 – Alkaline Electrolysis devices

The principle of the alkaline water electrolysis is quite straight forward. Oxygen and hydrogen are separated from the water when the direct current is applied to the water, two water molecules dissociate, and hydrogen arises at the cathode by this reaction. At the anode, oxygen arises, and a water molecule is generated at the same time. As a result, when a water molecule dissociates, another water molecule moves to the anode. Alkaline electrolyzers contain caustic water solution and 25%-30% of potassium hydroxide (KOH).

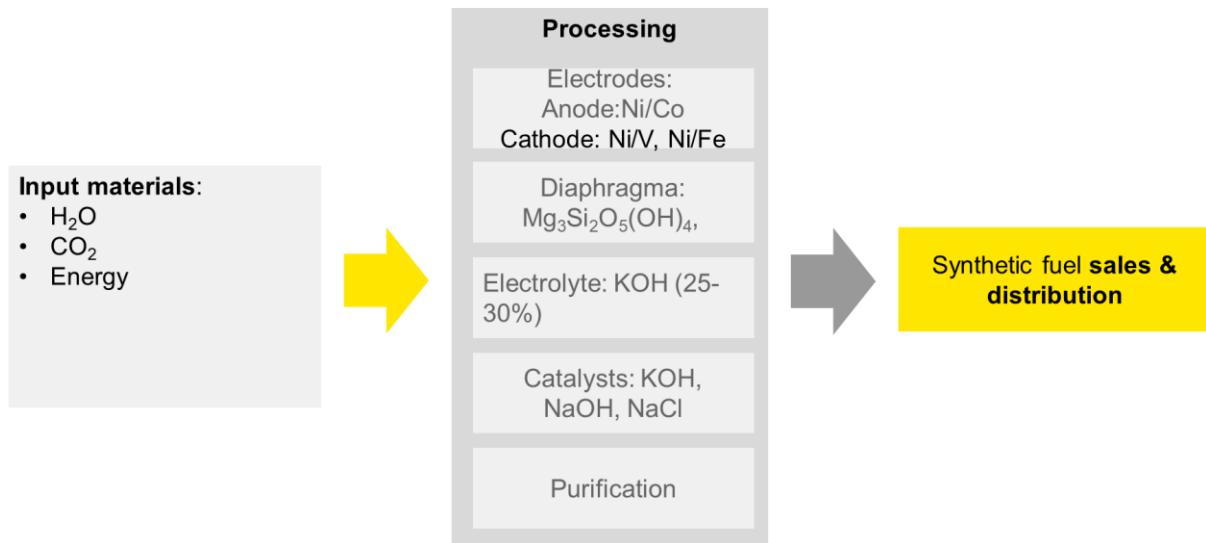


Figure 18 - Simplified scheme of Alkaline Electrolysis Cell (AEC) value chain to produce solarfuels

In the alkaline electrolysis cell (AEC) technology the sunlight is indirectly converted into chemical products.

In the **upstream** phase of the AEC value chain, solar radiation as primary energy source, electricity from solar cells as secondary energy source, water for Hydrogen generation and CO₂ for higher synthetic hydrocarbon fuels are identified. The required materials and their processes into electrolyser components like electrodes, catalysts, diaphragm and electrolytes are developed on industrial scale in TRL 8-9. The purification process for this technology is identified with technology readiness level 8-9.

The land use needs for this technology is rather extensive because of the low-cost green electricity needed for the electrolyser generated by large area solar farms in regions with high yearly solar radiation . For this reason, the AEC technology is predicted to find its application in centralized approaches, because it is highly dependent from low-cost secondary energy sources like green electricity produced by solar cells.

In the **intermediate** phase of the AEC value chain, differentiation need to be made between Hydrogen and hydrocarbon solar fuels. For the case of AEC generating hydrogen, this chemical can be used directly as fuel in hydrogen fuel cells for traffic applications (e.g. cars, busses, trucks, folk lifter, etc), mixed to a certain percentage into the existing gas grid (the exact injection amount is still under discussion and can vary between different countries), act as seasonal storage for gas turbines (re-electrification), be converted into NH₃ using the Haber-Bosch process or liquified for transport in ships or pipelines. If hydrogen is used as an energy vector it can be used to react with CO₂ using the Fischer-Tropsch process to generate hydrocarbon solar fuels.

In a **downstream** phase of the AEC value chain the end-users of the produced solar fuels are either distributed in a localised grid to act for industrial and private sectors as industrial feedstock or for residential use (heating, cooling, electricity) or feeding refuelling stations and fuel cells for application in transport like personal cars, heavy commercial vehicles or trains.

For electrodes the most common materials used are steel plates with some kind of Ni treatment. It could, for instance, be Ni-plating, since nickel it is corrosion resistant in alkaline media and because it is a fairly low-cost metal. Different metals like cobalt, iron, and vanadium are used as additives to the electrodes. Cobalt is added to the anode, while iron and vanadium are used at the cathode. It was found that iron and vanadium can reactivate the cathode. The reactivation of the cathode is promoted by ions of iron or vanadium in solution rather than metal incorporated in an alloy. The deactivation of the cathode is ascribed as a formation of nickel hydride, which iron and vanadium can reverse.

Table 5 – Electrochemical pathway - Alkaline Electrolyser - Estimated TRL for each technology components

Pathway/Technology	Technology component	TRL
Electrochemical (Alkaline Electrolyser, AE)	Electrodes	8-9
	Electrolyte	8-9
	Diaphragma	8-9
	Catalysts	8-9
	Purification	8-9

The Alkaline Electrolysis Cell (AEC) [overvoltage](#) during operation is not only due the overpotentials from HER and OER, but also to the [ohmic loss](#) in the electrolyte, which includes the resistance from ionic transfer in the diaphragm. This ohmic loss induced by the presence of the diaphragm explains the reason why [lower current densities](#) can be applied to AE Cells in comparison with PEM Electrolyser Cells.

1.1.1.4. Polymer electrolyte membrane (PEM) water electrolysis

The major PEM water electrolysis cell components are membrane electrode assemblies (MEAs), current collectors (gas diffusion layers), and separator plates. Typical overview of PEM water electrolysis cell assembly was shown in Figure 19. However, heart of the electrolysis cell is MEA which is separated into two half cells (anode and cathode).

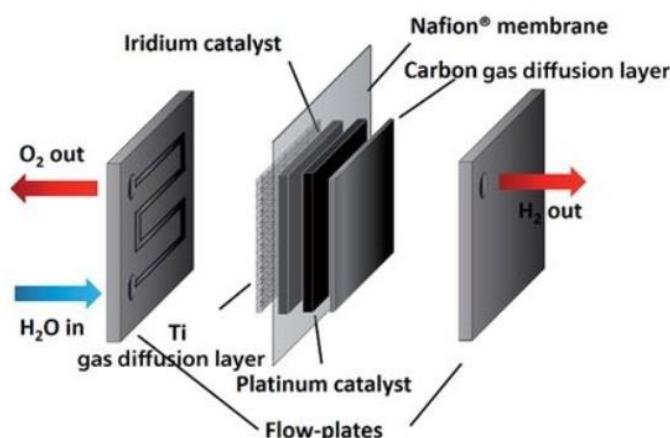


Figure 19 - Schematic of PEM showing the membrane electrode assembly, current collectors and flow plates

The membrane electrode assemblies are composed of a membrane, [ionomer](#) solution and anode, cathode electrocatalysts which is responsible 24% of overall cell cost. The membrane is the back bone of the PEM cell, the most commonly used membranes are Perfluorosulfonic acid polymer membranes such as Nafion®, Fumapem®, Flemion®, and Aciplex®. These membranes have unique properties such as high strength, high efficiency and high oxidative stability, dimensionally stable with change of temperatures, good durability and high proton conductivity. However, currently Nafion® membranes (Nafion® 115, 117, and 212) are mostly used in PEM water electrolyzers because Nafion® membranes have tough advantages such as operating at higher current densities (2 A/cm^2), high durability, high proton conductivity and good mechanical stability.

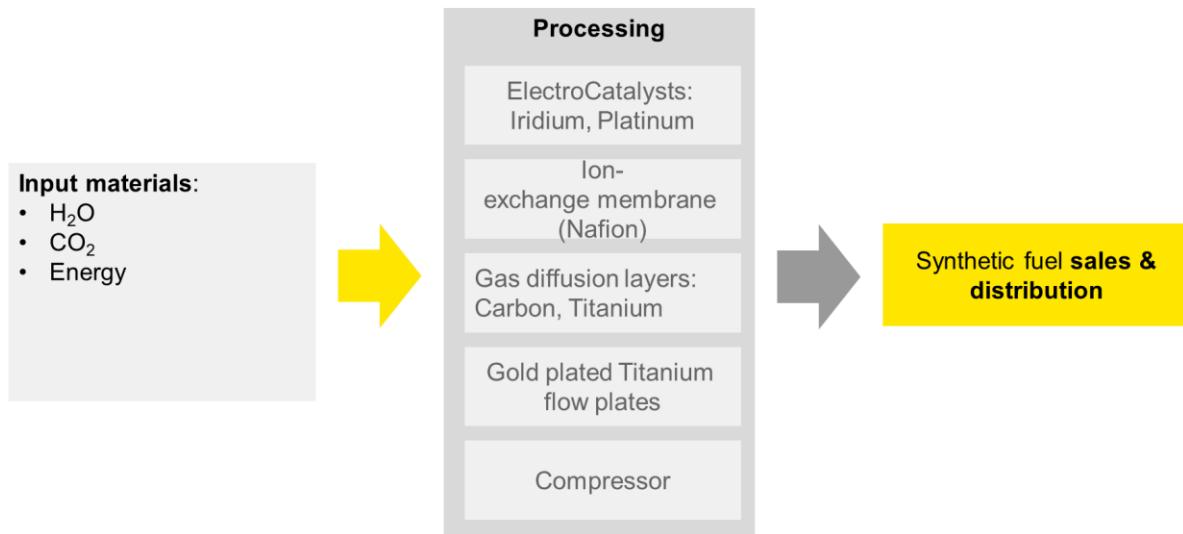


Figure 20 - Simplified scheme of Proton Exchange Membrane Electrolysis Cell (PEMEC) value chain to produce solar fuels

In the Proton Exchange Membrane Electrolysis Cell (PEMEC) technology the sunlight is indirectly converted into chemical products.

In the **upstream** phase of the PEMEC value chain, solar radiation as primary energy source, electricity from solar cells as secondary energy source, water for Hydrogen generation and CO₂ for higher synthetic hydrocarbon fuels are identified. The required materials and their processes into electrolyser components like electrodes, catalysts, electrolyte, ion exchange membrane, gas diffusion layer and flow plates are developed on industrial scale in TRL 7-8. The compression process for this technology is identified with technology readiness level 7-8.

The land use needs for this technology is rather extensive because of the electricity needed for the electrolyser. For this reason, the PEMEC technology is predicted to find its application in centralized approaches, because it is highly dependent from low-cost secondary energy sources like green electricity produced by large area solar farms in regions with high yearly solar radiation.

In the **intermediate** phase of the PEMEC value chain, differentiation need to be made between Hydrogen and hydrocarbon solar fuels. For the case of PEMEC generating hydrogen, this chemical can be used directly as fuel in hydrogen fuel cells for traffic applications (e.g. cars, busses, trucks, folk lifter, etc), mixed to a certain percentage into the existing gas grid (the exact injection amount is still under discussion and can vary between different countries), act as seasonal storage for gas turbines (re-electrification), be converted into NH₃ using the Haber-Bosch process or liquified for transport in ships or pipelines. If hydrogen is used as an energy vector it can be used to react with CO₂ using the Fischer-Tropsch process to generate hydrocarbon solar fuels.

In a **downstream** phase of the PEMEC value chain the end-users of the produced solar fuels are either distributed in a localised grid to act for industrial and private sectors as industrial feedstock or for residential use (heating, cooling, electricity) or feeding refuelling stations and fuel cells for application in transport like personal cars, heavy commercial vehicles or trains.

The current collectors must be [corrosion resistance](#), they need good electrical conductivity due to the acidic environment, high over potential and presence of oxygen. The current collectors also deliver good mechanical strength to the membrane. Moreover, they have an optimized porosity and pore volumes due to the produced gases being effectively expelled. Water must be reaching the catalytic sites of the electrode surface, therefore optimized current collectors are required. Typically in PEM water electrolysis porous [titanium](#) plates are used as promising current collectors due to the these materials having unique properties such as good electrical conductivity, mechanical stability and corrosion resistant under acidic medium. The porous titanium plates act as current

collectors and gas diffusion layer (GDL) for both sides of the MEA and enclosed by bipolar plates followed by [gaskets](#). The current collectors are used to allow the electrical current to flow between the electrodes and bipolar plates. In many studies, titanium grids/meshes/felts, carbon current collectors and stainless-steel grids are used, but the electrochemical performance is lower than porous titanium plates.

Table 6 - Electrochemical pathway - Proton Exchange Membrane - Estimated TRL for each technology component

Pathway/Technology	Technology component	TRL
Electrochemical (Proton Exchange Membrane, PEM)	Electrodes/Catalysts	7-8
	Electrolyte	7-8
	Ion exchange membrane	7-8
	Gas diffusion layer	7-8
	Flow plates	7-8
	Compressor	7-8

1.1.1.5. Solid Oxide Electrolysis Cell (SOEC)

The solid oxide electrolysis (SOE) was first introduced by Dönitz & Erdle (1985) in the 1980s. Solid oxide electrolysis has attracted great attention due to the electrical energy converting into the chemical energy along with producing the ultra-pure hydrogen with greater efficiency. Solid oxide electrolysis operates at high pressure and high temperatures (500–850 °C) and utilizes the water in the form of steam. Solid oxide electrolysis process conventionally uses the O²⁻ conductors which are mostly from nickel/yttria stabilized [zirconia](#) (Emrullahoglu Abi, 2015), operating principle of SOE has shown. Nowadays, some of the ceramic proton conducting materials have been developed and studied in solid oxide fuel cells. However, increasing attention was granted to ceramic proton conducting materials for SOE electrolysis process, due to these materials demonstrating high efficiency and superior [ionic conductivity](#) (Owen, 1989) than O²⁻ conductors at an operating temperature of 500–700°C. The main characteristic of solid oxide electrolysis technology is its higher operating temperature which makes it advantageous compared with low temperature electrolysis. SOE nevertheless faces issues related to a lack of stability and degradation, which must be solved before going to commercialization on a large scale.

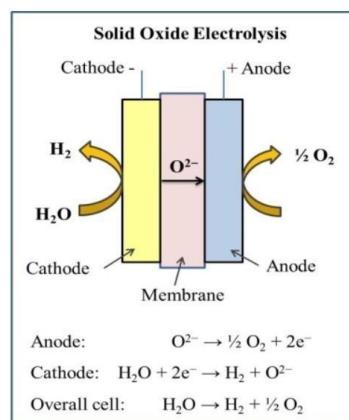


Figure 21 - Solid Oxide Electrolysis

The electrolyte is a gas-tight ceramic membrane which can conduct ions and is located between two porous electrodes that can conduct electrons: steam/hydrogen electrode (anode) and the air/oxygen electrode (cathode). The design of the solid-oxide cell includes the use of a sweep gas to avoid the degradation of the electrode. Possible sweep gases are air, steam and oxygen. The steam, mixed with hydrogen to maintain reducing conditions on the anode side, is fed to the cathode. The water molecules dissociate to form hydrogen and oxygen ions. The oxygen ions are transported through the electrolyte on the anode where they are oxidized to form oxygen gas.

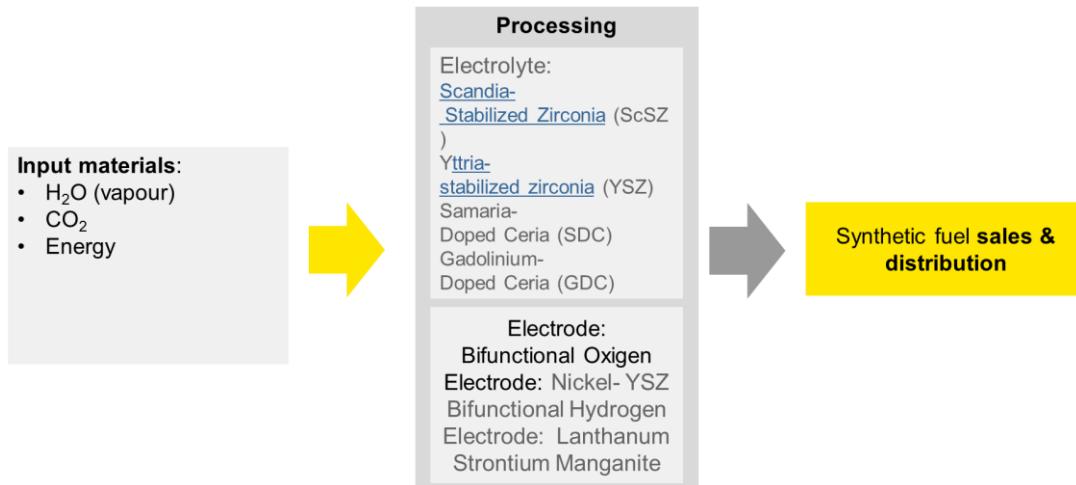


Figure 22 - Simplified scheme of Proton Exchange Membrane Electrolysis Cell (PEMEC) value chain to produce solar fuels

In the Solid Oxide Electrolysis Cell (SOEC) technology the sunlight is indirectly converted into chemical products.

In the **upstream** phase of the SOEC value chain, solar radiation as primary energy source, electricity from solar cells as secondary energy source, water for Hydrogen generation and CO₂ for higher synthetic hydrocarbon fuels are identified. The required materials and their processes into electrolyser components like electrodes, electrolyte structure and redox material are developed on industrial scale in TRL 6-7. The reactor geometry for this technology is identified with technology readiness level 6-7.

The land use needs for this technology is rather extensive because of the electricity needed for the electrolyser. For this reason, the SOEC technology is predicted to find its application in centralized approaches, because it is highly dependent from low-cost secondary energy sources like green electricity produced by large area solar farms in regions with high yearly solar radiation

In the **intermediate** phase of the SOEC value chain, differentiation need to be made between Hydrogen and hydrocarbon solar fuels. For the case of SOEC generating hydrogen, this chemical can be used directly as fuel in hydrogen fuel cells for traffic applications (e.g. cars, busses, trucks, folk lifter, etc), mixed to a certain percentage into the existing gas grid (the exact injection amount is still under discussion and can vary between different countries), act as seasonal storage for gas turbines (re-electrification), be converted into NH₃ using the Haber-Bosch process or liquified for transport in ships or pipelines. If hydrogen is used as an energy vector it can be used to react with CO₂ using the Fischer-Tropsch process to generate hydrocarbon solar fuels.

In a **downstream** phase of the SOEC value chain the end-users of the produced solar fuels are either distributed in a localised grid to act for industrial and private sectors as industrial feedstock or for residential use (heating, cooling, electricity) or feeding refuelling stations and fuel cells for application in transport like personal cars, heavy commercial vehicles or trains.

SOEC can also electrolyze carbon dioxide (CO_2) to carbon monoxide (CO). If water is electrolyzed at the same time (co-electrolysis), a mixture of hydrogen and CO is produced. This mixture, called syngas, is the starting point of a large number of syntheses of hydrocarbons in the chemical industry. In this way, liquid transport fuels can be produced synthetically. If the electricity is generated by wind turbines or solar cells, the use of the fuel is CO_2 neutral.

Table 7 – Electrochemical pathway - Solid Oxide Electrolysis - Estimated TRL for each technology component

Pathway/Technology	Technology component	TRL
Electrochemical (Solid Oxide Electrolyser, SOEC)	Electrodes	6-7
	Electrolyte structure	6-7
	Redox material	6-7
	Reactor geometry	6-7

Research topics for SOEC:

- Density-functional based modelling in combination with model electrodes and in situ studies to clarify how the interplay of materials properties and geometry impacts electrode performance;
- Novel processing routes such as net shaping to achieve stronger cells with a large footprint;
- Sealants, interconnects, protective coatings for and design of SOEC stacks;
- High pressure co-electrolysis for production of synthetic fuels.

1.1.2. Thermochemical pathway

Thermochemical methods are described as high-temperature two-step processes. The two-step process involving the thermal decomposition of metal oxides followed by re-oxidation by reacting with H₂O to yield H₂ is an attractive and viable process that can be rendered to become an isothermal process.

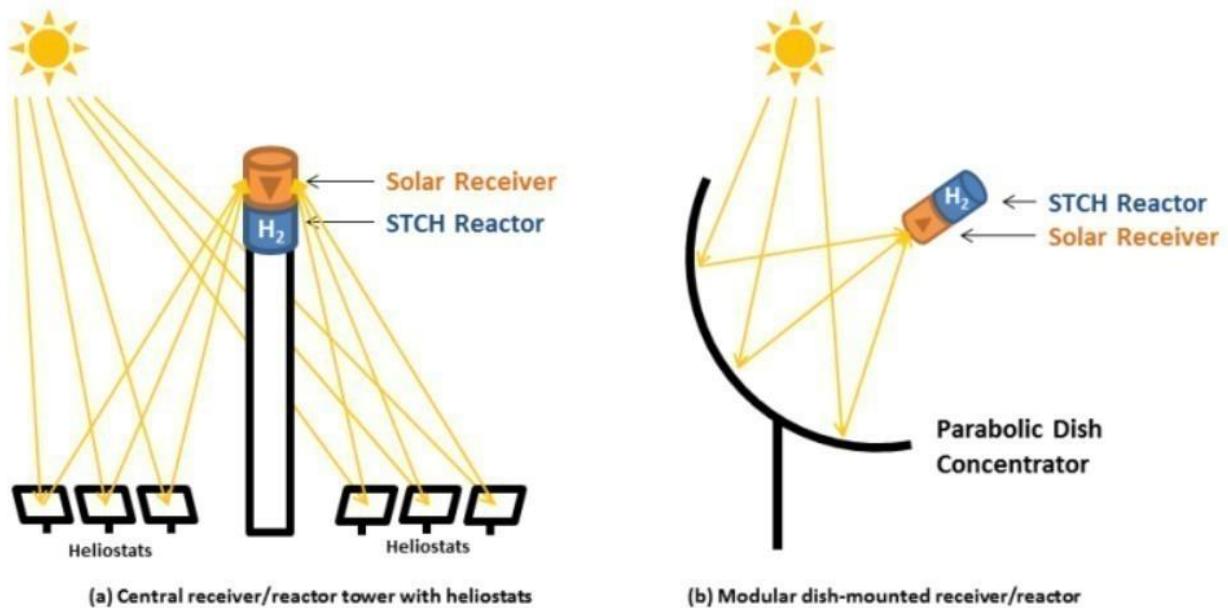


Figure 23 - High Temperature two-step processes

Solar Thermo Chemical Hydrogen reactor using the heat coming from the solar receiver to produce hydrogen in a thermochemical reaction. T>1000°C.

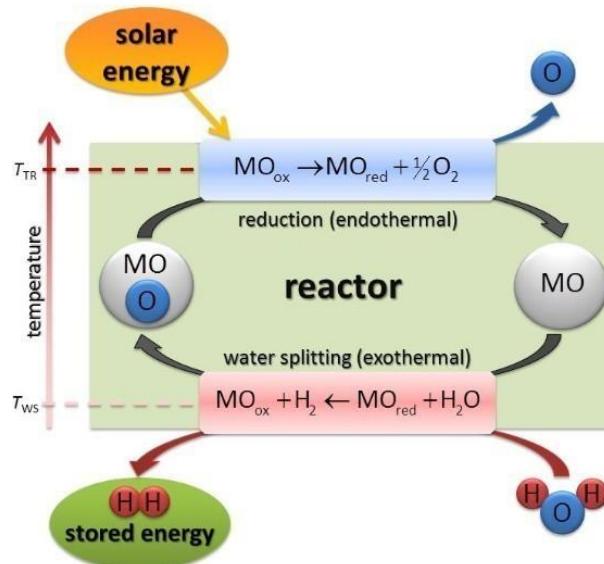


Figure 24 - Schematic representation of the two-step solar thermochemical splitting of H₂O using nonstoichiometric metal oxide redox pairs and concentrated solar energy

During the endothermal reaction, the metal oxide (MO_n) reduces to oxygen-vacant MO_{n-δ} with the evolution O₂(g) along with inert gas. In the exothermal step, MO_{n-δ} takes back oxide ions from H₂O and goes back to initial MO_n for cycling with the evolution of H₂(g).

In the thermochemical water splitting technology the sunlight is indirectly converted into chemical products.

In the **upstream** phase of the thermochemical water splitting value chain, solar radiation as primary energy source, concentrated solar radiation from mirrors as secondary energy source, water for Hydrogen generation and CO₂ for higher synthetic hydrocarbon fuels are identified. The required materials and their processes into electrolyser components like redox material and redox absorber are developed on industrial scale in TRL 5-7. The high reflective mirrors required for this technology are identified with technology readiness level 7-9.

The land use needs for this technology is rather extensive because of the concentrated light needed for the electrolyser is produced either by mirror fields or parabolic dish mirrors. For this reason, the thermochemical water splitting technology is predicted to find its application in centralized approaches, because it is highly dependent from low-cost secondary energy sources like concentrated light generated by highly reflective mirrors.

In the **intermediate** phase of the thermochemical water splitting value chain, differentiation need to be made between Hydrogen and hydrocarbon solar fuels. For the case of thermochemical water splitting generating hydrogen, this chemical can be used directly as fuel in hydrogen fuel cells for traffic applications (e.g. cars, busses, trucks, folk lifter, etc), mixed to a certain percentage into the existing gas grid (the exact injection amount is still under discussion and can vary between different countries), act as seasonal storage for gas turbines (re-electrification), be converted into NH₃ using the Haber-Bosch process or liquified for transport in ships or pipelines. If hydrogen is used as an energy vector it can be used to react with CO₂ using the Fischer-Tropsch process to generate hydrocarbon solar fuels.

In a **downstream** phase of the thermochemical water splitting value chain the end-users of the produced solar fuels are either distributed in a localised grid to act for industrial and private sectors as industrial feedstock or for residential use (heating, cooling, electricity) or feeding refuelling stations and fuel cells for application in transport like personal cars, heavy commercial vehicles or trains.

Table 8 – Thermochemical pathway - Metal Oxide Reactor - Estimated TRL for each technology component

Pathway/Technology	Technology component	TRL
Thermochemical (Metal Oxide Reactor)	Mirrors	7-9
	Redox material	5-7
	Reactor absorber	5-7

1.1.3. Biochemical pathway

The biochemical pathway includes technologies and value chains entailing the use of living organisms to produce solar fuels. In this framework, two different concepts have been included in the study: biohybrid system (also called 'bionic leaf') and microalgae-based system.

1.1.3.1. Biohybrid system

One of the latest developments in the framework of artificial photosynthesis is represented by the so-called 'biohybrid system' (or 'bionic leaf'). This technology, which has been implemented at very low TRL so far (TRL 2-3), mainly consists in the coupling of chemical and biochemical catalysis able to convert water (through electrolysis) and carbon dioxide (through metabolic pathways) into e.g. alcohols such as isopropanol, isobutanol and isopentanol, by realising oxygen as co-product.

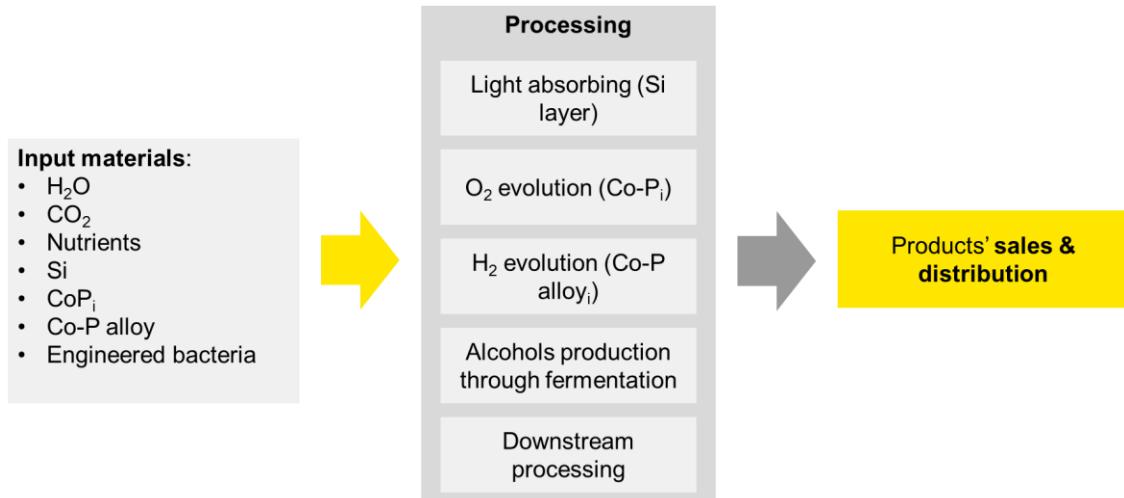


Figure 25 - Simplified scheme of value chain based on biohybrid system to produce solar fuels

The main **upstream** technologies and materials mainly consist in light absorption through photosensitive materials, materials for the electrolysis cell (cathode, anode, etc), as well as components related to the 'bio' part of the system, including engineered bacteria. One of the possible configurations of the system mainly entails a silicon layer as sunlight absorber, while a cobalt phosphate (CoP_i) catalyst and a Co-P alloy catalyst act respectively as anode and cathode to perform H₂O electrolysis and obtain H₂ and O₂. Then, a layer of engineered bacteria (e.g. Ralstonia eutropha) converts the hydrogen into alcohols, i.e. the targeted biofuels.

It is worth considering that in case a different bacteria strain is used, a different product can be obtained: it is the case, for example, of Xanthobacter autotrophicus, able to convert nitrogen (coming e.g. from the air) into ammonia. However, the latter concept is still under development at a very low scale (TRL 2).

Several technological concepts are linked to the **upstream** phase. Concerning the materials to be used as light absorber, the objective is to identify less critical materials and increase their durability and light harvesting efficiency, by also enlarging the light spectrum utilisation. The engineering of the bacteria used to convert the reducing equivalents (electrons or hydrogen) into the targeted biofuels should also benefit from the technological and research developments in this field, including synthetic biology: in particular, the investigation of enhanced metabolic pathways and enzymes can represent a factor able to effectively foster the implementation and exploitation of such technology at higher scales.

Some other aspects that should be considered in the framework of upstream processing are mainly linked to the production of the nutrients/fertilizers needed for growing the bacteria: indeed, such processes usually entail non-negligible resource requirements in terms of energy and water. Therefore, the identification and the potential usage of nutrients' sources at lower costs is one of the main factors to be taken into account within the implementation of biohybrid systems value chains.

Concerning the CO₂ usage, effective carbon capture technologies should be applied to increase the availability of this compound to the biohybrid system. Important advantages are indeed associated with the biohybrid systems, which are able to exploit CO₂ and convert it into targeted compounds, with subsequent benefits in terms of reduction of greenhouse gases emissions. The latter aspect is particularly significant in case flue gases are utilised, even though the logistics linked to the CO₂ supply are to be properly taken into account (transportation, proximity to the industrial plant from which the flue gas is originated, etc).

From the **land use's** perspective, no particular constraints are associated with the biohybrid system if we consider the reactor itself because of the high potential to pursue an effective compact design, including both the photoelectrochemical and the biological

section. However, considering the sunlight requirements and the need of nutrients and CO₂, the siting of the potential plant has to be properly identified.

The **intermediate and downstream** infrastructures are mainly related to the targeted biofuels, which can vary according to the specific bacteria strain that is used. Most of the applications, even though they are currently deployed at very low TRL, seem to focus on bioalcohols. However, while methanol, ethanol and butanol can be used in petrol engines, normally propanol is not employed as direct fuel source. Along with its employment as solvent, propanol is in some cases utilised in fuel cells as hydrogen source, even though methanol is still the most preferred alcohol in such applications.

As further described in the following chapter on microalgae-based value chain, one of the main advantages of such solar (bio)fuels is linked to the fact that, being liquid fuels, they do not require any specific actions to the current state-of-the-art automotive engine technologies, as well as they are compatible with the existing distribution infrastructures

The table below summarise the current TRL of the analysed technology components of biohybrid system (bionic leaf) technology.

Table 9 – Biochemical pathway - Biohybrid system - Estimated TRL for each technology components

Pathway/Technology	Technology component	TRL ^{22,23,24,25,26}
Biochemical (biohybrid system)	Light absorber	2- 3
	Anode	2- 3
	Cathode	2- 3
	Engineered bacteria	2- 3

1.1.3.2. Microalgae

Another biochemical concept mainly consists in the use of phototrophic microorganisms such as microalgae and cyanobacteria, which can exploit (solar) light as energy source and carbon dioxide as main carbon source.

In the present study, microalgae-based value chains have been selected as reference to describe biochemical pathways and identify the main advancements in this field along with the main techno-economic issues still preventing the implementation of such solutions at higher scales.

A plethora of biofuels can be obtained through biochemical pathways including among others: hydrogen, biogas and syngas, methane, ethanol, biodiesel, other alcohols. Bio-

²² Chartier, O., Baker, P., Oberč, B. P., de Jong, H., Yagafarova, A., Styring, P., Bye, and J., Janssen, R., Raschka, A., Carus, M., Evangelopoulou, S., Zazias, G., Petropoulos, A., Capros, P., & Zakkour, P. (2016). Artificial photosynthesis: potential and reality (Issue November).

²³ Liu, Chong, Sakimoto, K. K., Colón, B. C., Silver, P. A., & Nocera, D. G. (2017). Ambient nitrogen reduction cycle using a hybrid inorganic–biological system. Proceedings of the National Academy of Sciences, 114(25), 6450–6455. <https://doi.org/10.1073/pnas.1706371114>.

²⁴ Khajuria, A., & Kotwal, H. (2018). Bionic Generation : A New Approach To Power Generation. International Journal of Computational Engineering Research (IJCER), 8(7), 20–24.

²⁵ SUNRISE Technological Roadmap, February 2020.

²⁶ Nørskov, J. K., Latimer, A., & Dickens, C. F. (2019). Research needs towards sustainable production of fuels and chemicals. Energy-X project roadmap.

based value chains, i.e. value chains entailing the utilisation of biomass, are often very complex. A typical microalgae-based value chain is reported in Figure 26 below.

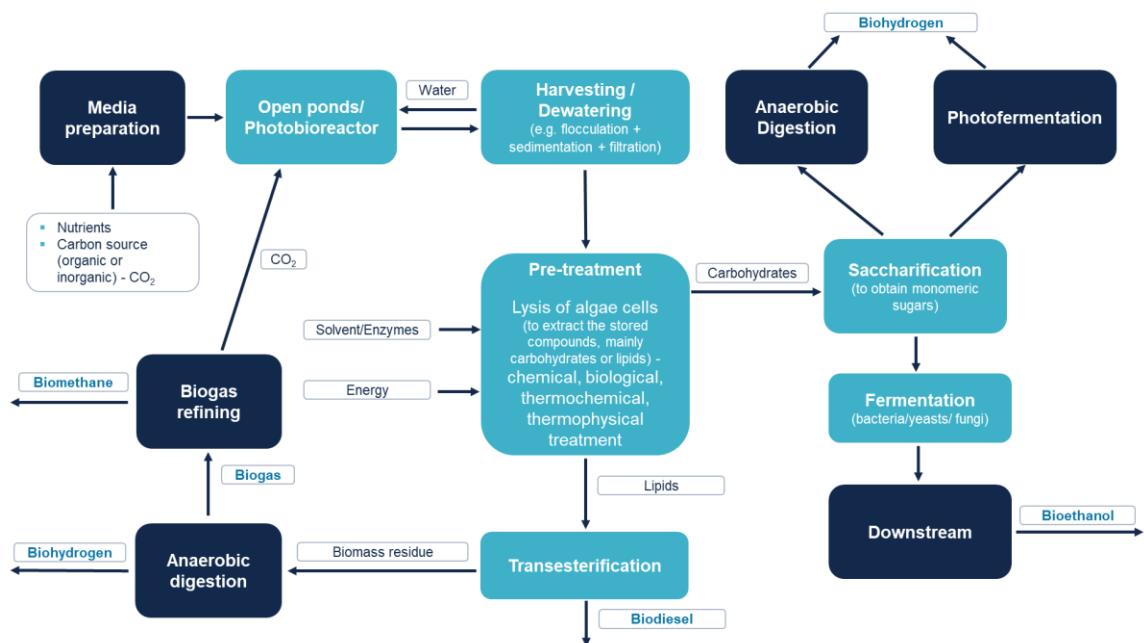


Figure 26 - Example of microalgae-based value chain with biofuels that can be potentially obtained

The technological steps reported are summarised as presented in Figure 27 below.

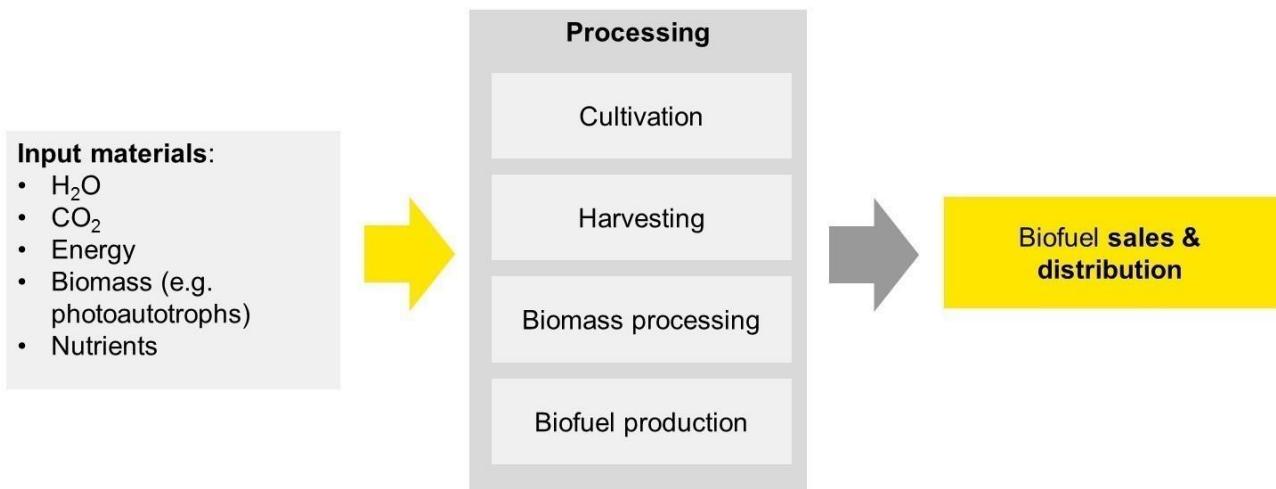


Figure 27 - Simplified scheme of value chain based on microalgae to produce solar fuels

The estimated TRL, as reported in literature, of the main components are reported in Table 10 below.

Concerning the **upstream** phase, most of the technologies and materials are focused on the effective supply of nutrients, water and CO₂ for the microalgae cultivation step. A relevant amount of nutrients (both macro- and micro-nutrients) are required for cultivating algae: therefore, the identification of low-cost and sustainable sources of nutrients is important. In this framework, wastewater plant or anaerobic digestion systems can be included in the upstream phase of microalgal value chains. Similarly, the use of non-competing water sources (such as wastewaters, brackish or seawater), with related infrastructures, can significantly increase the sustainability and feasibility of large-scale cultivation of microalgae towards biofuels.

Other upstream technologies are then linked to the CO₂: considering that microalgae require CO₂ to grow, with the subsequent potential benefits in terms of reduction of GHG emissions, the identification of sustainable CO₂ sources is required. In case of CO₂ from flue gases is targeted, it should be taken into account that, unless microalgae strains are used that are able to tolerate gaseous components other than CO₂, the separation and purification of CO₂ from the bulk gas is often an energy-intensive process.

Materials and technologies aiming to effectively distribute nutrients, light and CO₂ within the microalgae culture are to be considered as relevant components for the cultivation phase.

In terms of **land use**, microalgal cultivation presents the potential to be implemented in non-arable, or even marginal lands, without directly competing with food production chain or other agro-forestry feedstocks. Land use is indeed strictly related to the configurations chosen for the cultivation step, i.e. open ponds and closed photobioreactors. Moreover, the identification of the site where microalgal plants should be established can depend on several factors, such as: sunlight exposure, proximity to the target sources for water, nutrients and CO₂, logistics and infrastructures-related aspects²⁷.

In addition, it is worth considering that land use, as well as upstream processes, can be further influenced by the potential application of more complex design and plant configuration, able to integrate recycling and circular economy concepts in order to reduce the resource requirements in terms of energy and/or raw materials. In this framework, several opportunities exist, depending also on the targeted biofuels and downstream processes: nutrients recycling from anaerobic digestion of residual biomass, water recycling from dewatering and drying steps, biogas (from anaerobic digestion) usage for thermal or electric energy production, CO₂ recycling through biogas refining.

Concerning **intermediate and downstream** infrastructures, they mainly depend on the targeted biofuels. In the case of bioethanol, it can be blended with gasoline and different mixtures can be identified according to the percentage of bioethanol in the overall blended fuel: E10 and E85, for example, respectively identify gasoline mixed with 10% and 85% of bioethanol by volume. A similar situation can be seen for the biodiesel, which can be blended with conventional diesel fuel, by originating diesel blends according to the different percentages of biodiesel used (e.g. B7 and B20, with 7% and 20% of biodiesel by volume, respectively).

In particular, fuel blends with low percentages of biofuel (e.g. E10 or B7) do not require any specific amendments to fuel infrastructures, being they suitable for conventional engines. However, the large-scale implementation of biofuels into e.g. internal combustion engines has been up to now partially hindered by the sustainability constraints associated with first generation biofuels and their potential direct or indirect (e.g. Indirect Land Use Change²⁸) competition with food, thus moving the focus on alternative solutions such as fully electric or hydrogen-fuelled vehicles: in this framework, microalgae-based biofuels (also called 'third generation' biofuels) can foster the market deployment of biofuels and the introduction of blended fuels with higher 'bio' content (e.g. E85).

In terms of storage and distribution, the fact that bioethanol and biodiesel are liquid fuels just like gasoline and conventional diesel implies that the existing downstream infrastructures can be maintained and utilised: this is a relevant aspect that should be considered when comparing liquid solar fuels to alternative solutions entailing e.g. installation of fuel cells or batteries.

²⁷ Coleman, A. M., Wigmosta, M. S., Hellwinckel, C. M., Brandt, C. C., Langholtz, M. H., & Eaton, L. M. (2016). Potential land competition between open-pond microalgae production and terrestrial dedicated feedstock supply systems in the U.S. *Renewable Energy*, 93, 201-214.

²⁸ https://ec.europa.eu/commission/presscorner/detail/en/MEMO_19_1656

While in Europe, the standard biofuel at petrol stations is E10 fuel, fuel blends with higher-ethanol content (E85) are already available in some countries, including United States. Moreover, flexible-fuel vehicles able to exploit more than one kind of fuel represent another design solution to boost the usage of fuel blends with higher content in terms of biofuels²⁹.

Table 10 – Biochemical pathway - Microalgae - Estimated TRL for each technology components

Pathway/Technology	Technology component	TRL ^{30,31,32,33,34}
Biochemical/microalgae	Media preparation	7-8
	CO ₂ storage	7-8
	Open pond/Photobioreactor	6
	Light harvester and sparger	5
	Mixing/recirculation system	7
	Microalgae harvesting and dewatering	7
	Biofuel extraction (e.g. algal biomass pre-treatment, saccharification, fermentation)	6
	Products from microalgae: purification	6

The main technological steps are described as follows:

Cultivation

Through this process microalgae exploits light, e.g. sunlight, as energy source to convert water and CO₂ into biomass components, such as carbohydrates and lipids. To foster an effective growth of the microorganisms, a specific medium culture is required. Indeed, along with water and carbon dioxide, microalgae also need specific nutrients for growing,

²⁹ Bonenkamp, T. B., Middelburg, L. M., Hosli, M. O., & Wolffenduttel, R. F. (2020). From bioethanol containing fuels towards a fuel economy that includes methanol derived from renewable sources and the impact on European Union decision-making on transition pathways. Renewable and Sustainable Energy Reviews, 120, 109667.

³⁰ Chartier, O., Baker, P., Oberč, B. P., de Jong, H., Yagafarova, A., Styring, P., Bye, and J., Janssen, R., Raschka, A., Carus, M., Evangelopoulou, S., Zazias, G., Petropoulos, A., Capros, P., & Zakkour, P. (2016). Artificial photosynthesis: potential and reality (Issue November).

³¹ Ruiz, J., Olivieri, G., de Vree, J., Bosma, R., Willems, P., Reith, J. H., Eppink, M. H. M., Kleinergis, D. M. M., Wijffels, R. H., & Barbosa, M. J. (2016). Towards industrial products from microalgae. Energy Environmental Science, 9, 3036-3043.

³² Khan, M. I., Shin, J. H., & Kim, J. D. (2018). The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. Microbial Cell Factories, 17 (36), 1-21.

³³ SUNRISE Technological Roadmap, February 2020.

³⁴ Nørskov, J. K., Latimer, A., & Dickens, C. F. (2019). Research needs towards sustainable production of fuels and chemicals. Energy-X project roadmap.

mainly nitrogen and phosphorus. Other nutrients required are the macronutrients Na, Mg, Ca and K, and the micronutrients Fe, Mo, Mn, B, Co and Zn.

Along with nutrients requirement and availability, several other factors can affect microalgae culturing and the subsequent biomass yields: temperature, pH, salinity, oxygen, light intensity, CO₂, mixing efficiency. The latter, for example, can significantly impact on the distribution of nutrients, CO₂ and air within the microalgae culture.

Currently, two main configurations are envisaged for the cultivation of microalgae: closed systems like photobioreactors (e.g. horizontal tubular PBR, flat panels PBR, bubble column PBR) and open systems like open ponds (e.g. raceway open ponds).

Depending on the cultivation system and microalgae species, freshwater, brackish water or seawater can be used for the cultivation (growth medium). In some cases even wastewater can be used (in the latter case the amount of nutrients and water required can be lowered). Main advantages or disadvantages linked to each cultivation system will be further analysed in the framework of the technology roadmap as part of this report.

Harvesting and dewatering

The scope of the harvesting phase is to separate microalgal biomass from the culture medium, mainly consisting in water and nutrients that can be recycled to the cultivation systems. In order to improve the harvesting efficiency, flocculants can be added. Typical harvesting technologies are: flocculation, centrifugation, sedimentation, filtration and flotation. According to the specific configuration envisaged, different yields can be obtained.

Once the microalgae have been harvested and separated from the culture medium, they must be dewatered: this operation is implemented by applying different drying technologies (e.g. solar drying, open sunlight, drum drying, cold drying).

Biomass processing

In this phase, the targeted compounds stored within the microalgae cells (mainly carbohydrates or lipids) are recovered: this step consists in the lysis of the cells by applying chemical, biological, thermochemical or thermophysical treatments. Energy and/or chemical solvents or enzymes can be employed to obtain sufficient yields in the targeted products.

Biofuel production

Depending on the targeted biofuels, different processing can be envisaged.

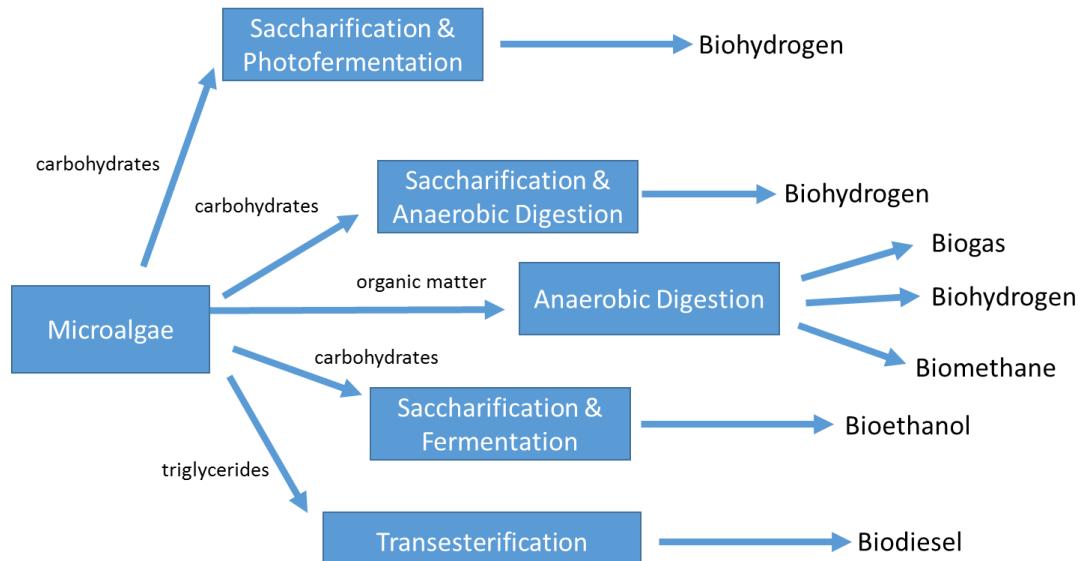


Figure 28 - Biofuels production from microalgae

As shown in the Figure 28 above, different biofuels can be potentially derived from microalgal biomass and its metabolic compounds: biodiesel, bioethanol, biohydrogen, biogas (to be potentially refined to biomethane). Apart from the technology used, each biofuel production process mainly differs from the others depending on the starting material used: it can be the carbohydrate fraction, the lipid fraction (triglycerides) or even organic matter like 'spent cells'.

Thus, the main focus of the biochemical pathway has been put on bioethanol and biodiesel, provided they are the most promising biofuels that can be obtained in a sustainable and feasible way from microalgae. Indeed, microalgae does not allow for the large production of biohydrogen and other technologies can produce hydrogen more efficiently. Moreover, bioethanol production can be made more sustainable and feasible if kept in combination with the production of biodiesel and/or other added-value products (e.g. ingredients for food/feed, nutraceuticals, cosmetics).

Furthermore, while bioethanol is already produced at commercial scale starting from first- and second-generation biomasses, microalgae-derived bioethanol (so-called 'third generation bioethanol') is still to be efficiently deployed at relevant scale, although the advantages of such value chains in terms of e.g. land use, no competition with food chain and the potential to use wastewater streams as raw materials for algae cultivation and growing.

Along with bioethanol and biodiesel, biogas or biomethane could be also analysed as a potential by-product derived from residual streams valorisation (such as the 'spent algal biomass' or died cells derived from the fermentation step). Indeed, such 'additional' biofuels can represent a valuable means to optimise and increase the environmental and economic sustainability of the overall value chains, by applying cascading and circular economy approaches and reducing waste streams and energy inputs to the processes.

Finally, it is worth highlighting that the current selection of biofuels has been discussed and validated by stakeholders during the workshops, in order to ensure focus on the most relevant and promising bio-based solar fuels.

1.2. Solar Fuel Value Chain analysis: Key findings

The aim of the value chain analysis is to provide an overview of the current cost components of the solar fuel technologies analysed as part of the study. The groundworks of this analysis was laid out in the methodology section, presenting the structure of our LCOE economic model, used as basis for the value chain analysis. The results of the LCOE model in defining solar fuel value chain analyses are therefore discussed in this section. The analysis is structured by solar fuel. It is important to revisit Figure 1 on the LCOE model mechanics while examining the value chain charts. We refer to our work in Power BI for further analysis as this report covers the base case scenario: Europe region, normal input/assumptions range and input energy from solar PV. The results for Europe are presented in this section.

1.2.1. Hydrogen

The hydrogen value chains covered here are the chains being enabled by the Electrochemical, Thermochemical and Chemical pathways. Specifically, these pathways are being realised in this analysis by the AEC, PEMEC, SOEC, PEC and Artificial Leaf technologies. Regarding PEC, given its low TRL, the technology was modelled from 2050 onwards when clear developments are expected to occur. For this reason the technology's current value chain will not be analysed as part of this report but will be considered from 2050 onwards in the subsequent economic roadmap report of this study. Similarly, the Artificial Leaf was not modelled due to the technology's low TRL and resulting lack of input data.

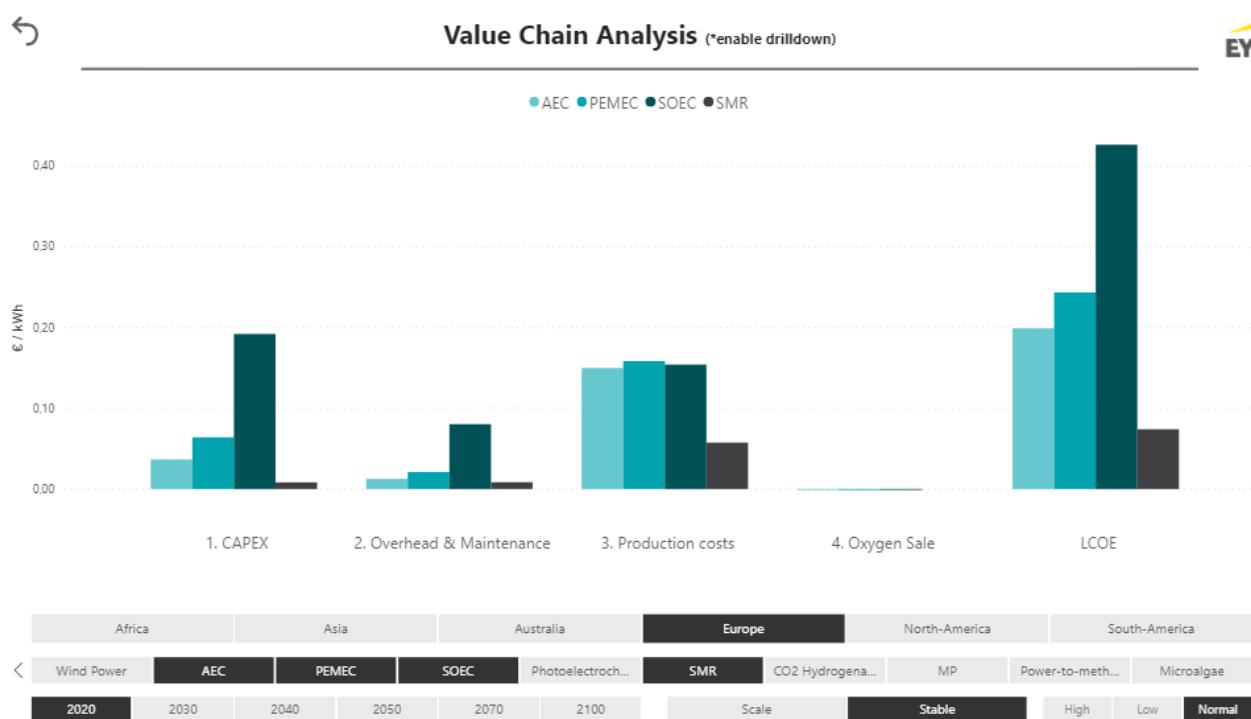


Figure 29 - Electro- and Thermochemical pathway VCA 2020

Figure 29 shows the value chain analysis of the electrochemical and thermochemical solar fuel technologies. The chart shows that the value performance of the electrolyser technologies is heavily dependent on the production costs. For SOEC, CAPEX represents a major cost in the technology's value chain, almost three times as high as PEMEC and 4,75 times as high as AEC. Currently, electrolyser technologies face both a strong CAPEX and production cost disadvantage compared to fossil-based SMR. We can also observe that cost recuperation through the sale of oxygen is found to be negligible for all technologies. The overall LCOE for these technologies is representative of the cost decomposition achieved

in this value chain analysis: SMR still benefits from a strong cost advantage compared to the three electrolyser technologies.

The following Figure 30 allows us to drill down on the production costs.

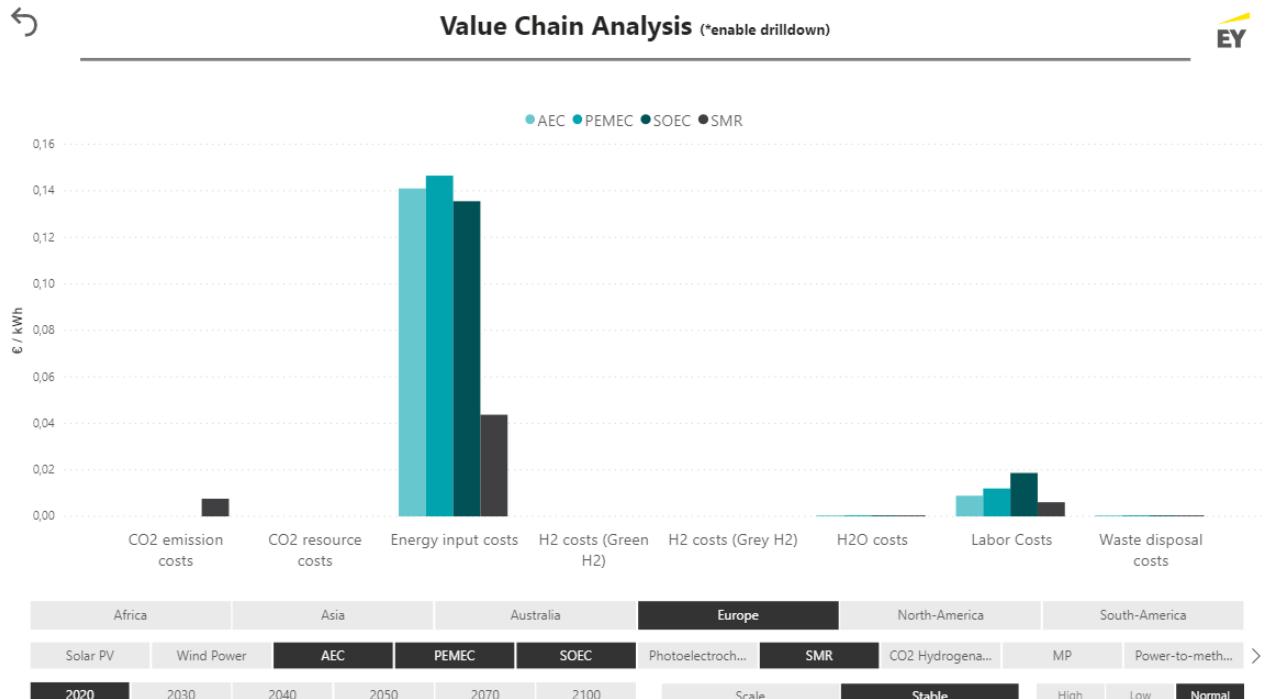


Figure 30 - Electro- and Thermochemical pathway production costs detail VCA 2020

This figure highlights the importance of the energy input costs as part of the total production cost of hydrogen technologies. For SMR, these energy input costs are comprised of the cost of natural gas and conventional electricity, with the latter to a small degree. The other technologies solely depend on the costs of solar PV, which is in fact the bottom line LCOE of that technology. Once again, Figure 1 on the model mechanics highlights this relationship. We can also observe on this graph the CO₂ emission costs of the SMR technology in the column to the far left. Although currently representing a small portion of the total costs of the technology, it remains an important one equalling the technology's labour costs. With that said, the left-most column does not capture all the underlying CO₂ emission costs as non-visible emission cost are part of the conventional electricity price, although to a small degree.

1.2.2. Methanol

The methanol value chains considered in this study are the chains being enabled by the CO₂ hydrogenation and MP technologies. The two technologies are in fact the same, apart from the fact that the CO₂ hydrogenation technology uses hydrogen produced by PEMEC technology (green). MP, on the other hand, uses hydrogen produced by the SMR process (grey). Figure 31 presents the value chain analysis of the hydrogenation technologies.



Value Chain Analysis (*enable drilldown)

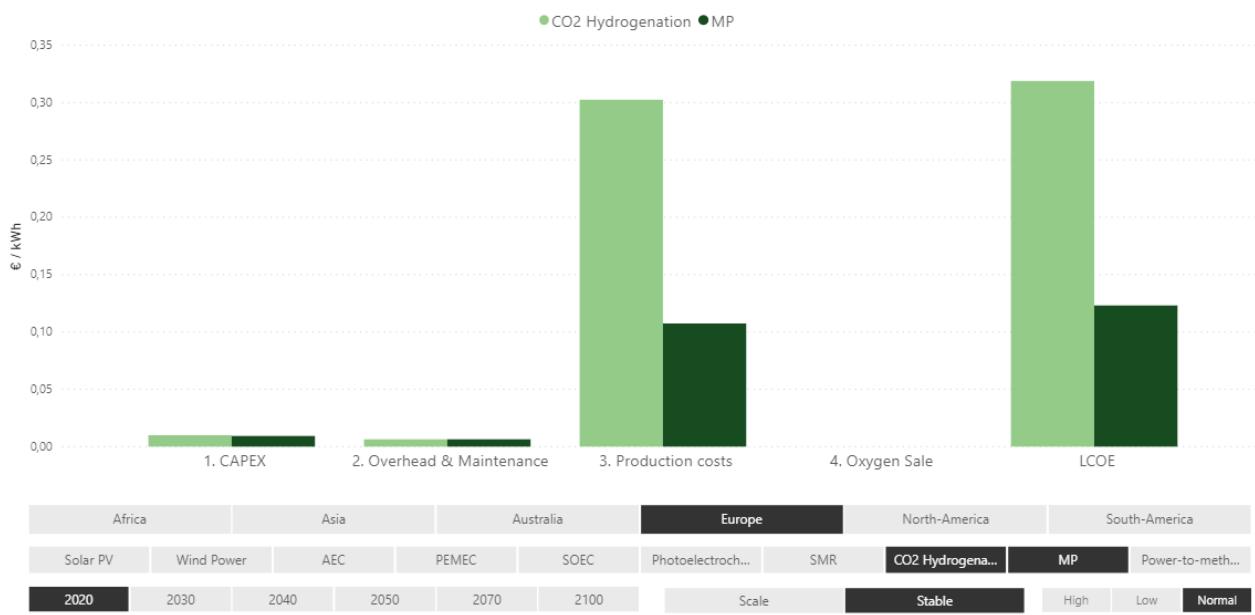


Figure 31 - Hydrogenation pathway VCA 2020

As was the case with the hydrogen value chains, the production costs are also the most significant cost driver of the methanol value chains. This is due to the fact that the LCOE of the former is captured in the production costs of these two methanol value chains. With respect to CAPEX and overhead and maintenance expenses, the simulation shows that they represent a relatively small portion of the total value chain costs. This is a natural outcome given the high maturity level of these methanol technologies.



Value Chain Analysis (*enable drilldown)

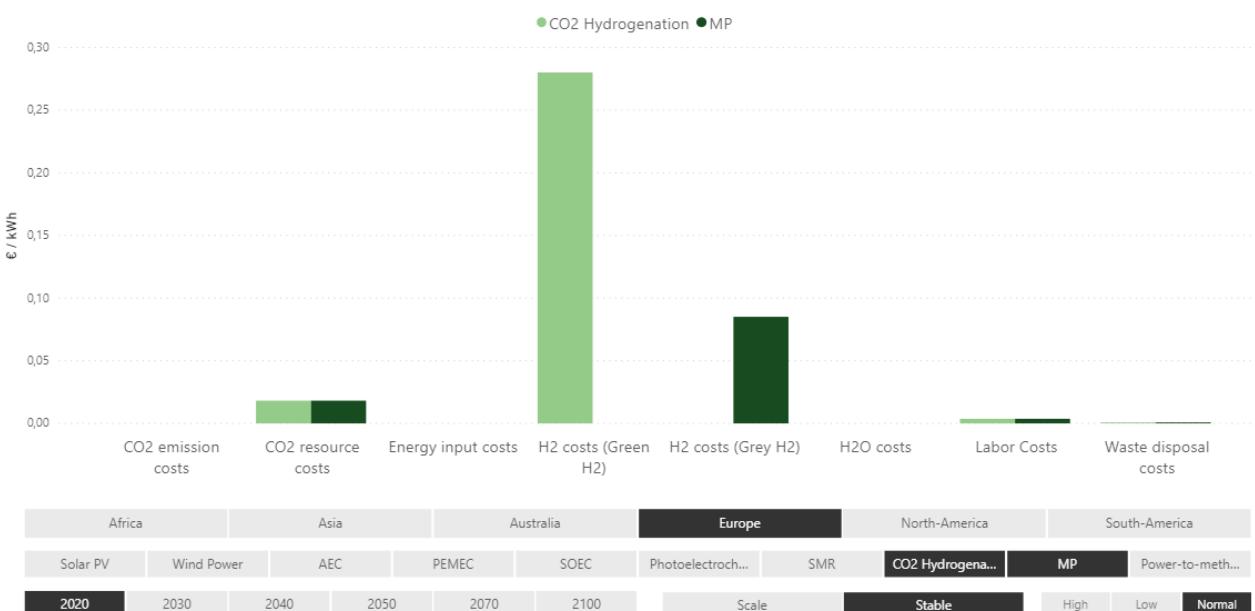


Figure 32 - Hydrogenation pathway production costs detail VCA 2020

Taking a more detailed view on these production costs, we can observe their correlation with the hydrogen value chains. Hydrogen costs, being the total value chain cost of a hydrogen technology, serves as input to this value chain (Figure 1). We document that

currently, the fossil-based value chain still has the upper hand in light of cost efficiency. However, the green technology is trailing by only a small margin.

Compared to the hydrogen technology, the methanol value chain is at a cost disadvantage. In practice, however, methanol remains a more workable fuel than hydrogen. The latter being highly volatile and susceptible to leakage issues in distribution/transportation. Additionally, methanol does not need to be pressurized.

1.2.3. Ethanol

The technology considered regarding the ethanol solar fuel is the microalgae technology. As comparables to this bio-ethanol technology are not covered within the scope of this study, this value chain analysis will focus on the microalgae technology. Consequently, a single waterfall chart presented below allows to directly observe a complete overview of the whole value chain, including a detailed production cost overview.

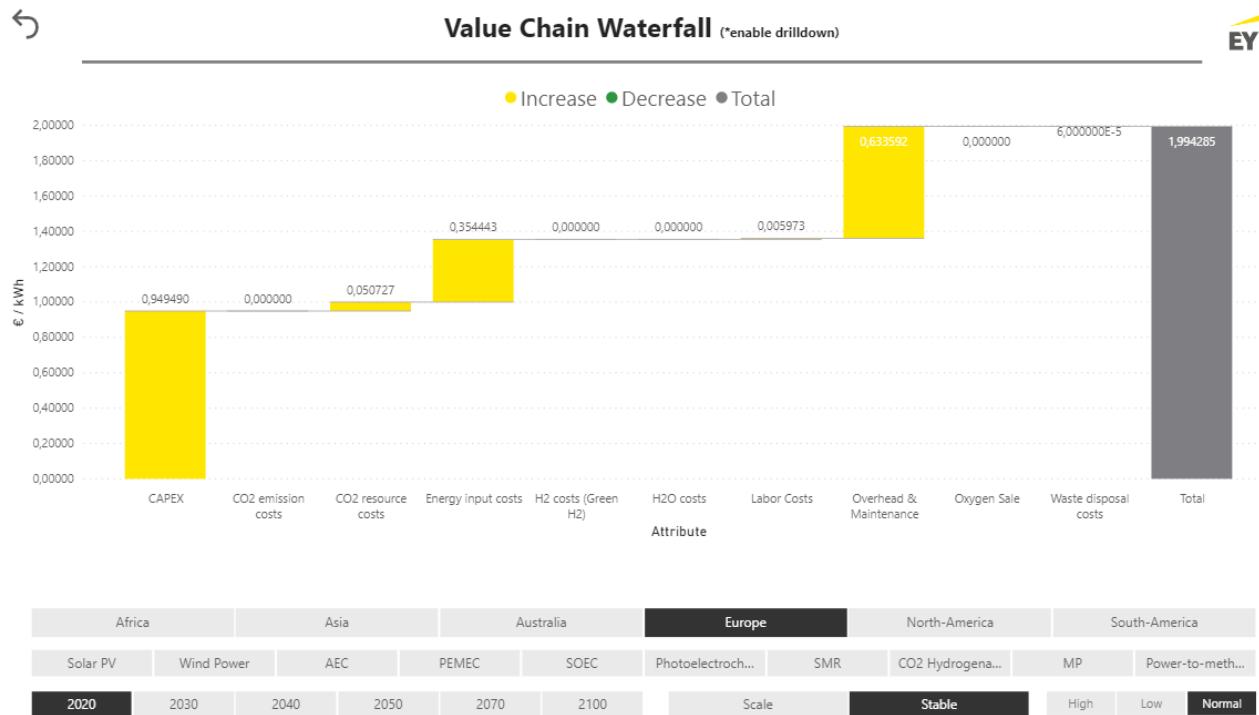


Figure 33 - Biochemical pathway VCA 2020

The current value chain waterfall confirms the fact that the microalgae technology is still in early development. Indeed, the technology's value chain is largely driven by important CAPEX and related fixed overhead & maintenance cost drivers. The latter, in particular, is relatively significant compared to other solar fuel value chains because of the inherent characteristic of microalgae requiring constant tending to. In addition, the organic and watery environment puts the equipment under heavy strain. CAPEX on the other hand is substantial because of the inefficiency of the organic system in producing ethanol. Extensive production area and sufficient time is required to obtain a tangible amount of energy output of microalgae's bio-ethanol. This results in a high CAPEX costs per kW of installed plant capacity.

1.2.4. Methane

Within the scope of this study, power-to-methane is the sole technology considered in the methane solar fuel value chain. Nevertheless, a comparable is present in this case: natural gas or CH₄. Power-to-methane is unlikely to become more cost advantageous than CH₄ in the short term, as it involves more process nodes, thus inefficiencies. However, if natural gas availability was to reduce and to require large surface research costs to find and tap into new sources, the power-to-methane process could be a viable alternative.



Value Chain Waterfall (*enable drilldown)



Figure 34 - Methanation pathway VCA 2020

Similar to the green methanol value chain, the methane value chain is assumed in this study to be dependent on the green hydrogen obtained from the PEMEC electrolyser technology (Figure 1). Therefore, aside from energy input efficiency discrepancies, the H₂ costs are comparable between the CO₂ hydrogenation technology and the power-to-methane technology. We document that the hydrogen to methane conversion process is mature, with CAPEX and overhead & maintenance expenses having a small impact on the total value chain costs.

1.2.5. LCOE for all technologies

The analysis of all technologies' current LCOE provides a summarized picture of the decomposed value chain analyses that were presented above per fuel. Looking at the LCOE in this manner allows us to draw a comparison between all technologies regardless of the fuel produced. In this context, Figure 35 presents the LCOE of all technologies for 2020.

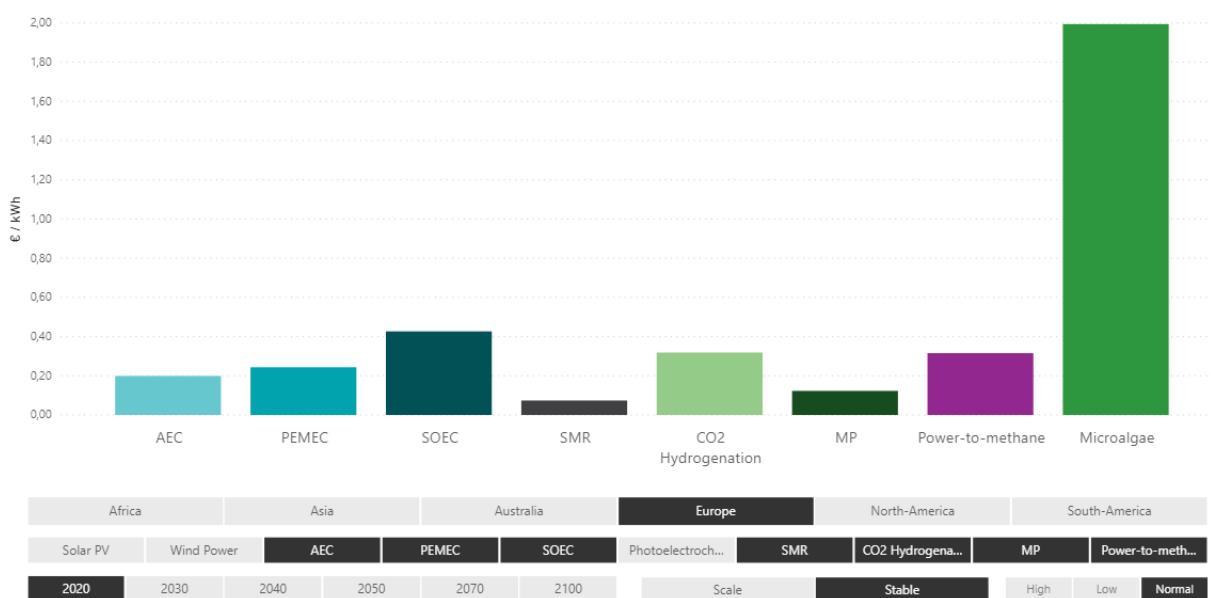


Figure 35 – LCOE for all technologies 2020

One key takeaway from the figure is the current cost advantage of fossil-based technologies against their green counterparts. Indeed, SMR and MP still benefit from the lowest LCOE compared to AEC, PEMEC, SOEC, CO₂ Hydrogenation and power-to-methane. The graph is highly reflective of the maturity of the technologies: AEC and PEMEC as high TRL technologies benefit from a cost advantage amongst the green technologies while microalgae is characterised by a substantially higher LCOE due to the experimental nature of the technology. From this analysis, we can deduct that AEC currently is the most competitive solar fuel technology from a cost perspective. It benefits from an LCOE advantage followed by PEMEC, power-to-methane and CO₂ hydrogenation.

The following figure provides a summary and conclusion to the value chain and LCOE analyses covered in this report, by outlining the LCOE composition of all technologies for 2020.

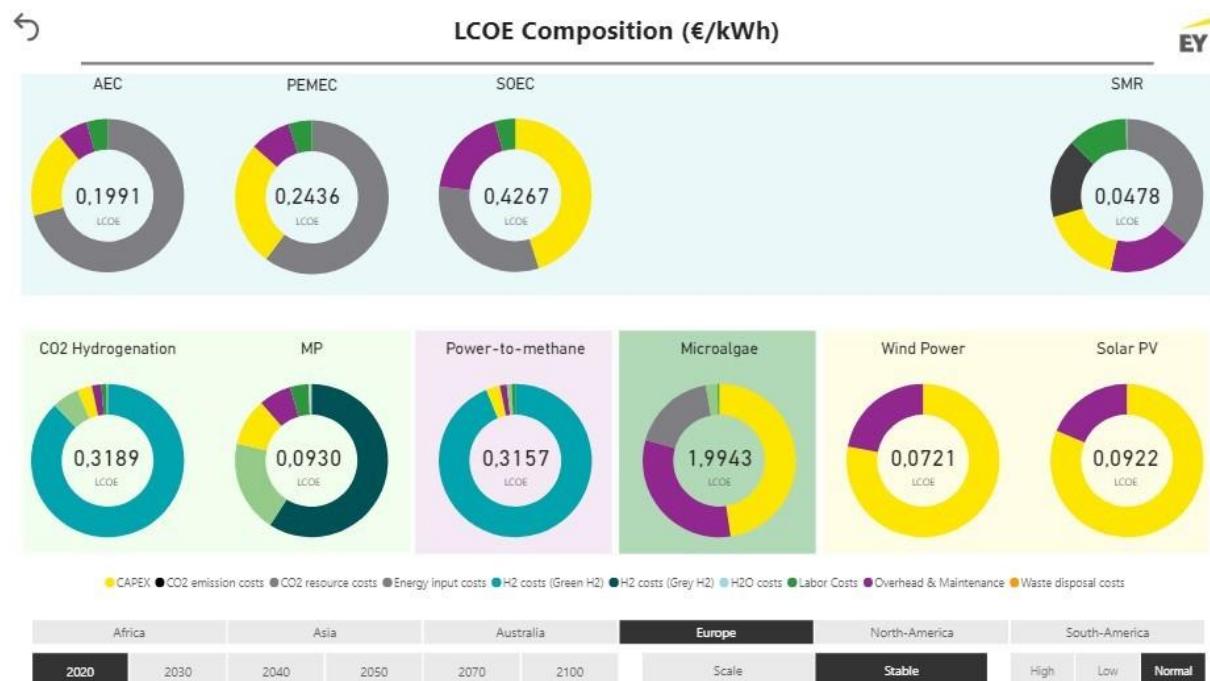


Figure 36 – LCOE composition for 2020 – all technologies

Figure 36 highlights that production costs and most specifically energy input costs are key drivers of the hydrogen system technologies' LCOE, namely AEC, PEMEC, SOEC and SMR. We can observe the high share of CO₂ emission costs of the SMR technology relative to its green counterparts. CO₂ hydrogenation and power-to-methane display high green hydrogen input costs, as they rely on the H₂ produced from the hydrogen system technologies. In contrast, the MP technology incurs high costs for grey hydrogen. For energy sources, both wind power and solar PV have high CAPEX due to the capital intensive nature of the technologies. Similarly, microalgae faces high a CAPEX as well as high overhead and maintenance costs, which largely reflects the low maturity of the technology.

To conclude, this section provided an assessment of solar fuel value chains and LCOE analysis for all studied technologies for Europe in 2020. The full results of the value chain and LCOE analysis taking into account the various regions and ranges covered by our model are accessible in the study's dedicated PowerBI. The forward-looking value chain and LCOE estimations are presented in section 2.2 of this study, looking at LCOE results for all technologies through 2100.

1.3. Conclusion

This chapter has presented key solar fuel value chains through four specific production pathways: Chemical, Electrochemical, Thermochemical and Biochemical. For each technological pathway, the main technological components associated with their fuel production processes were firstly outlined in a qualitative manner. It identified the various raw materials and resources needed for each technology to produce a specific solar fuel. This categorisation was conducted for the following pathways and technologies:

- ▶ Electrochemical pathway: AEC, PEMEC, PEC, SOEC
- ▶ Thermochemical pathway: Solar Thermo Chemical reactor
- ▶ Chemical pathway: Artificial Photosynthesis (Artificial Leaf)
- ▶ Biochemical pathway: Biohybrid system (Bionic Leaf), Microalgae

The aim of this qualitative analysis and selection was to focus on the most relevant value chains in terms of their potential for technological and economic improvements. It provided the basis for the economic and quantitative analysis of the technologies' value chains. The quantitative analysis included additional promising technologies which were covered under the Hydrogenation and Methanation pathways. The value chain analysis was performed based on a Levelized Cost of Energy ("LCOE") economic modelling exercise, decomposing the LCOE variables into a set of value chain components including capital expenditures ("CAPEX"), overhead and maintenance, production costs including labour and energy input costs, and considering the valorisation of certain by-products. The analysis was carried out for the year 2020 and per fuel, for example looking at all relevant technologies producing hydrogen, and allowed for the comparison of green solar technologies against their fossil-based counterparts.

The analysis revealed that production costs, comprising primarily energy input costs, are the key driver of technologies' current LCOE in most pathways, namely Electrochemical, Thermochemical, Hydrogenation and Methanation. The energy inputs to the Electrochemical and Thermochemical pathways consist in electricity derived from solar PV, whose costs themselves are primarily driven by CAPEX. The capital expenditures for solar PV are therefore embodied in the costs of green hydrogen produced through the Electrochemical and Thermochemical pathways, and end up determining a substantial portion, up to 60 percent, of the costs of green hydrogen. The costs of green hydrogen represent 87 percent and 93 percent of the LCOE for fuels produced through the Hydrogenation and Methanation pathways in 2020, respectively, thereby implying that the capital expenditures for solar PV are indirectly responsible for over half of the LCOE for solar fuels produced through the Hydrogenation and Methanation pathways.

CAPEX is the highest cost component for SOEC and mainly for microalgae, reflecting the low maturity level of both technologies. In this context, microalgae also experiences high overhead and maintenance costs, reflecting its given the technology's experimental nature.

One clear observation emanating from the value chain and LCOE analysis is the cost advantage that fossil fuel technologies, including steam methane reforming and the methanol process, benefit from compared to their green counterparts. Another key takeaway is that the current cost of solar fuels is mostly driven by the high CAPEX associated with solar PV, despite significant cost reductions in the past decade. Therefore, achieving low cost solar PV is a key objective for making solar fuels competitive.

This analysis has therefore provided a snapshot of the current state of the studied technologies' value chains, in the form of a decomposed LCOE. The LCOE model also allows for a forward-looking time-series analysis through 2100, estimating performance of the technologies over time and assessing at which point in time the green technologies could overcome the cost competitiveness of their fossil counterweights. This analysis is presented in the following section of this report, drawing a technological roadmap (for 2030 and 2060) and economic roadmap to 2100 for all studied technologies.

2. Roadmap for Solar Fuels and Market Outlook

This chapter will present our study results aiming at establishing a roadmap and outlook for solar fuels development. It will, in a first place, present our technology roadmap for solar fuels, identifying key challenges and bottlenecks in the technologies' developments. Our economic roadmap for solar fuels, assessing the cost competitiveness of the studied technologies over time will then be presented, followed by our Market Outlook for solar fuels, forecasting potential future demand for solar fuels through 2100.

2.1. Technology roadmap for solar Fuels for 2030 and 2050

2.1.1. Analysis of Mission Innovation countries' Solar Fuel Road mapping efforts

In order to develop our solar fuels technology roadmap, we have identified, reviewed and integrated roadmaps produced by Mission Innovation countries. Our research highlighted that the development of solar fuels technology roadmaps is an early stage exercise and no roadmaps specifically dedicated to solar fuels were found to have been published among Mission Innovation countries.

In Australia, the EU, Germany and the US, solar fuels roadmaps were produced mainly in the framework of green Hydrogen roadmaps. Indeed, most of the Mission Innovation member countries have developed Hydrogen roadmaps recently. These include the production of Hydrogen using:

- Large scale electrolyser powered by renewable energy like wind and solar;
- Biomass;
- Steam methane reforming combined with carbon capture and storage (CCS) (blue Hydrogen).

Along with roadmaps specifically dealing with solar fuels and/or hydrogen production, the analysis also focused on roadmaps concerning biofuels production, in particular microalgae-derived fuels. A few Countries published roadmaps or strategic documents specifically focusing on microalgal fuels (e.g. US, UK), while different studies exist targeting innovation and development initiatives on new and sustainable sources of energy and fuels (including aviation fuels), including biochemical routes.

The complete results of our analysis are depicted in the table below, categorizing member countries in their road mapping efforts.

Table 11 - Categorization of Mission Innovation member countries' effort in developing a solar fuel roadmap. (state November 2020)

	Australia	Austria	Brazil	Canada	Chile
Hydrogen	● ●	●	●	●	●
Biofuels (incl. microalgae-based fuels)	●	●	●	●	●
China					
Hydrogen	●	●	● ●	●	●
Biofuels (incl. microalgae-based fuels)	●	●	● ●	● ●	●
Germany					
Hydrogen	● ●	●	●	●	●
Biofuels (incl. microalgae-based fuels)	●	●	●	●	●
Mexico					
Hydrogen	● ●	● ●	●	●	●

Biofuels (incl. microalgae-based fuels)					
Hydrogen					
Biofuels (incl. microalgae-based fuels)					

All existing roadmaps as highlighted in the table were reviewed and taken into account in our own technology road mapping exercise. Overall, the analysis demonstrated that solar fuel roadmaps are only partially defined to date (state Nov. 2020). Within this project, the roadmaps for indirect solar fuels PV+EC (PEM, SOEC), direct solar fuels PEC and particle/colloidal systems were developed based on the information from the latest roadmaps produced in Australia, EU, Germany and the US. A similar approach has been followed for the biochemical route, even though most of biofuels-related roadmaps were not specifically focused on microalgae and often they dated back to many years ago.

In addition, roadmaps developed by international organisations including FCHJU, IRENA, IEA, SolarPower Europe and outcomes from international project collaborations and studies within the EU framework program Horizon 2020 were used to develop our solar fuel roadmap. The exhaustive list of roadmaps used in our analysis is presented in the References section.

2.1.2. Chemical and electrochemical pathway

For the development of the roadmap the following solar fuel technologies have been studied: Proton Exchange Membrane electrolyser (PEMEL), Solid Oxide Electrolyser Cell (SOEC), Photoelectrochemical Cell (PEC) with electrodes and Photocatalysis (PC) with particulate or colloidal matter. In the TRL analysis of the value chain analysis (Section 1), Alkaline Electrolysis (AE) was also investigated. This technology has been identified with a TRL of 8-9 and was introduced to the market already many years ago. For this reason, no roadmap for AE was developed in this study.

The identification of the state of the art of each technology, the related components of the value chain and the bottleneck/critical issue determination were described in detail in the value chain analysis (Section 1). The component TRL study results were benchmarked with stakeholders through discussions in 3 workshops and dedicated polls. Following the methodology described in section 0.2, patent, literature and a SWOT analysis were performed in order to execute the Gap Analysis. In combination with the bottleneck/critical issues determination, the technology developments that are required to evolve to the next technology readiness level could be identified. This approach is applied to four technologies identified within the chemical and electrochemical solar fuel pathways. By adding a timeline to this procedure, a graph can be extracted showing the evolution of a technology over time. This can be defined as the roadmap of the technology. The road mapping results have been benchmarked with the stakeholders in a 2-day workshop and break out session event.

2.1.2.1. Proton exchange membrane electrolysis (PEMEC)

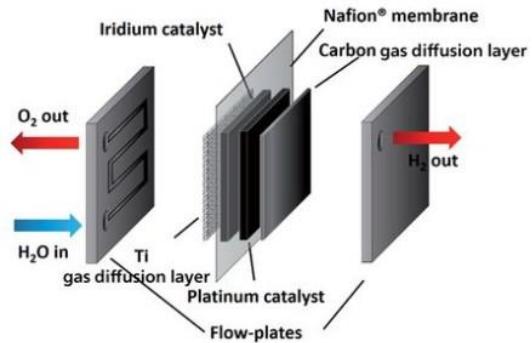


Figure 37 - schematic drawing of a PEM electrolyser³⁵

State of the art and identification of the main technological challenges

Table 12- TRL of each component of the Proton exchange membrane electrolysis system

	Technology component	TRL	'Main checkpoint'
Proton exchange membrane electrolysis system	Electrodes/Catalysts	7-8	For these 6 components the technology is demonstrated in field under different working conditions ^{36 37}
	Electrolyte	7-8	
	Ion exchange membrane	7-8	
	Gas diffusion layer	7-8	
	Flow plates	7-8	
	Compressor	7-8	

Table 13 - Main technological challenges linked to the PEMEC system

	Technological challenges	System Components
Proton exchange membrane electrolysis system	Compact system design	Membrane electrode assembly
	Platinum group metals (PGM)	Electrodes/catalyst
	Ti and noble metal	Field plates
	Scalability to GW	PGM catalysts

³⁵ Greig Chisholm , Philip J. Kitson , Niall D. Kirkaldy , Leanne G. Bloor and Leroy Cronin ; *Energy Environ. Sci.*, 2014, **7**, 3026-3032; DOI: [10.1039/C4EE01426J](https://doi.org/10.1039/C4EE01426J)

³⁶ Carmo, Marcelo, Fritz, David L, Mergel, Jürgen, and Stolten, Detlef. "A Comprehensive Review on PEM Water Electrolysis." International Journal of Hydrogen Energy 38.12 (2013): 4901-934. Web.

³⁷ Schropp, Elke, Naumann, Gabriel, and Gaderer, Matthias. "Life Cycle Assessment of a Polymer Electrolyte Membrane Water Electrolysis." Progress in Life Cycle Assessment 2019. Cham: Springer International, 2020. 53-66. Sustainable Production, Life Cycle Engineering and Management.

Patent analysis results

The figure reports on the patent publications on the field of PEM electrolysis. The patent applications have seen a significant growth from 2000 until 2005 and then remain on a level of 400-600 patent publications per year. Please note the number for 2020 only takes the first three quarters into account. The graph shows that the field is lively and despite the high TRL of 7-8 there are still a lot of inventions being made.

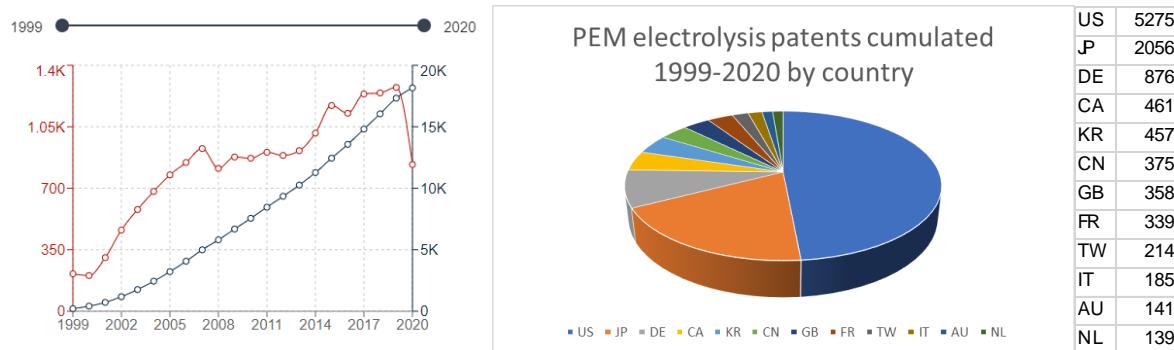


Figure 38 - Cumulated (black) and patent publications per year (red) for proton exchange membrane electrolysis from 1999-2020. Cumulated patent publications per country for proton exchange membrane electrolysis. (Espacenet search terms : Proton AND exchange AND membrane AND electrolysis).

Most of the patents have been published in the US and Japan, (2/3 of all publications). This picture changes when analysing the patent publications from 2015-2020. In this case, the number of publications is more equally distributed between the countries and a strong increase of publications from Asia is detected.

Literature analysis results

A literature search study has been performed to detect the main research topics published on the field of PEMEC. The search has been limited to the last year in order to determine the latest trends.

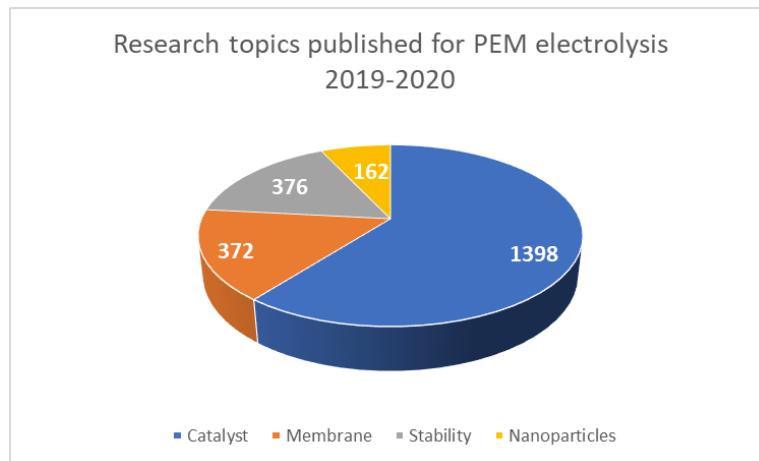


Figure 39 - Main research topics identified for the PEM electrolysis.

Four main research topics could be identified: catalysts, membrane, stability and nanoparticles. The publications on PEM catalyst are by far the largest group of publications clearly indicating the need for a solution to the non-abundant catalyst problem. Interestingly, the amount of papers on the topic of nanoparticles, depicting the effort of the community to reduce the use of PGM material with nanotechnological techniques.

SWOT analysis

The main strengths, weaknesses, opportunities and threats associated with the PEMEC systems are summarised here below. They are mainly derived from literature analysis, patent analysis and direct stakeholders' consultation through surveys, workshops and dedicated calls^{38 39 40 41}.

Strengths

- Efficiency of 80%, will be increased to 85%
- System lifetime, robust system with high durability
- Stable and durable membrane technology for proton transport
- Flexibility, fast response time (in combination with renewables)
- Clean product gases (H₂ and O₂)

Weaknesses

- Platinum group metals needed in combination with the acidic electrolyte
- Platinum group metal catalyst are preventing the fast exploitation to GW scale
- Nafion membrane prevents higher current densities
- Ti based field plates with noble metal coatings
- Complicated and bulky stack configuration (MEA, Field Plates, etc..)

Opportunities

- Centralized, high volume production of Hydrogen
- Large scale electrolyser can provide low cost Hydrogen
- Due to high flexibility good combination with low cost renewable electricity sources like solar and wind
- Possible exploitation in lower developed regions with cheap access to renewable energy
- Alkaline electrolyte could pave the way towards abundant catalysts like Ni or Fe

Threats

- Centralized production will take place outside Europe at places with the cheapest energy supply, e.g. Magreb, Chili, Persian Gulf
- Europe's dependency on importing energy remains
- Hydrogen transport infrastructure need to be exploit
- Large investment in infrastructure (e.g. piping system) required
- Still to be decided if acidic or alkaline electrolyte will become the major technology for market deployment.
- Alkaline exchange membranes show lower TRL (5-6) than PEM and need to be developed for mass production. This will further delay the way to the market

Gap analysis

The gap analysis assembles the study of the literature and patents with the SWOT analysis to identify the major technology developments needed to promote a technology to the next technology readiness level.

³⁸ Nørskov, J. K., Latimer, A., & Dickens, C. F. (2019). Research needs towards sustainable production of fuels and chemicals. *Energy-X project roadmap*

³⁹ https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

⁴⁰ https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf

⁴¹ SUNRISE Technological Roadmap, February 2020

Proton exchange membrane electrolysis is a mature technology with TRL of 7-8 being on the cusp of mass fabrication.

Taking the last steps for upscaling to the market, the use of abundant material for the catalyst is required. The research and development effort investigates this in two specific ways. One possibility is to remain with an acidic electrolyte and further reduce significantly the use of PGM by using core shell or nanoparticles. Another effort studies the application of an alkaline electrolyte paving the way towards abundant catalysts like Ni or Fe. This would require the development of an alkaline exchange membrane which has a state of the art TRL of 5-6.

In summary, the main challenges to overcome in the next 5 years for this technology will be in particular:

- Decision need to be made, if the mass production will rely on acidic electrolyte, focussing on the reduction of the non-abundant catalyst material or to mitigate to alkaline electrolytes with the advantage of abundant catalysts and focus on the development of an alkaline exchange membrane (e.g. Hydroxyl exchange membrane)
- Novel techniques for reducing PGM catalyst material need to be developed, this will happen mainly on the field of thin film and nanotechnology like atomic layer deposition, core shell particles and other nanostructures like wires, meshes and colloids.
- Novel membrane technologies for enabling ion transport need to be developed, this will enable the use of Hydroxyl exchange membranes and allow for the use of alkaline electrolytes in order to mitigate to earth abundant catalyst materials.

Technological roadmap

In the following figure the main actions to be carried out in order to reach a large-scale deployment of solar fuels production based on Proton Exchange Membrane electrolysis are summarised.

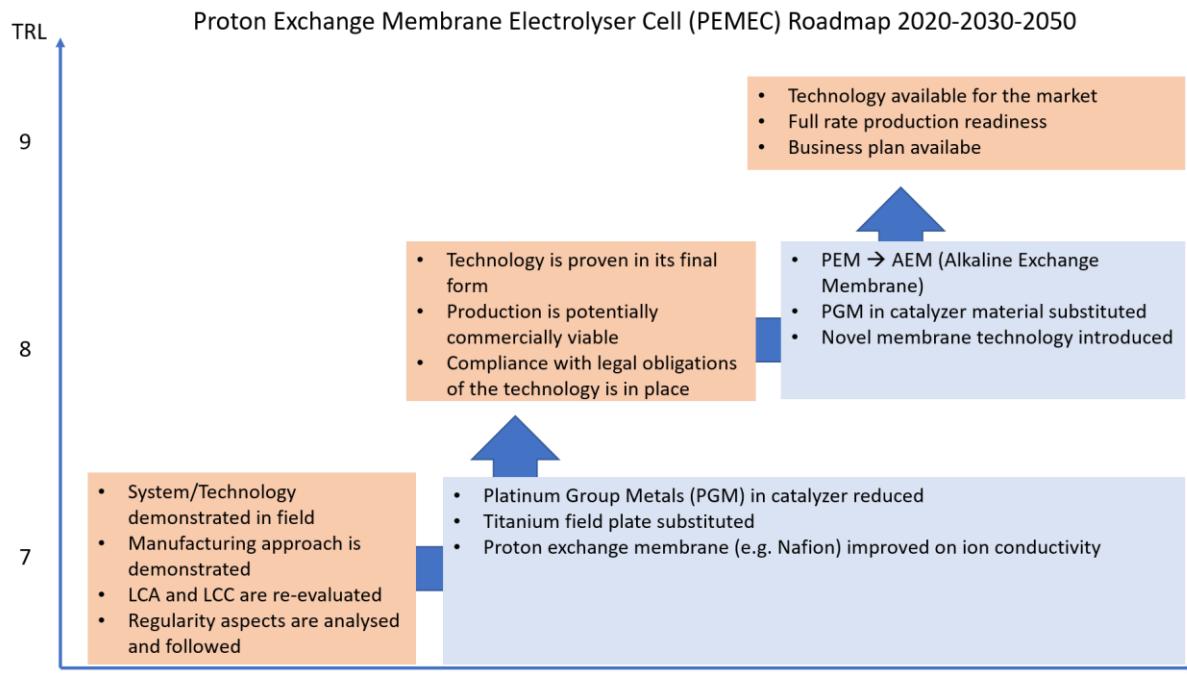


Figure 40 - Technology roadmap for PEMEC 2020-2050

Technology Readiness Level vs timeline is depicted in this figure. The TRL checkpoints are indicated in the blue box. The technology challenges to overcome in order to evolve to the next TRL are indicated next to the star symbol.

Conclusion PEMEC

The PEMEC technology is used in the electrochemical pathway of solar fuels in combination with photovoltaics. The state of the art TRL of PEMEC has been identified to be between 7 and 8. The advantages of PEMEC are the fast response time, that makes it very attractive to work with intermittent renewable electricity sources and the high purity of the product gases. This technology has the potential to reach within 5 years from now full market availability. There are only a few critical issues to overcome. Upscaling to GW production requires the strong reduction or substitution of noble metal catalysts like PGM. There are two ways to address this bottleneck. One is the mitigation from proton exchange membrane to hydroxyl exchange membranes and thus operations in alkaline instead of acidic electrolytes. This will reduce the pressure on the electrode/catalyst material because more abundant metals like Ni or Fe could be applied. On the other hand, it shifts the development effort towards the membrane, because hydroxyl exchange membranes are not commercially available with the same technology readiness level than proton exchange membranes. The other possibility to accelerate the PEM technology would be the strong reduction of PGM catalysts by novel material technologies like core shell nanoparticles or novel thin film process technologies where only a fraction of the noble metal catalysts is needed.

2.1.2.2. Solid oxide electrolysis cell (SOEC)

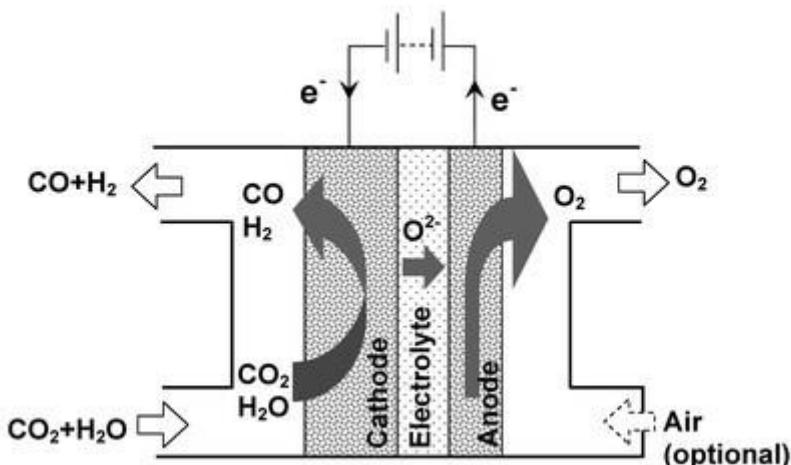


Figure 41 - Schematic drawing of a SOEC electrolyser⁴²

State of the art and identification of the main technological challenges

Table 14 - TRL of each component of the SOEC system

	Technology component	TRL	'Main checkpoints'
Solid Oxide Electrolysis Cell	Electrodes	6-7	A pilot-scale prototype is fine-tuned to a variety of operating conditions together with other subsystems and in compliance with intended working conditions (on field) including the exploitation of actually available solar resource ^{43 44}
	Electrolyte structure	6-7	
	Redox material	6-7	
	Reactor geometry	6-7	

⁴² Wang, Yao, Liu, Tong, Lei, Libin, and Chen, Fanglin. "High Temperature Solid Oxide H₂O/CO₂ Co-electrolysis for Syngas Production." Fuel Processing Technology 161 (2017): 248-58. ; DOI: 10.1016/j.fuproc.2016.08.009 ;

⁴³ Dehghanimadvar, Mohammad, Shirmohammadi, Reza, Sadeghzadeh, Milad, Aslani, Alireza, and Ghasempour, Roghaye. "Hydrogen Production Technologies: Attractiveness and Future Perspective." International Journal of Energy Research 44.11 (2020): 8233-254.

⁴⁴ D, Grieshammer, S, Schroeder, M, Martin, M, Al Daroukh, M, Tietz, F, Schefold, J, and Brisse, A. "Microstructural Comparison of Solid Oxide Electrolyser Cells Operated for 6100 h and 9000 h." Journal of Power Sources 275 (2015): 901-11.

Table 15 - Main technological challenges linked to the SOEC system

	Technological challenges	System Components
Solid Oxide Electrolysis Cell	Stability	Membrane, Electrodes
	Durability	Membrane, Electrodes, Reactor material
	Design	Reactor
	Flexibility	Electrode/membrane stack

Patent analysis results

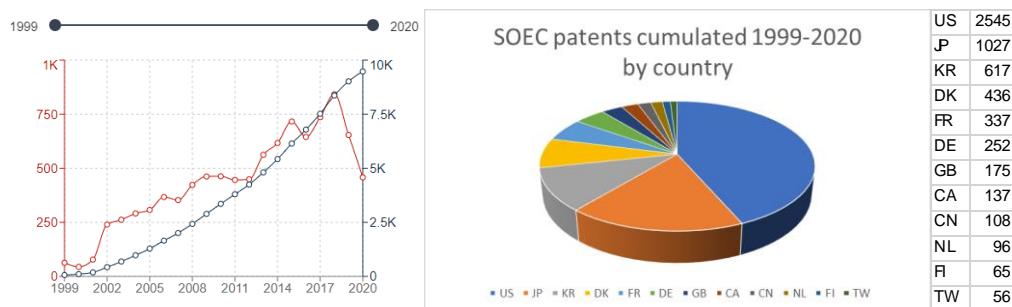


Figure 42 - Cumulated (black) and patent publications per year (red) for solid oxide electrolysis cell. Cumulated patent publications per country for solid oxide electrolysis. (Espacenet search terms: Solid oxide AND electrolysis)

Literature analysis results

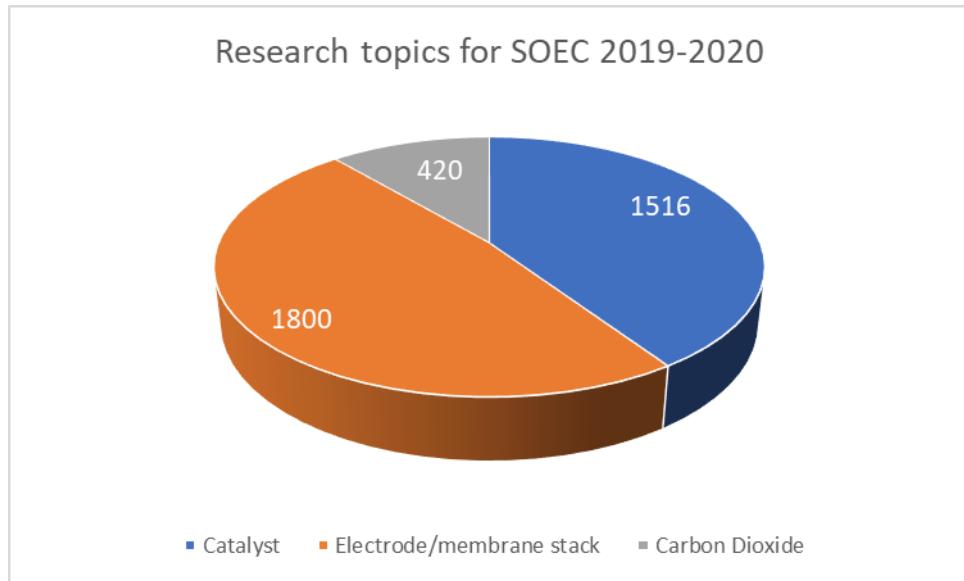


Figure 43 - Main research topics identified for the SOEC electrolysis.

SWOT analysis

The main strengths, weaknesses, opportunities and threats associated with the solid-oxide electrochemical cell value chains are summarised here below. They are mainly derived

from literature analysis, patent analysis and direct stakeholders' consultation through surveys, workshops and dedicated calls^{45 46 47 48}.

Strengths

- Higher efficiency due to high temperature
- The electrical energy needed to split the feed molecules is lower
- The high temperature cells have a lower internal resistance than low temperature cells
- Low operation cost
- Fuel flexibility

Weaknesses

- Further processing of product gas (H₂ + steam)
- System lifetime
- Cycle stability
- Dynamic thermal management system required
- Mechanical compatibility
- Diffusion due to high temperature
- Chemical stability

Opportunities

- Offers the possibility for heat integration system lifetime
- Potential use for co-electrolysis
- Potentially add Fischer-Tropsch for higher hydrocarbon fuels (Synthetic Kerosene, Synthetic Diesel)

Threats

- Material durability due to high temp
- Low flexibility (in combination with renewables)
- Delamination and cracks of the material due to high mechanical stress
- Complex chemical processes not fully understood

Gap analysis

The gap analysis assembles the study of the literature and patents with the SWOT analysis to identify the major technology developments needed to promote a technology to the next technology readiness level.

Solid oxide electrolysis is a pre-mature technology with TRL of 6-7, with prototype system already operating in the field.

Last steps for market upscaling will require the long-term stability of the SOEC system. The high temperatures of up to 1000°C request a high material durability. Mechanical stress due to different thermal expansion coefficients, diffusion and delamination are the main challenge of this technology today.

The main challenges to overcome in the next 5-10 years for this technology will be in particular:

⁴⁵ Nørskov, J. K., Latimer, A., & Dickens, C. F. (2019). Research needs towards sustainable production of fuels and chemicals. Energy-X project roadmap

⁴⁶ SUNRISE Technological Roadmap, February 2020

⁴⁷ https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf

⁴⁸ Artificial Photosynthesis : potential and reality ; <https://op.europa.eu/en/publication-detail-/publication/96af5cc3-2bd6-11e7-9412-01aa75ed71a1/language-en>; DOI: 10.2777/410231

- Thermally matched materials for the electrode/membrane/electrode stack;
- Development of materials that allow operations at lower temperatures;
- Reduction of ramp up times or the incorporation of batteries for constant operation at high temperature;
- Integration of co-electrolysis to process syngas (CO+H₂) from CO₂ and H₂O;
- In longer terms, the integration of a Fischer-Tropsch process to provide higher value hydrocarbon fuels like synthetic kerosene and synthetic diesel.

Technological roadmap

In the following figure the main actions to be carried out in order to reach a large-scale deployment of solar fuels production based on solid oxide electrolysis are summarised.

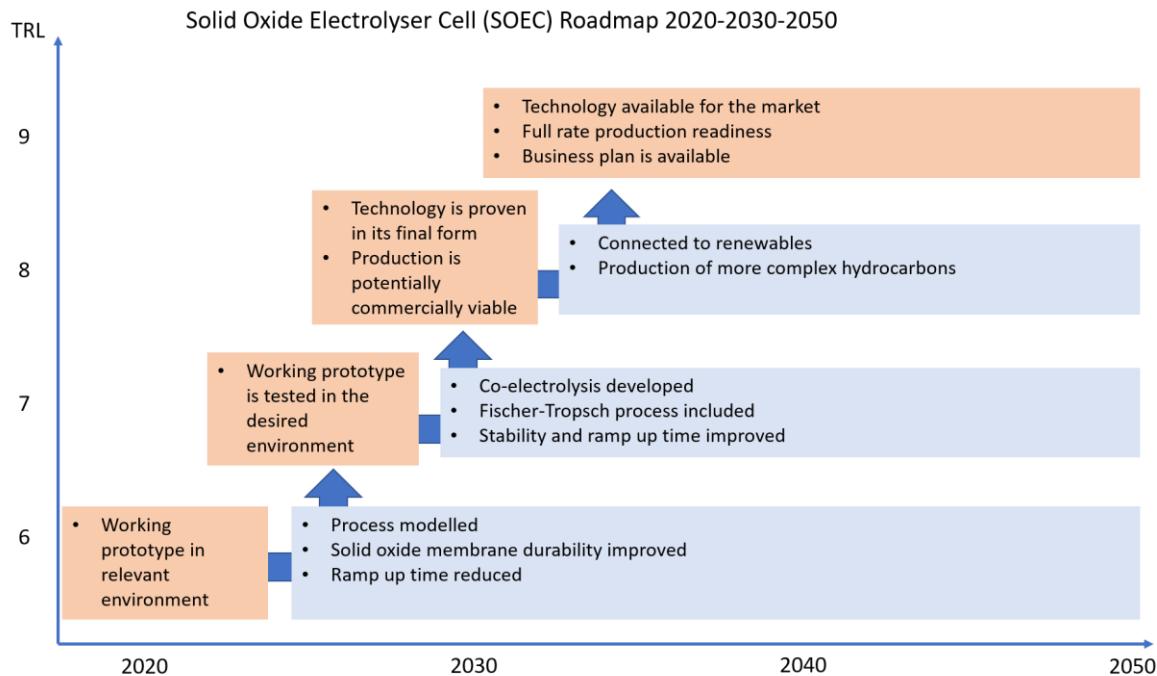


Figure 44 - Technology roadmap for SOEC 2020-2050

Technology Readiness Level vs timeline is depicted in this figure. The TRL checkpoints are indicated in the blue box. The technology challenges to overcome in order to evolve to the next TRL are indicated next to the star symbol.

Conclusion SOEC

The state-of-the-art technology readiness level of the SOEC technology within the electrochemical pathway of solar fuels is determined to be between 6 and 7. This means that prototypes have been tested in the field and in compliance with intended working conditions. Due to the high system temperature co-electrolysis with CO₂ is possible. As a product, syngas (CO+H₂) could be utilised in combination with a Fischer-Tropsch process directly into higher hydrocarbons like synthetic kerosene or synthetic diesel. The bottlenecks this technology needs to overcome, towards market implementation mainly consist in the stability of the solid oxide membrane and the high operation temperature. There is a serious constraint on the reactor materials due to the high temperatures of ~1000 °C introducing mechanical stress. Long ramp up time due to the high operation temperature prevents the direct coupling with highly intermittent renewable electricity sources like solar and wind. In the future, when battery cost further drops, low cost batteries can be used to buffer and provide a constant electricity supply. Material development and reactor design effort is needed to make this technology available on the market in the next 10 years. Market availability will also depend on the integration of low-

cost batteries to keep the system in operation for low renewable power generated at night, clouds or low wind.

2.1.2.3. Photoelectrochemical cell with electrodes (PEC)

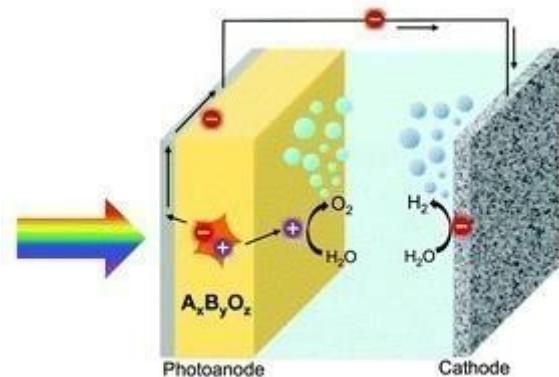


Figure 45 - Schematic drawing of a Photoelectrochemical cell using a semiconductor anode and a metal cathode as electrodes⁴⁹

Photoelectrochemical (PEC) water splitting is a promising solar-to-hydrogen pathway for hydrogen production offering the potential for high conversion efficiency at low operating temperatures using cost-effective thin-film and/or particle semiconductor materials. The PEC cell is the most compact embodiment of this approach where photogenerated electrons are utilized to reduce H₂O directly at a Semiconductor/electrolyte interface. These approaches suffer under low solar to fuel or solar to hydrogen efficiencies (typically StH% <10%).

State of the art and identification of the main technological challenges

Table 16 - TRL of each component of the PEC system

	Technology component	TRL	'Main checkpoints'
Photoelectrochemical Cell (PEC)	Electrodes	3-4	For these 2 components the technological concept is experimented and validated at laboratory scale and partially Small-scale prototype of the system or sub-systems is developed in laboratory ⁵⁰
	Catalyst	3-4	
	Electrolyte	4	Small-scale prototype of the system or sub-systems is developed in laboratory

Table 17 - Main technological challenges linked to the PEC system

	Technological challenges	System Components
Photoelectrochemical Cell	Photosensitivity	Photoelectrode semiconductor
	Bandgap straddling the redox potential of water	Photoelectrode semiconductor
	Ion transport properties	Photoelectrode semiconductor

⁴⁹ Chem. Soc. Rev., 2019, 48, 2126-2157 ; <https://doi.org/10.1039/C8CS00761F>

⁵⁰ Roger, Isolda, Shipman, Michael A, and Symes, Mark D. "Earth-abundant Catalysts for Electrochemical and Photoelectrochemical Water Splitting." Nature Reviews. Chemistry 1.1 (2017): Nature Reviews. Chemistry, 2017-01-11, Vol.1 (1).

Patent analysis results

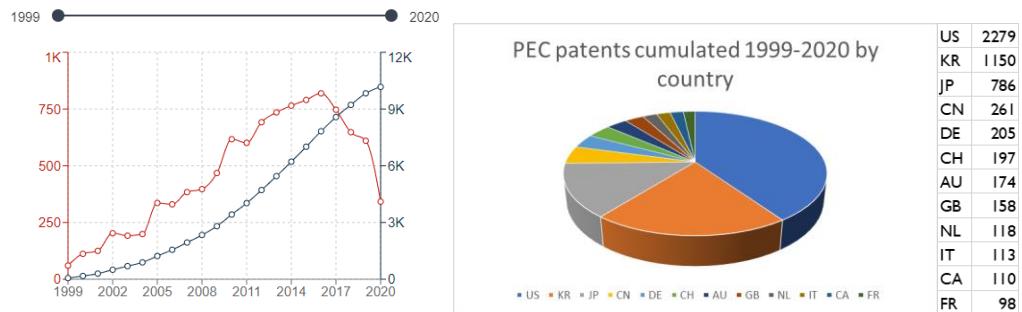


Figure 46 - Cumulated (black) and patent publications per year (red) for photoelectrochemical cell. Cumulated number of patents published per country for photoelectrochemical cell. (Espacenet search terms: Photoelectrochemical AND cell)

Literature analysis results

A literature search study has been performed to detect the main research topics published on the field of Photoelectrochemical cell electrolysis. The search has been limited to the last years in order to determine the latest trends.

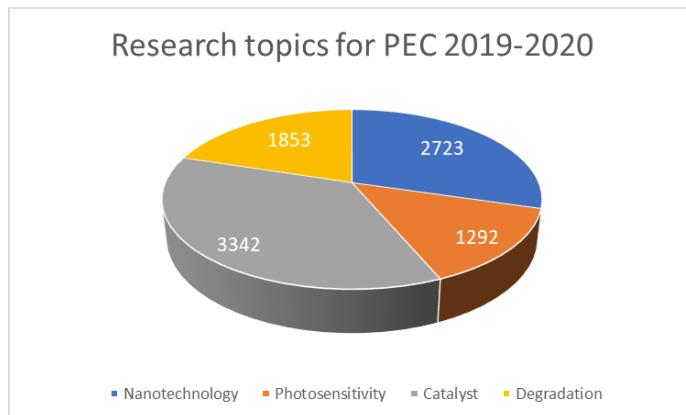


Figure 47 - Main research topics identified for the PEC electrolysis

Thermodynamically, water splitting requires 1.229 V and with overpotential losses, an electrochemical bias of at least 1.5 to 2.0 V is required. For a one-cell single-junction PEC-device, this translates into a band gap of 1.9–2.3 eV or more. A band gap of 2.3 eV gives a maximum current density corresponding to 10% solar-to-hydrogen (STH) efficiency. The literature analysis shows a major activity on the catalyst activity which is identified as one of the challenges of this technology. Catalysts need to survive on the semiconductor surface in contact with the liquid electrolyte. Photosensitivity is another issue addressed in literature. The wide bandgap semiconductor needed for providing the required voltage for the water splitting process is usually not a very good ion conductor. Another topic prominent in literature is the degradation of the semiconductor surface in contact with the electrolyte liquid. Nanotechnologies are investigated for catalytic coatings and surface morphology.

SWOT analysis

The main strengths, weaknesses, opportunities and threats associated with the photoelectrochemical cell value chains are summarised here below. They are mainly derived

from literature analysis, patent analysis and direct stakeholders' consultation through surveys, workshops and dedicated calls.^{51 52 53 54}

Strengths

- Direct conversion (no cabling)
- Lower overpotential due to integration
- Lower current densities lead to reduced constrain on catalyst material

Weaknesses

- PEC System suffers from low
 - Stability
 - Efficiency
 - Scalability

Opportunities

- Allows decentralized, autonomous production of Hydrogen
- Support microgrids, Local Energy Communities (LEC) or single households
- Reduce transportation cost
- No cabling
- Low water consumption
- Roll to roll processes for upscaling

Threats

- Strongly depends on progress in different technologies
 - Photon management
 - Novel Catalyst materials
 - Novel Photosensitive semiconductor materials
 - Novel self-assembly and self-repairing nanomaterial systems

Gap Analysis

The state-of-the-art technology readiness level of the Photoelectrochemical water splitting technology is determined to be 3-4. This means that the technological concept is experimented and validated at laboratory scale and partially small-scale prototype of the system or sub-systems is developed in the laboratory.

Along with improvements dealing with the catalytic part, specific interventions are also needed for the photosensitive semiconductor:

- Enhancing the light absorption of the materials, e.g. by increasing the light spectrum utilisation and the light harvesting efficiency of the photoactive semiconductor materials.
- Optimising transfer mechanisms from the semiconductor/catalyst surface to the liquid electrolyte, by minimising losses and potential side-reactions.
- Increasing the durability of the materials used in the photosensitive semiconductor, which can be also affected by discontinuous and variable light intensity.

⁵¹ Young, J., Steiner, M., Döschner, H. et al. Direct solar-to-hydrogen conversion via inverted metamorphic multi-junction semiconductor architectures. *Nat Energy* 2, 17028 (2017). <https://doi.org/10.1038/nenergy.2017.28>

⁵² SUNRISE Technological Roadmap, February 2020

⁵³ Nørskov, J. K., Latimer, A., & Dickens, C. F. (2019). Research needs towards sustainable production of fuels and chemicals. *Energy-X project roadmap*

⁵⁴ https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf

- Investigating for new and less critical materials to be applied in the semiconductor/electrolyte interface.
- Understanding of the complex catalytic interface processes is required to develop novel materials or nanotechnological approaches.

When the prototyping phase has been reached (TRL 6-7) upscaling of the technology need to be addressed. This means the technology development need to focus on large area, high volume processing methods using earth abundant materials.

Technology roadmap

In the following figure the main actions to be carried out in order to reach a large-scale deployment of solar fuels production based on Photoelectrochemical cell are summarised.

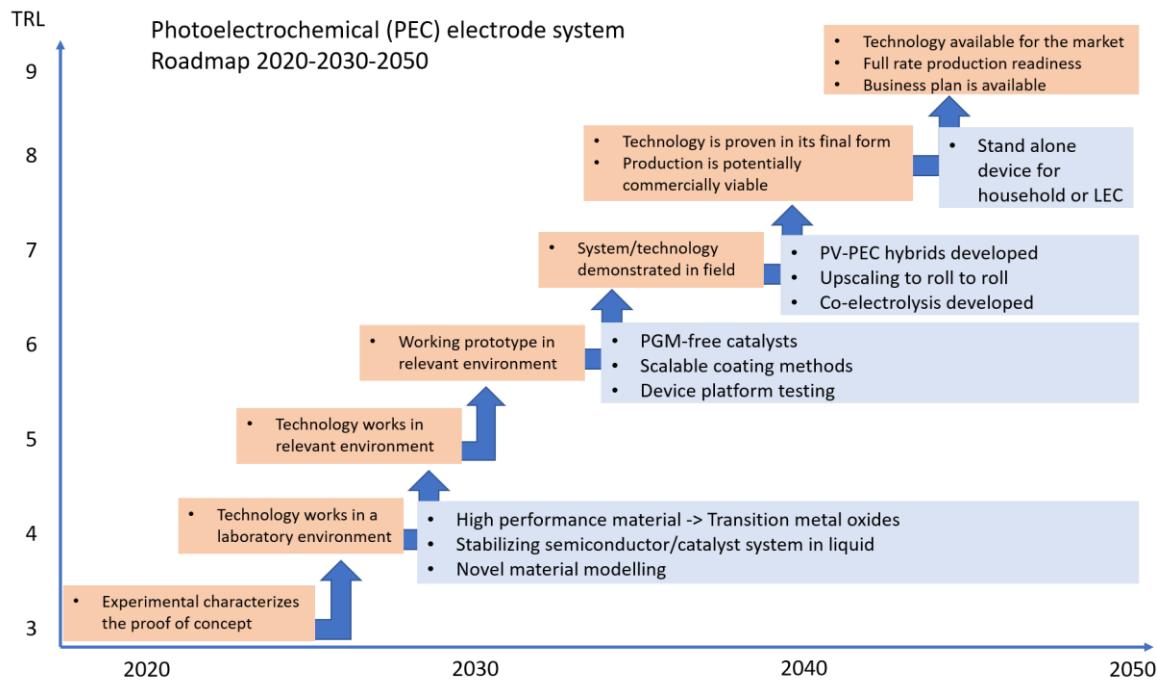


Figure 48 - Technology roadmap for Photoelectrochemical Cell (PEC) 2020-2050

Technology Readiness Level vs timeline is depicted in this figure. The TRL checkpoints are indicated in the blue box. The technology challenges to overcome in order to evolve to the next TRL are indicated next to the star symbol. The dashed lines show the error margin of the roadmap prediction.

Conclusion Photoelectrochemical cells

The state of the art of the PEC technology within the electrochemical pathway of solar fuels is determined to be between 3 and 4. This means that small-scale prototype of the system or sub-systems is developed in laboratory. The bottlenecks/critical issues to overcome to obtain a stable system and provide prototype operations is corrosion, which occurs with all materials over long periods of time, catalyst poisoning, which is caused by the introduction of solution impurities, and it has been shown that low concentrations of impurities can have a huge impact on electrode efficiency and changes to the composition and morphology (structure/structural features) of the electrode can decrease their efficiency. Within the next 10 years this technology will successfully demonstrate prototyping. But then the challenge will come with the upscaling of the technology to proof operations in the field under real conditions. For this large-scale processing methods are required like roll to roll production and high-volume deposition techniques. This technology will be applied in stand-alone systems for households or local energy communities. We expect a market introduction of this technology in the 2040s.

2.1.2.4. Photocatalytic particulate or colloidal systems

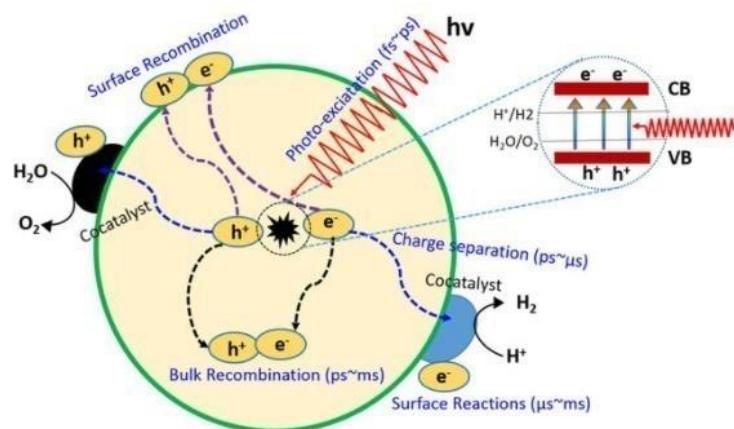


Figure 49 - Schematic drawing of a photocatalytic particle or colloidal system⁵⁵

A photocatalytic semiconductor particle is suspended into an electrolyte solution. Illumination of a semiconductor with a photon of energy $h\nu$ is followed by charge carrier separation and the surface redox reaction occurring at the surface of the co-catalyst particles. Here, dual co-catalyst functionalization (e.g. hydrogen and oxygen evolution) are driven by different co-catalysts.

State of the art and identification of the main technological challenges

Table 18 - TRL of each component of the photocatalytic particle or colloidal system

	Technology component	TRL	'Main checkpoints'
Photocatalytic particulate or colloidal systems	Electrodes	2-3	For these 2 components the technical analysis of the concept is investigated and partially the technological concept is experimented and validated at laboratory scale ⁵⁶
	Catalyst	2-3	
	Electrolyte	3	The concept is tested at laboratory scale ⁵⁷

Table 19 - Main technological challenges linked to the photocatalytic particle or colloidal system system

	Technological challenges	System Components
Photocatalytic particulate or colloidal	Surface migration/dissolution	catalyst
	Corrosion/oxidation	catalyst

⁵⁵ Giménez, Sixto, and Bisquert, Juan. Photoelectrochemical Solar Fuel Production. Cham: Springer International AG, 2016. DOI: 10.1007/978-3-319-29641-8

⁵⁶ Zhang, Hao, Tang, Guogang, Wan, Xiong, Xu, Jing, and Tang, Hua. "High-efficiency All-solid-state Z-scheme Ag₃Po₄/g-C₃N₄/MoSe₂ Photocatalyst with Boosted Visible-light Photocatalytic Performance for Antibiotic Elimination." Applied Surface Science 530 (2020): 147234. DOI: 10.1016/j.apsusc.2020.147234

⁵⁷ Shaban, Yasser A. "Electrocatalysts for Photoelectrochemical Water Splitting." Methods for Electrocatalysis. Cham: Springer International, 2020. 353-74. DOI: 10.1007/978-3-030-27161-9_14

	Core shell formation	catalyst
	Particle size	Semiconductor particle

Patent analysis results

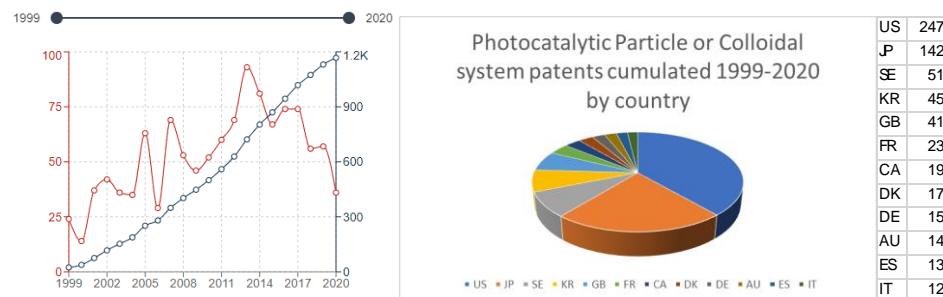


Figure 50 - Cumulated (black) and patent publications per year (red) for Photocatalytic particulate or colloidal systems. Cumulated number of patents published per country for Photocatalytic particle or colloidal systems. (Espacenet search term: Photocatalytic particle AND system)

Literature analysis results

A literature search study has been performed to detect the main research topics published on the field of Photocatalytic particle and colloidal systems. The search has been limited to the last years in order to determine the latest trends.

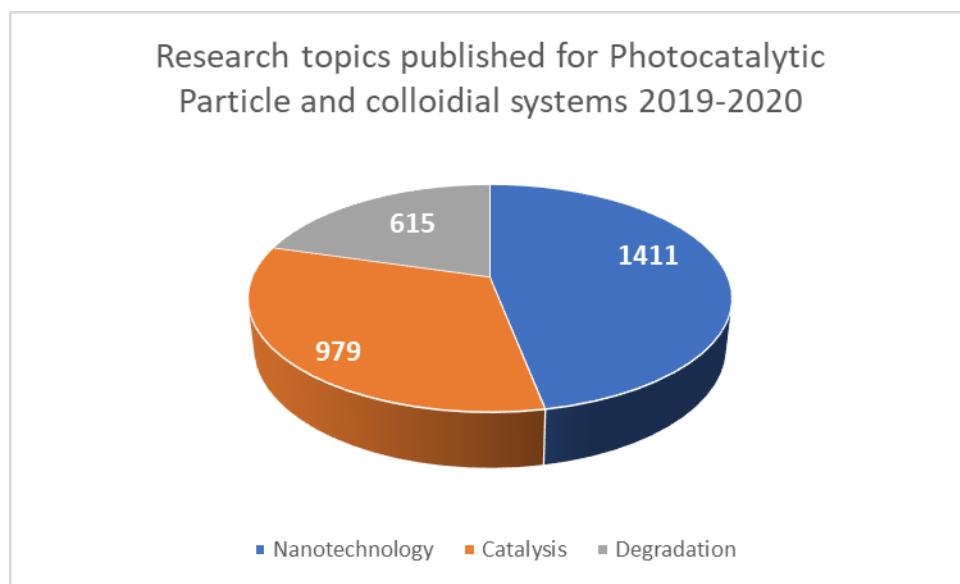


Figure 51 - Main research topics identified for the Photocatalytic particle and colloidal system

The major research topics have been identified. The deactivation of a co-catalyst/semiconductor composite might occur because of (1) changes of the light absorbing semiconductor material (e.g., by corrosion); (2) changes/rearrangement of the applied co-catalysts, in particular modification of the physiochemical properties of a cocatalyst, such as oxidation state, phase composition, particle size and atomic structure.

SWOT analysis

The main strengths, weaknesses, opportunities and threats associated with the photocatalytic particle and colloidal systems value chains are summarised here below. They

are mainly derived from literature analysis, patent analysis and direct stakeholder consultation through surveys, workshops and dedicated calls.^{58 59 60 61 62}

Strengths

- Direct conversion (no cabling)
- Lower overpotential due to integration
- Lower current densities lead to reduced constrain on catalyst material

Weaknesses

- Photocatalytic particle or colloidal systems suffers from low
 - Stability (corrosion)
 - Efficiency
 - Scalability
- Product gas separation

Opportunities

- Allows decentralized, autonomous production of Hydrogen
 - Support Local area networks or single households
 - Reduce transportation cost
- No cabling
- Low water consumption
- Roll to roll processes for upscaling

Threats

- Strongly depends on progress in different technologies
 - Photon management
 - Catalysts materials
 - Photosensitive semiconductor materials
 - Nanomaterial self-assembly and self-repairing material systems

Gap analysis

The TRL analysis of this technology provided a technology readiness level of 2-3. From the patent search results, the literature study and the swot analysis, the gaps preventing photocatalysis particles and colloidal systems to evolve to higher TRL could be determined. The main research topics identified are the application of nanomaterials, improving catalyst reactions, stability and efficiency. After TRL 6 prototyping is demonstrated, the upscaling task needs to be addressed. This means the development of large area, high throughput processes like roll to roll and the strong reduction or mitigation of Platinum Group Metals (PGM).

To bring the technology to TRL 5-6, prototyping, the following challenges need to be addressed:

⁵⁸ Ye, Kai-Hang, Li, Haibo, Huang, Duan, Xiao, Shuang, Qiu, Weitao, Li, Mingyang, Hu, Yuwen, Mai, Wenjie, Ji, Hongbing, and Yang, Shihe. "Enhancing Photoelectrochemical Water Splitting by Combining Work Function Tuning and Heterojunction Engineering." *Nature Communications* 10.1 (2019): 3687. DOI: 10.1038/s41467-019-11586-y

⁵⁹https://science.osti.gov/-/media/bes/pdf/reports/2020/Solar_Fuels_Brochure.pdf?la=en&hash=8F16DD447672592D60FB2C35DC6B3991D9BAF02#:~:text=Basic%20Energy%20Sciences%20held%20a,as%20the%20only%20energy%20input.

⁶⁰ https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf

⁶¹ SUNRISE Technological Roadmap, February 2020

⁶² Nørskov, J. K., Latimer, A., & Dickens, C. F. (2019). Research needs towards sustainable production of fuels and chemicals. Energy-X project roadmap

- Enhancing the light absorption of the materials, e.g. by increasing the light spectrum utilisation and the light harvesting efficiency of the photoactive semiconductor materials.
- Development of a cathode material for dye sensitive photocatalysis
- Optimising transfer mechanisms from the co-catalyst interface to the liquid electrolyte, by minimising losses and potential side-reactions.
- Increasing the durability of the materials used in the photosensitive semiconductor, which can be also be affected by discontinuous and variable light intensity.
- Investigating for new and less critical materials to be applied in the semiconductor/electrolyte interface.
- Understanding of the complex catalytic interface processes is required to develop novel materials or nanotechnological approaches.
- Development of a gas separation membrane for two step photoexcitation systems (z-scheme)

When the prototyping phase has been reached (TRL 6-7) upscaling of the technology need to be addressed. This means the technology development need to focus on large area, high volume processing methods using earth abundant materials.

Technology roadmap

In the following figure the main actions to be carried out in order to reach a large-scale deployment of solar fuels production based on Photocatalytic particulate or colloidal systems are summarised.

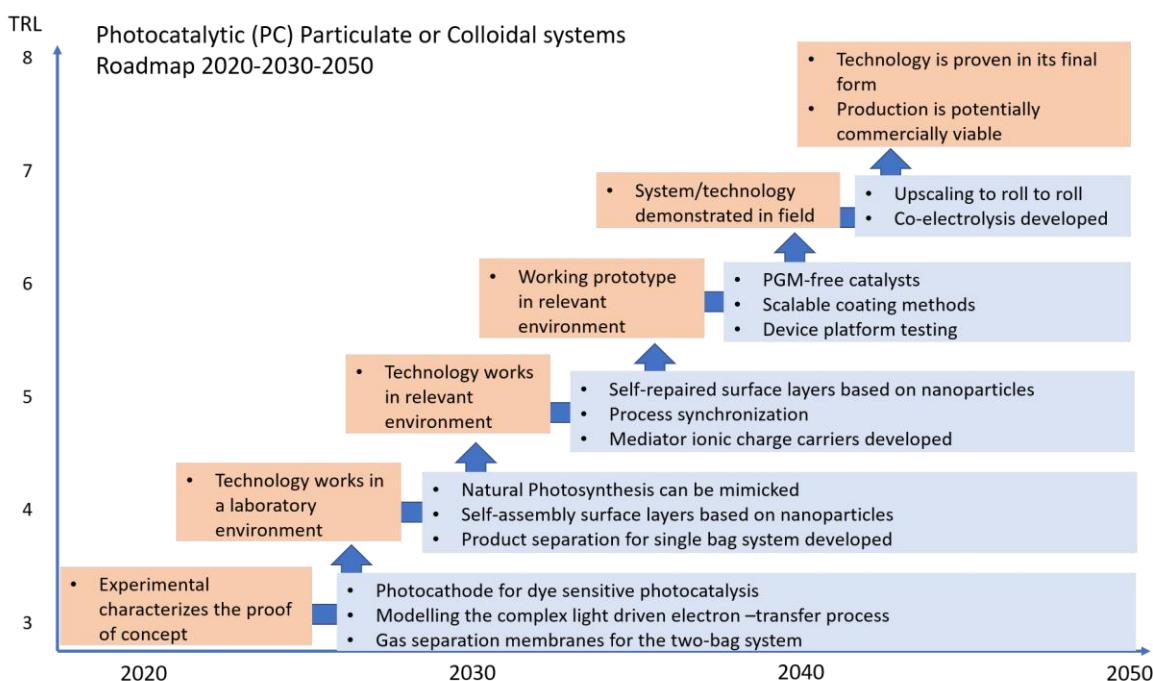


Figure 52 - Technology roadmap for Photocatalytic particulate or colloidal systems 2020-2050

Technology Readiness Level vs timeline is depicted in this figure. The TRL checkpoints are indicated in the blue box. The technology challenges to overcome in order to evolve to the next TRL are indicated next to the star symbol. The dashed lines show the error margin of the roadmap prediction.

Conclusion Photocatalytic particulate or colloidal systems

The state of the art of the Photocatalytic particulate or colloidal systems technology within the chemical pathway of solar fuels is determined to be between 2 and 3. This means the technical analysis of the concept is investigated and partially the technological concept is experimented and validated at laboratory scale. The first bottlenecks/critical issues to overcome towards a proof of concept system are the development of a gas separation membranes, ionic charge carrier mediators and materials that provide process stability, high catalyst efficiency and high photosensitivity. A major breakthrough for this technology will be the development of self-assembled and self-repairing nanomaterials. After the prototyping is demonstrated the upscaling challenge need to be addressed. The same constraints to the materials apply like in the PEC upscaling challenge. For that large-scale processing methods are required like roll to roll production and high-volume deposition techniques. This technology will be applied in standalone systems for households or local energy communities. We expect market introduction of these systems in the 2050s.

2.1.3. Thermochemical pathway

The concept behind the thermochemical methods is that of high-temperature two-step processes, which involve thermal decomposition of metal oxides followed by re-oxidation by reacting with H₂O to yield H₂. A temperature higher than 1000°C is needed for the reactions, thus solar thermochemical hydrogen reactors need to be coupled with concentrating solar systems using mirrors. A conceptual scheme of the system is presented in Figure 53 for the solar part and in Figure 54 for the thermochemical part.

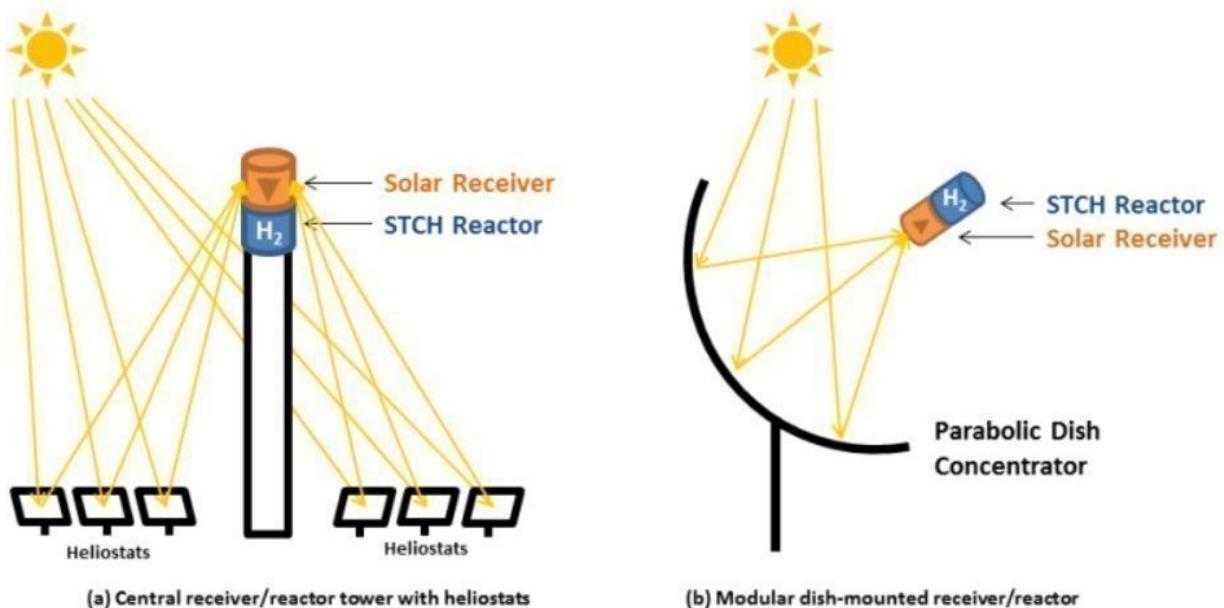


Figure 53 - High Temperature two-step processes

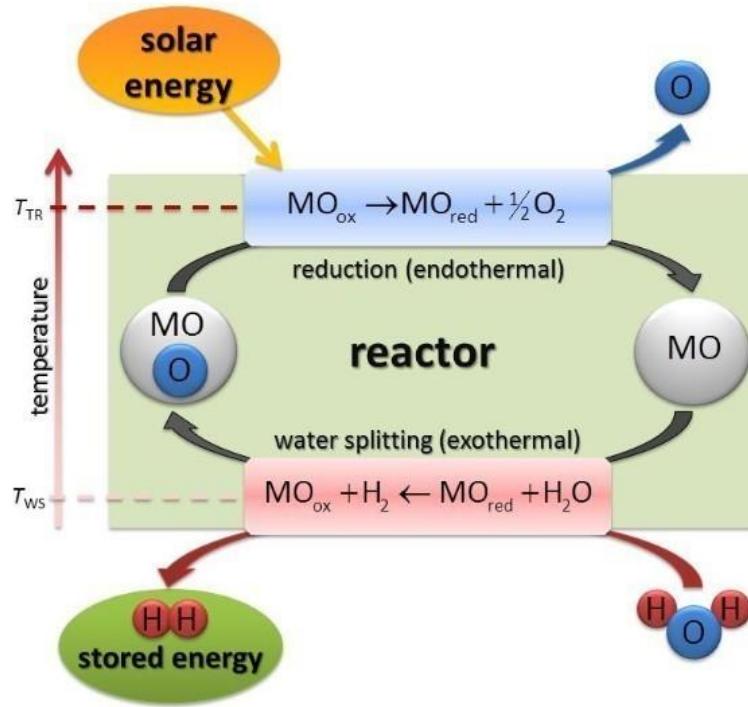


Figure 54 - High Temperature two-step processes

State of the art and identification of the main technological challenges

The state of the art of the identified technology with the current TRL of the related components was assessed. This was the outcome of the activities carried out within the value chain analysis (Section 1), i.e. literature analysis and TRL ‘stage-gate approach’, as well as of the inputs collected during the workshops from the stakeholders.

The following Table 20 summarises the TRL of each component of the thermochemical hydrogen production system, along with the associated checkpoint corresponding to the ‘TRL 5-7’ for redox material and reactor absorber and to ‘TRL 7-9’ for mirrors.

Table 20 - TRL of each component of the solar thermochemical hydrogen production system

	Technology component	TRL	'Main checkpoint'
Thermochemical	Mirrors	7-9	Manufacturing issues solved, first of a kind commercial system obtained.
	Redox material	5-7	Prototype system tested in intended environment.
	Reactor absorber	5-7	

Composed of a solar radiation capture system and a reactor for thermochemical hydrogen production, the system is characterized by several technological challenges preventing the technology’s development at higher maturity stages. These challenges are associated both with the own characteristics of the two stages and with the overall structure of the system.

The main technological challenges identified for the solar thermochemical hydrogen production system are reported in the following Table 21, together with the relative processing steps they are mostly linked to.

Table 21 - Main technological challenges linked to the solar thermochemical hydrogen production system

	Technological challenges	Processing step
Thermochemical Hydrogen Production System	Solar radiation captation system	Optimization of the system
	Reactor design and geometry	Overall structure of the system
	Electrodes	Overall structure of the system
	Electrolyte structure	Overall structure of the system
	Redox material	Overall structure of the system
	Hydrogen recovery	Downstream processing

Patent analysis

The patent analysis has been focused on patents registered over the timeframe between 2005 and 2020 dealing with the production of hydrogen from thermochemical pathway, as shown in the query detail in Table 22.

Table 22 - Queries utilised in the patent research for the selected solar thermochemical reactor

	Timeframe	Query	IPC code	Results (INPADOC families)
Query	01/01/2005 – today	((thermochemic*) AND (hydrogen))	-	160 (79)

In the following paragraphs a presentation of the main outcomes of the patent analysis is reported. It is worth considering that the results related to the last 18 months, i.e. results related to the year 2019 and 2020, are only partial.

Figure 55 reports the publication trend related to the patents focusing on the production of hydrogen from thermochemical pathway. It can be noticed that this field is characterized by a limited number of patents compared to other pathways; however, the interest in this field is growing, especially after 2015. This is an opposite trend compared to the trend for biofuels, because the production of hydrogen is not directly linked with the crude oil sector and therefore with its price.

Patent publishing trends

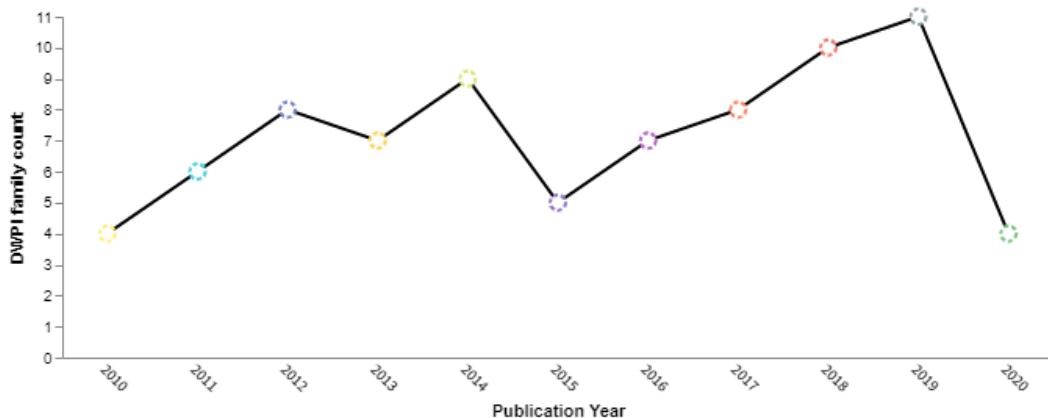


Figure 55 - Patent publication trend related to the production of hydrogen from thermochemical pathway

Regarding the patent assignees, i.e. the entities that have the property right to the patent, Figure 56 clearly shows that companies, universities or research centres from China and South Korea are leading in terms of number of patents submitted. The entities with the highest number of registered patents are Tsinghua University and China Nuclear Power Design Institute (6 patents each).

As already stated for other pathways, one of the main reasons for the high number of patents registered by Chinese and South Korean entities is linked to the increasing political support and incentives coming from local governments to boost the development of alternative fuels characterized by lower carbon dioxide emissions.

Top Optimized Assignees

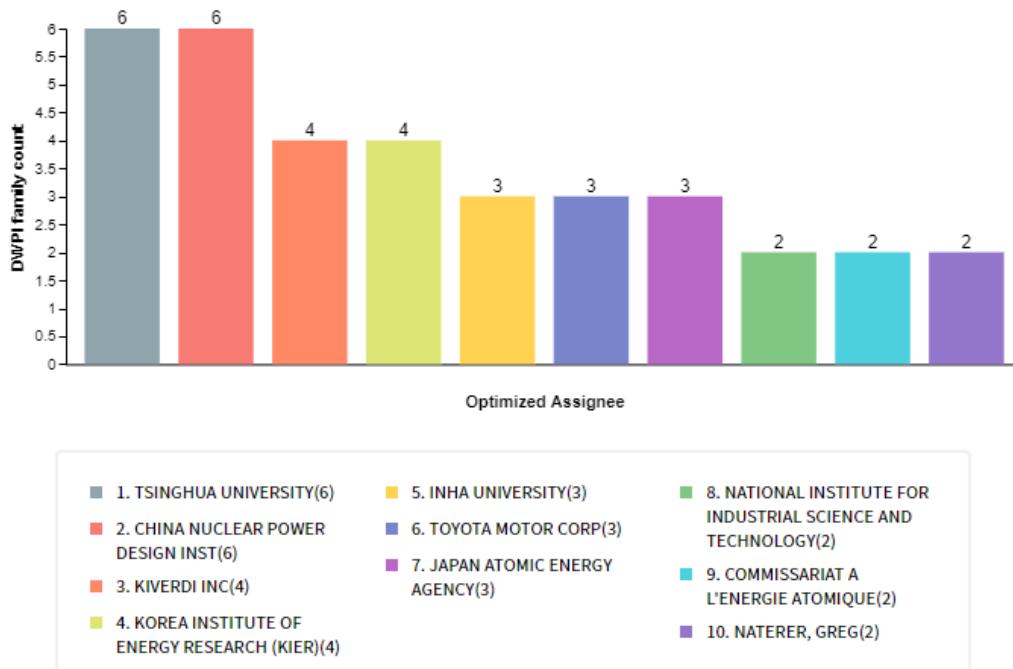


Figure 56 - Top assignees of patents concerning the production of hydrogen from thermochemical pathway

The overall scenario in the field of solar thermochemical hydrogen production systems is also confirmed by the patents distribution worldwide (Figure 57), where China (29 patents), United States (17 patents), South Korea (10 patents) and Japan (8 patents)

present the highest number of registered patents in the considered timeframe (2005 – 2020).

Top countries/regions

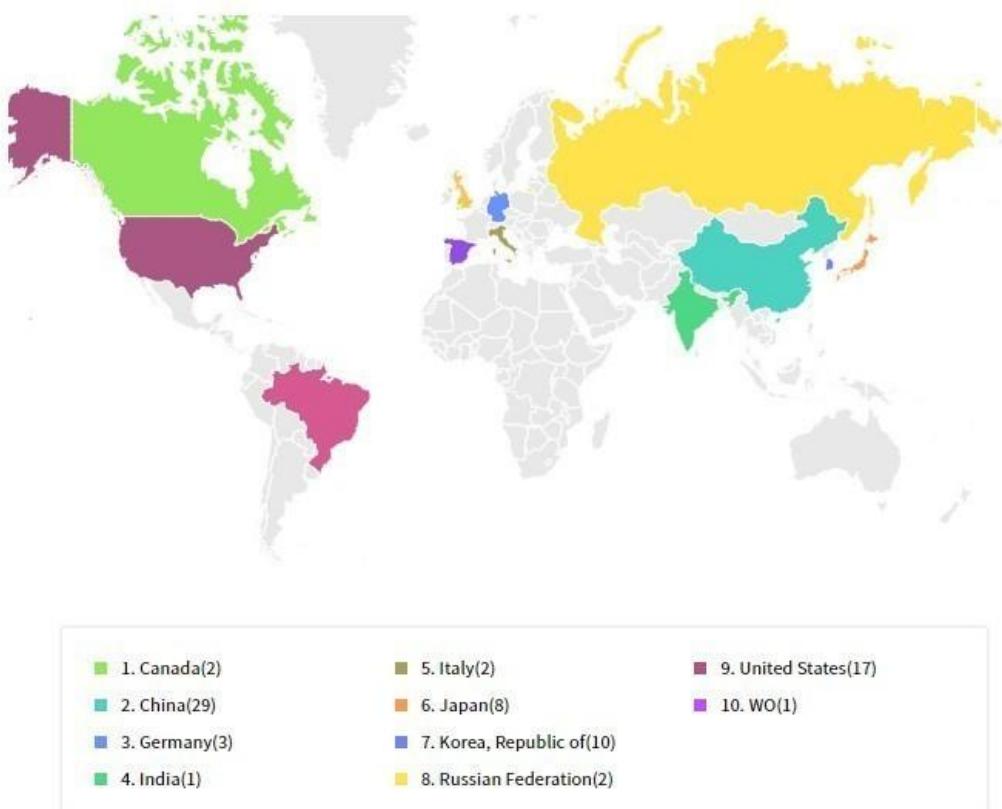


Figure 57 - Worldwide distribution of patents dealing with the production of hydrogen from thermochemical pathway

One of the aims of this first 'generic' query was to identify the most represented IPC code among the ones registered; this allowed focusing the subsequent part of the analysis, with the related queries, on a specific IPC code, i.e. the one that seems to be the nearest to the focus of the present study. In particular, as shown in Figure 58, the following IPC code proved to be the most appropriate: C01B/3 – "Production of hydrogen or of gaseous mixtures containing hydrogen" either generically (C01B/3/02 – 9 patents) or via different pathways, including "by reaction of inorganic compounds containing electro-positively bound hydrogen, e.g. water, acids, bases, ammonia, with inorganic reducing agents" (C01B/3/06 – 16 patents), "by decomposition of inorganic compounds, e.g. ammonia" (C01B/3/04 – 13 patents), "with metals" (C01B/3/08 – 9 patents).

Top IPCs

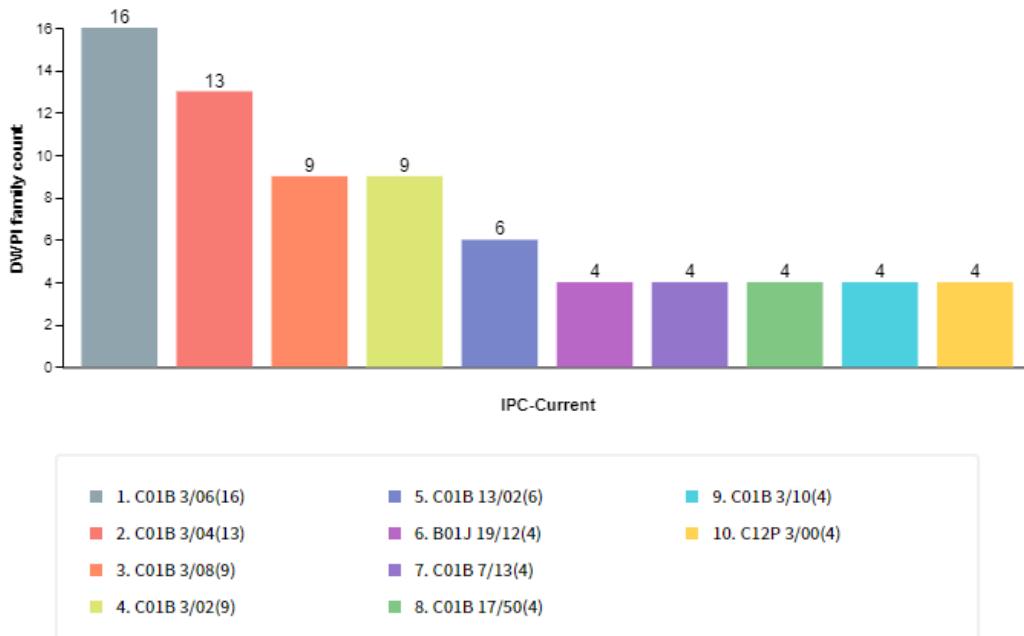


Figure 58 - Most represented IPCs among the patents linked to the production of hydrogen from thermochemical pathway

A selection of the patents identified through the patent analysis is reported in the Annexes.

SWOT analysis

The main strengths, weaknesses, opportunities and threats associated with the solar thermochemical hydrogen production system are summarized in the following sections.

Strengths:

- High efficiency since solar heat is directly fed to the reactor with no intermediate energy conversions (e.g. electricity);
- The process is reversible, i.e. the mediating oxygen-carrying material is typically not consumed or consumed at a very low rate;
- Solar radiation concentrating systems are an almost consolidated technology and however, knowledge from research on concentrated solar power is beneficial also to solar thermochemical hydrogen production;
- Energy input required is lower compared to other hydrogen production pathways;
- Compared to other solar fuel pathways, it produces a fuel characterized by zero-GWP both in the production and in the use phase.

Weaknesses:

- Efficiency and durability of reactant materials need to be improved;
- Reactor designs compatible with high temperatures and thermal cycles need to be developed;
- Storage systems for the produced gaseous fuel need to be improved in terms of resistance to high-pressure;
- Relatively long start-up of solar radiation-receiving reactor, reducing the potential number of daily and annual working hours;
- For some of the solutions under investigation, materials and membrane degradation issues (e.g. hybrid sulfur) need to be solved;
- For other solutions (e.g. photolytic sulfur ammonia), the identification of suitable non-precious catalysts needs to be carried out;
- Relatively large area required for solar radiation captation system based on mirrors;

- Relatively high O&M costs related to solar field and reactor management;
- The research on part of the initially proposed solutions (e.g. zinc oxide and partially sodium manganese) was terminated after negative results in the tests.

Opportunities:

- High-purity oxygen is a by-product of the hydrogen production process and can potentially be sold to the industrial market;
- Some of the emerging solutions (e.g. ALD Ferrite) seem promising regarding durability but significant research and testing efforts are still needed;
- Significant investments in research and demonstration activities are still needed, both regarding the system as a whole and its sub-components;
- Relatively low size of the hydrogen production reactor, therefore quite easy to test at laboratory scale;
- Costs of concentrating mirror systems are starting to decrease thanks to research activities in concentrated solar power generation;
- High fossil fuels prices can incentivize development of this alternative pathway.

Threats:

- Competition with other solar fuels and alternative hydrogen production pathways, including grey hydrogen ones, from fossil sources;
- Thermal energy demand is very high since a large amount of oxygen exchange material needs to be heated to allow reactions;
- Low heat recovery rate from exothermal step to endothermal step;
- Heat losses from the reactor strongly affect hydrogen production efficiency, thus significant amounts of refractory materials are needed;
- Many proposed solutions for this pathway (e.g. sulfur iodine) have been only successfully tested at laboratory scale, out of intended environment;
- Other solutions (e.g. photolytic sulfur ammonia) have been preliminarily tested at demonstrative level but conceptual design issues still exist.

Gap analysis

Based on the analysis carried out on the state-of-the-art and of the registered patents and summarized in the SWOT analysis in the previous section, the solar thermochemical pathway for the production of hydrogen is characterised by the presence of a series of barriers that hinder its development at commercial scale and the exploitation of its full potential.

First of all, it is recalled that the system is composed of three main parts, i.e. the solar radiation capture and concentration system, the thermochemical reactor for hydrogen production and the gas storage system and its interface with the distribution system.

In the present paragraph, focus is given to the thermochemical reactor, since this is the core part of the system and even because barriers related to the solar and the hydrogen parts are well known, analysed and investigated in-depth by many research activities carried out in the field.

Regarding the thermochemical reactor, since the fundamental principles are quite clear and many potential technical solutions have been identified and tested or under testing, the main barriers identified are those related to the materials to be used. Indeed, reactants, membranes, potential catalysts, refractory are the key elements to be analysed with further research activities in order to identify the most suitable materials in order to:

- Maximize hydrogen production efficiency in terms of output as chemical energy of hydrogen per unit of solar energy input (this aspect is mainly related to reactants and potential catalysts);
- Resist to high temperature and thermal cycles with sufficient durability (regarding all components);
- Ensure a sufficiently high internal heat recovery rate (regarding especially reactants);

- Reduce CAPEX and O&M costs (as a consequence of all the previous bullets and referring to all components, including but not limited to catalysts that are typically made of precious materials).

Technological roadmap

As outlined – out of the many documents and roadmaps available – by the European Commission in the “A hydrogen strategy for a climate-neutral Europe”⁶³, hydrogen is expected to play a key role in the energy transition.

According to the recent “Fuel Cells and Hydrogen 2 Joint Undertaking” report, published in 2019 and focusing on “Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition”⁶⁴, hydrogen can account for 24% of final energy demand, reduce GHG emissions by 560 million tCO₂/y and employ 5.4 million people in the EU by 2050.

The role of hydrogen in decarbonization will be especially important in the gas grid, the transport sector and in industrial processes requiring high-grade heat and hydrogen as chemical feedstock. Moreover, the development of hydrogen technologies could support the electrification of the European economy allowing large-scale seasonal storage for electricity produced from intermittent renewables, as well as the efficient transport of energy across different regions.

Of course, hydrogen can be produced via many alternatives, starting from conventional options like steam reforming of methane or gasification of coal, i.e. the so-called “grey hydrogen” production paths, or through more eco-friendly options, the so-called “green hydrogen” production processes. Among “green hydrogen” pathways, direct and indirect solar-based solutions are present, including solar electricity production+electrolysis pathways and solar thermochemical cycles.

Solar hydrogen produced via thermochemical pathways shall therefore face the competition with other production processes in terms of technology readiness level, production costs and environmental issues including GHG emissions.

Although the comparison in terms of LCOE is done in the economic roadmap section of the present assignment, it is important to mention in this roadmap that a significant factor influencing the potential diffusion of solar thermochemical hydrogen production is the price of conventional fossil fuels, mainly represented by crude oil. Indeed, with current oil prices around 50 USD/barrel and the consequent low level of gas prices, the potential for penetration of solar thermochemical pathways in the hydrogen production market is very low. An oil price of at least 100 USD/barrel, or on the other hand a significant taxation on GHG emissions, would be needed in order to allow an enhanced competition of solar fuels with conventional ones.

Based on the above, provided that oil & gas prices will increase as expected and that public support to the hydrogen sector and specifically to solar fuels will be confirmed by the European Commission and Member States Governments as per the principles of the Green New Deal for Europe and of the Next Generation EU recovery plan after COVID-19 pandemic, the following timeline could be foreseen for solar thermochemical hydrogen production systems:

- The identification of the most suitable materials following the gaps identified in the previous paragraph can be completed in a 5-year timeline, thus achieving the demonstration at TRL 6 of a pilot plant in real operational environment by 2025; the pilot is expected to have a size of at least 250-300 kWt in terms of thermal power and an efficiency of 15% from solar radiation to fuel and to have sufficiently good heat recovery and materials separation rates;

⁶³ https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

⁶⁴ https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf

- Based on the outcomes of the pilot plant, further research is made aimed at increasing the competitiveness of the technology through two main pillars, i.e. an increase of the efficiency and a reduction of the hydrogen production costs, both potentially linked to the reduction of the process operating temperatures; following these further improvements, a full-scale demonstrator at TRL 7 is achieved by 2030; the reduction of costs will also benefit of the research carried out in parallel on the solar components of concentrated solar power plants;
- after the minor updates and optimization activities are carried out based on the testing under a full range of different working conditions of the full-scale demonstrator, the first-of-a-kind plant is realized around 2035 and a full commercial development of the technology is reached in the immediately following years.

The above outlined timeline is summarized in the technological roadmap chart shown in Figure 59.

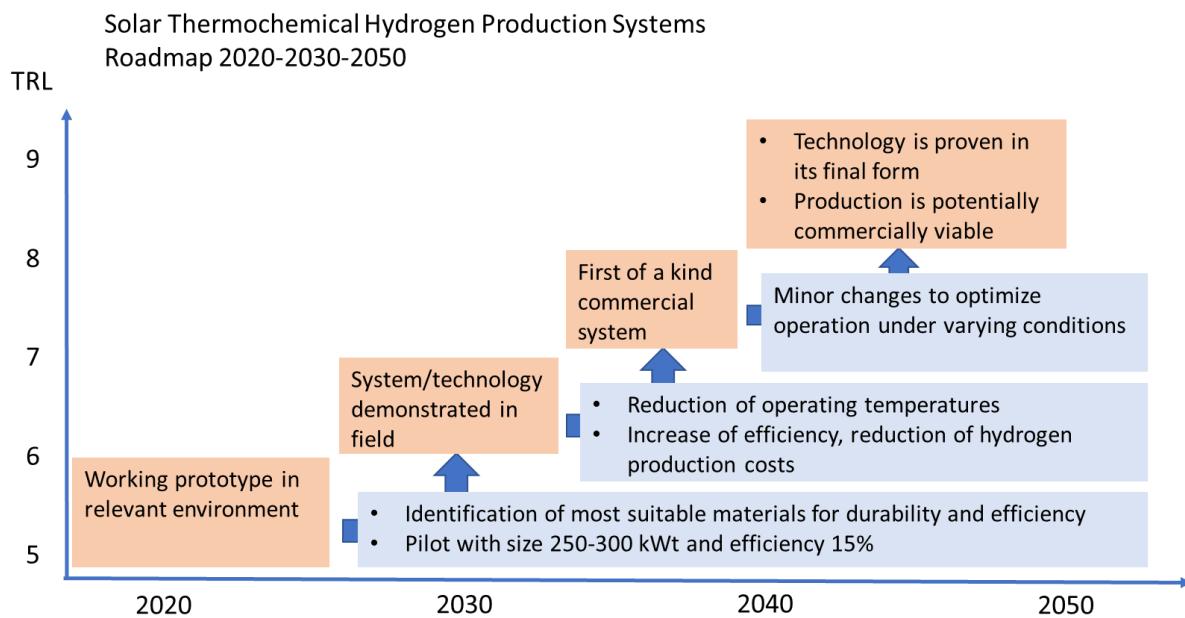


Figure 59 - Technological Roadmap for Solar Thermochemical Hydrogen Production Systems

2.1.4. Biochemical pathway

In the present study two main technologies have been taken into consideration as representative cases to describe the biochemical pathway towards solar fuels. They consist in biohybrid systems and in microalgae-based systems (Figure 60).

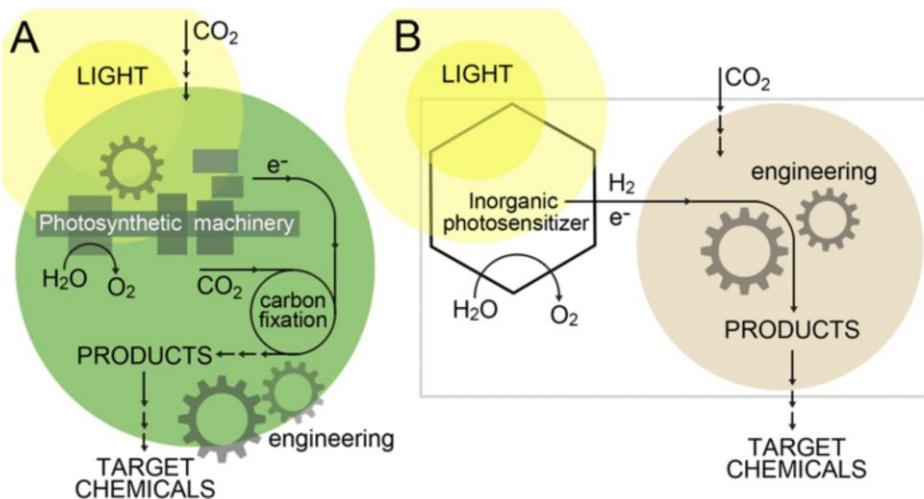


Figure 60 - Comparison between photosynthetic microbial system (e.g. microalgae, cyanobacteria) and biohybrid system⁶⁵

2.1.4.1. Biohybrid systems

The concept behind biohybrid systems aims at combining a photoelectrochemical stage with a biocatalytic step: the light harvesting step based on inorganic photosensitizer provides reducing equivalents such as H₂ or electrons to the non-photosynthetic microorganisms in suspension or in biofilm, which are responsible for the production of the targeted biofuels.

State of the art and identification of the main technological challenges

The state of the art of the identified technology with the current TRL of the related components was assessed. This was the outcome of the activities carried out within the value chain analysis, i.e. literature analysis and TRL 'stage-gate approach', as well as of the inputs collected during the workshops from the stakeholders.

The following Table 23 summarises the TRL of each component of the biohybrid system, along with the associated checkpoint corresponding to the 'TRL 2-3'.

Table 23 - TRL of each component of the biohybrid system

	Technology component	TRL	'Main checkpoint'
Biohybrid system	Light absorber	2 - 3	For all the respective components the technological concept is defined
	Anode	2 - 3	
	Cathode	2 - 3	
	Engineered bacteria	2 - 3	

⁶⁵ Nrskov, J. K., Latimer, A., & Dickens, C. F. (2019). Research needs towards sustainable production of fuels and chemicals. Energy-X project roadmap (figure courtesy of P. Kallio, Turku Synthetic Biology team)

Composed by a photoelectrochemical structure and a microbial part, the system presents several technological challenges preventing its further development at higher stages. These challenges are associated both with the own characteristics of the two stages and with the overall structure of the system, including the way the two subsystems (i.e. the photoelectrochemical and the biological part) are linked.

The main technological challenges identified for the biohybrid system are reported in the following Table 24, together with the relative processing steps they are mostly linked to.

Table 24 - Main technological challenges linked to the biohybrid system

	Technological challenges	Processing step
Biohybrid system	Efficiency	Light absorbing O ₂ evolution H ₂ evolution Overall structure of the system
	Bacteria-electrode interface	Overall structure of the system
	Reactor design	Overall structure of the system
	Hydrogen or electrons transfer and capture by bacteria	Overall structure of the system Biofuels production through fermentation
	Bacteria growth	Biofuels production through fermentation
	Fermentation yields	Biofuels production through fermentation
	Fuel recovery	Biofuels production through fermentation Downstream processing

Patent analysis on biohybrid systems

The patent analysis dealing with biohybrid systems revealed some difficulties, mainly linked to the novelty of the concepts behind such systems, as well as the lack of homogenous terminology used to identify these. For example, a query based on 'bionic leaf' did not result in any patent using such term.

In this framework, several attempts and iterations have been carried out in order to better focus the research and identify patents that specifically deal with biohybrid system.

Starting from these considerations, the patents search was based on queries (Table 25) addressing both the technology framework (i.e. artificial photosynthesis coupled with 'bio' elements) and a specific inventor (Professor Daniel G. Nocera from Harvard University): the latter allowed to identify some specific examples of patents related to biohybrid systems targeting different biofuels.

Table 25 - Queries utilised in the patent research for biohybrid systems

	Timeframe	Query	IPC code	Results (INPADOC families)
Query 1	01/01/2005 – today	((artificial ADJ photosynthesis) and (bio*))	-	67 (31)
Query 2		INVENTOR=(Nocera)	-	354 (114)

Due to the low number of results specifically focused on biohybrid systems, it was not possible to analyse either the patent publishing trend or the patents distribution among assignees or countries. For this reason, some examples of patents, also dealing with processes for ammonia production, that are currently valid ('alive') are reported among the Annexes.

Along with the patents reported in the Annexes, other patents identified through the applied queries focused on a specific technology or component of the biohybrid systems: this is the case for example of patents dealing with photoelectrochemical materials, specific enzymes or artificial photosynthesis devices.

SWOT analysis

The main strengths, weaknesses, opportunities and threats associated with the biohybrid systems are summarised here below. They are mainly derived from literature analysis, patent analysis and direct stakeholders' consultation through surveys, workshops and dedicated calls.

Strengths

- Exploitation of natural biologic processes by coupling them with (electro)chemical devices;
- The use of 'self-regenerating' microorganisms reduces the need for potentially critical raw materials;
- Several experts in different technological fields (e.g. photochemistry, electrochemistry, physics, biology) are working together in the field of artificial photosynthesis and similar systems (such as the biohybrid solutions);
- Mainly depending on the microbial strains used, different products can be targeted;
- CO₂ from other processes can be potentially used to feed the microorganisms;
- Microorganisms need CO₂ to grow, thus lowering GHG emissions;
- The process entails mild operating conditions.

Weaknesses

- Genetic modification of strains and/or enzymes is needed (it is a time-consuming process);
- Durability of materials can be affected by operating under discontinuous sunlight;
- Solar-to-fuels efficiency is still low and needs improvements to be become competitive against alternative solutions;
- Transfer mechanisms, especially at the bacteria-electrode interface, should be further investigated;
- Specific reactor design has to be improved to increase the overall efficiency and pave the way to the upscaling of such technologies;
- The technology is currently developed at very low TRL (TRL 2-3);
- Growth rate in some species needs to be improved;
- Fermentation yields have to be enhanced to allow further developments at higher scales;
- An effective recovery of the targeted biofuels should be further implemented.

Opportunities

- Market opportunities exist for sustainable fuels and their demand should increase in the future;
- More advanced research activities focusing on similar devices utilised to produce fine chemicals can be exploited;
- Genetic engineering can increase the yields in the target products;
- Increasing interest in artificial photosynthesis and in technological devices able to couple different pathways;
- Technology transfer of valuable solutions from other pathways may foster the development and enhancement of biohybrid systems;
- Potential incentives for market deployment of solar fuels;
- Potential incentives for CO₂ utilisation;

- High demand for bio-based products as sustainable alternatives for fossil-based counterparts;
- Synthetic biology concepts and their increasing progress can help boosting the development of biohybrid systems.

Threats

- Low industrial investments or interest in this technology (up to now research is mainly coming from academia or research centres);
- Competition with other production pathways for alternative fuels, including biofuels from other bio-based feedstocks;
- Low or fluctuating oil and carbon prices can significantly affect the market deployment of biofuels;
- Potential issues related to the supply of critical raw materials potentially used for the electrodes;
- Low public acceptance of technologies involving genetic-modified microorganisms;
- Potential shortage of (critical) raw materials needed for the photoelectrochemical part of the system.

Gap analysis

As previously mentioned, biohybrid systems aim at effectively coupling a photoelectrochemical device and a biocatalytic part mainly based on the use of engineered bacteria in suspension or in biofilm.

Although research in these systems is being carried out⁶⁶, several constraints still exist that hinder the upscaling of biohybrid systems at higher TRL.

Further actions are needed to improve the efficiency in the metabolic processes: by exploiting genetic engineering and synthetic biology concepts, the development of enzymatic systems able to increase the stability and improve the metabolic activities of the bacteria, also in terms of selectivity and productivity in the targeted products, is needed.

Along with improvements dealing with the biocatalytic part, specific interventions are also needed for the photoelectrochemical section, in particular:

- Enhancing the light absorption of the materials, e.g. by increasing the light spectrum utilisation and the light harvesting efficiency of the photoactive materials;
- Optimising transfer mechanisms of the reducing equivalents from the photoelectrochemical cell to the bacteria, by also minimising losses and potential side-reactions;
- Increasing the durability of the materials used in the photoelectrochemical part, which can be also affected by discontinuous and variable light intensity;
- Investigating for new and less critical materials to be applied in the photoelectrochemical section;

Finally, the reactor's design and configuration, including its shape, may play a significant role, targeting an increased stability of the system and the effective integration of the various components.

Technological roadmap

In the following Figure 61 the main actions to be carried out in order to reach a large-scale deployment of solar fuels production based on biohybrid system are summarised.

⁶⁶ Li, J., Tian, Y., Zhou, Y., Zong, Y., Yang, N., Zhang, M., Guo, Z., Song, H. (2020). Abiotic-Biological Hybrid Systems for CO₂ Conversion to Value-Added Chemicals and Fuels. *Transactions of Tianjin University*. 26, 237–247.

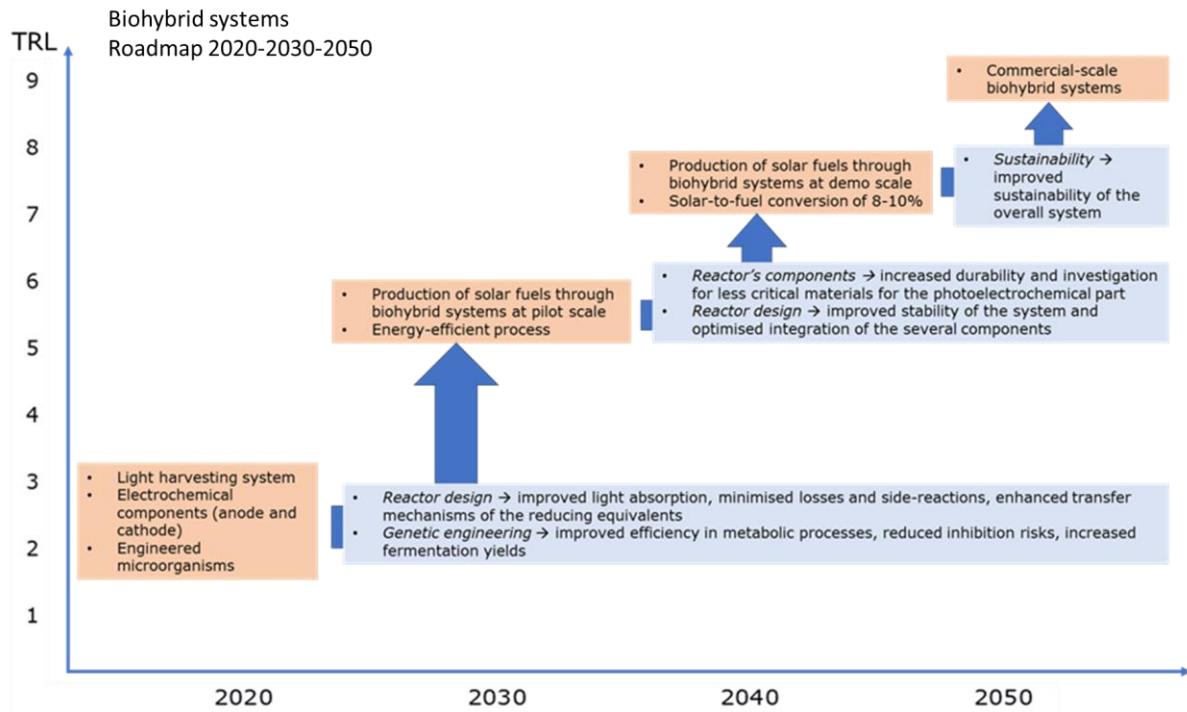


Figure 61 - TRL vs. Timing for biochemical pathway for solar fuels based on biohybrid system

Considering the current low TRL (TRL 2-3) of the biohybrid system, it is estimated that this technology may reach a full commercial scale by 2040-2050. Several improvements are indeed required and many challenges have to be overcome for such systems integrating photoelectrochemical and biological components.

It should also be considered that technological issues are only one of the aspects affecting the potential TRL advancements. Other aspects related to economic, social and political perspectives are also important.

In order to accelerate the developments and boost the research on biohybrid systems, a more direct involvement of industry is needed, with investments in artificial photosynthesis (AP) and related technologies.

Biohybrid systems and solar fuels derived from them can indeed represent sustainable alternatives for existing counterparts mainly consisting in fossil-based processes and products.

During the development of new technologies and in order to pave the way for their upscaling, social aspects and public acceptance should be always taken into account, by also implementing specific campaigns to increase public awareness on the benefits and potential sustainability of the developed solutions. In the context of biohybrid systems, these considerations are even more relevant because they entail the use of genetic modified microorganisms (GMOs) and potentially critical raw materials for the photoelectrochemical components. Moreover, the potential land use that may be required for the implementation of such technologies at higher scales should be also investigated.

As for the case of biofuels and for other configurations entailing the use of CO₂, the investments and the advancements in the research can be significantly affected by the oil price (and consequently by the market prices of fossil-based fuels) and by carbon taxes.

In this framework, political support and incentives may represent an important boost to the investigation of biohybrid systems and artificial photosynthesis in general as potential and effective alternatives for the production of fossil-based fuels and other kind of products.

Finally, as reported in the study published by the European Commission "Artificial Photosynthesis: Potential and Reality"⁶⁷, the protection of intellectual property rights represents an important aspect to be considered, especially when technologies at very low TRL are involved. Focusing on Europe, for example, the EC's report states that "it will be important to both protect European intellectual property rights while also follow global developments in AP-related patent-protected technologies, thereby ensuring that Europe has a secure strategic position in the AP field and avoiding potentially damaging dependencies on non-European technologies".

2.1.4.2. Microalgae-based systems

Another biochemical concept in the framework of solar fuels technologies is based on the use of phototrophic microorganisms such as microalgae and cyanobacteria, which are able to exploit solar light as energy source and carbon dioxide as main carbon source in order to produce specific compounds such as carbohydrates or lipids. The latter can be then recovered from the cells and used to produce different biofuels, among other bioethanol and biodiesel, through chemical or biological processes.

State of the art and identification of the main technological challenges

Starting from the activities carried out within the value chain analysis and considering the feedback gathered from stakeholders during our project workshops, the state of the art of microalgae-based technology along with the current TRL of each component of the value chain was assessed, as reported in the Table 26 below.

Table 26 - TRL of each component of the microalgae system

	Technology component	TRL	'Main checkpoint'
Microalgae system	Media preparation	7 – 8	For these 2 components the technology is demonstrated in field under different working conditions
	CO ₂ storage	7 – 8	The technology is demonstrated at pilot scale in working environment conditions
	Open pond/Photobioreactor	6	A large-scale laboratory prototype is realized and tested in intended working environment
	Light harvester and sparger	5	For these 2 components the technology is demonstrated in field under different working conditions
	Mixing/recirculation system	7	The technology is demonstrated at pilot scale in working environment conditions
	Microalgae harvesting and dewatering	7	For these 2 components the technology is demonstrated at pilot scale in working environment conditions
	Biofuel extraction (e.g. algal biomass pre-treatment, saccharification, fermentation)	6	For these 2 components the technology is demonstrated at pilot scale in working environment conditions
	Products from microalgae: purification	6	

Due to the complexity of the process and the different steps requiring specific operating conditions and control, microalgae-based value chains targeting the production of biofuels still entail several technological challenges to be overcome towards an effective deployment of such technologies at commercial scale

The main technological challenges identified for the microalgae system are reported in the following Table 27, together with the relative processing steps they are mostly linked to.

⁶⁷ European Commission, Directorate-General for Research & Innovation (Nov 2016). Artificial Photosynthesis: Potential and Reality.

Table 27 - Main technological challenges linked to the microalgae system

	Technological challenges	Processing step
Microalgae system	Light penetration and distribution in the cultivation system	Cultivation
	Mixing in the cultivation system (i.e. light, nutrients, air and CO ₂ distribution within the microalgae culture)	Cultivation
	Recovery of the targeted compounds (e.g. carbohydrates) from the dewatered algal biomass	Harvesting and dewatering Biomass processing
	Yields in the saccharification step	Biomass processing
	Yields in the fermentation step	Biofuel production
	Fuel recovery (downstream processing)	Biofuel production

Patent analysis on microalgae-based systems

The queries to be used for the patent search have been defined by means of successive iterations, in order to eliminate the "noise" generated by results not relevant for the objective of the search.

Firstly, the analysis has been focused on searching for patent, in a timeframe from 2005 to 2020, dealing with the production of biofuels, in particular bioethanol and biodiesel, from microalgae. The following queries have been built starting from the specific IPC code associated with microalgae, focusing on more specific aspects or processing steps in the framework of microalgae-based value chains, such as cultivation, harvesting and dewatering, as well as concepts dealing with the engineering of microalgae strain. The following Table 28 reports the queries utilised for the patent analysis of the microalgae-based biochemical pathway.

Table 28 - Queries utilised in the patent research for microalgae-based systems

	Timeframe	Query	IPC code	Results (INPADOC families)
Query 1	01/01/2005 – today	((microalgae) AND (biofuel OR bioethanol OR biodiesel))	-	2276 (973)
Query 2		(cult* AND ((open ADJ pond*) OR (photobioreactor OR PBR))) NOT (protein OR food OR feed)	C12N 1/12	1000 (392)
Query 3		((harvest* OR dewater*)) NOT (protein OR food OR feed)	C12N 1/12	
Query 4		(biofuel OR bioethanol OR biodiesel)	C12N 1/13	

Below is the explanation of the IPC code used in the analysis:

- C12N: Microorganisms or enzymes; Compositions thereof; Propagating, preserving, or maintaining microorganisms; Mutation or genetic engineering; Culture media;
- C12N/1: Microorganisms, e.g. protozoa; Compositions thereof; Processes of propagating, maintaining or preserving microorganisms or compositions thereof; Processes of preparing or isolating a composition containing a microorganism; Culture media therefor;

- C12N1/12: Unicellular algae; Culture media therefore;
 - C12N1/13 Unicellular algae; Culture media therefor; modified by introduction of foreign genetic material.
- In the following paragraphs a presentation of the main outcomes of the patent analysis is reported. It is worth considering that the results related to the last 18 months, i.e. results related to the year 2019 and 2020, are only partial.

Patent analysis on the scenario concerning the production of biofuels, in particular bioethanol and biodiesel, from microalgae

Figure 62 reports on the publication trend related to the patents focusing on the production of biofuels from microalgal biomass. As it can be seen, the interest in this field has significantly grown at least until 2015, while in the last years the number of submitted patents decreased: this can be mainly associated with the crisis of the crude oil sector, with the subsequent decrease of oil price. This situation has probably affected the biofuels sector, thus decreasing the related interest and search for fuels from alternative sources such as bio-based feedstock.

The influence of oil crisis is further confirmed by the fact that the patents dealing with microalgae in general or microalgae targeting products different from biofuels (e.g. ingredients for food, feed, nutraceuticals, cosmetics) present an increasing or at least stable trend, proving that the interest in this specific bio-based sector is still alive.

Patent publishing trends

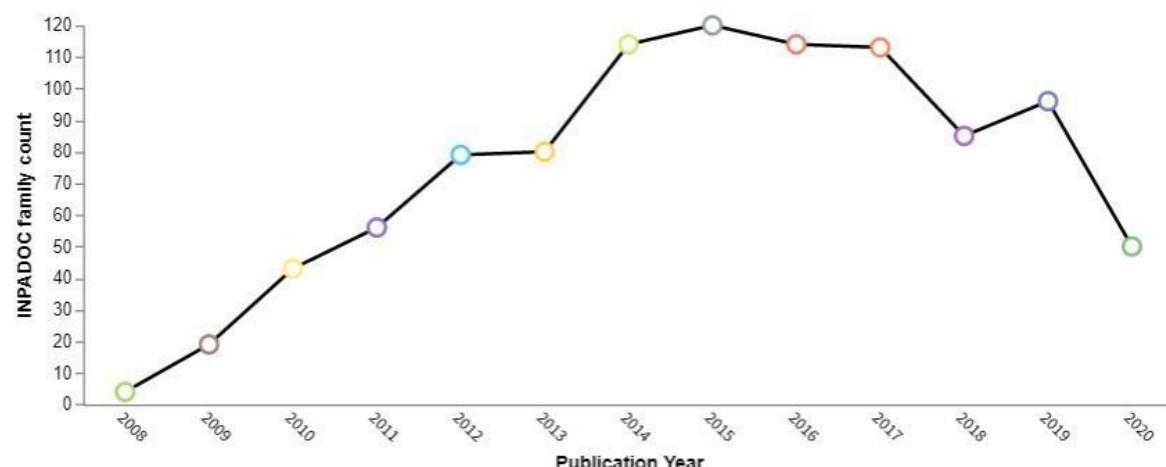


Figure 62 - Patent publication trend related to the production of biofuels from microalgae

Regarding the patent assignees, i.e. the entities that have the property right to the patent, Figure 63 clearly shows that companies, universities or research centres from China and South Korea are leading in terms of number of patents submitted.

Indeed, although the top assignee results to be TerraVia Holdings Inc (formerly Solazyme), this US biotechnology company has changed its focus from biofuel to other bioproducts since around 2016. Indeed, from 2005 until around 2016, the company was deeply involved in the microalgal biofuels sector, especially for jet fuel and biodiesel. However, due to the low oil prices and the uncertainty of US government policies in the biofuel sector, Solazyme officially changed its name to TerraVia Holdings Inc. in March 2016 and moved its focus on different sectors such as food, nutrition and personal care⁶⁸.

One of the main reasons of the high number of patents registered by Chinese and South Korean entities is to be linked to the increasing political support and incentives coming from Chinese and South Korean governments aiming to boost the development of biofuel,

⁶⁸ <https://biofuels-news.com/news/solazyme-abandons-algal-biofuels-refocuses-on-food/>

especially biodiesel, production. This is mainly linked to the fact that China and South Korea are one the main emitters of carbon dioxide, with a subsequent need to identify sustainable technologies able to capture and use CO₂, as well as look for alternatives for fossil-based fuels (which are mostly imported).

Top Optimized Assignees

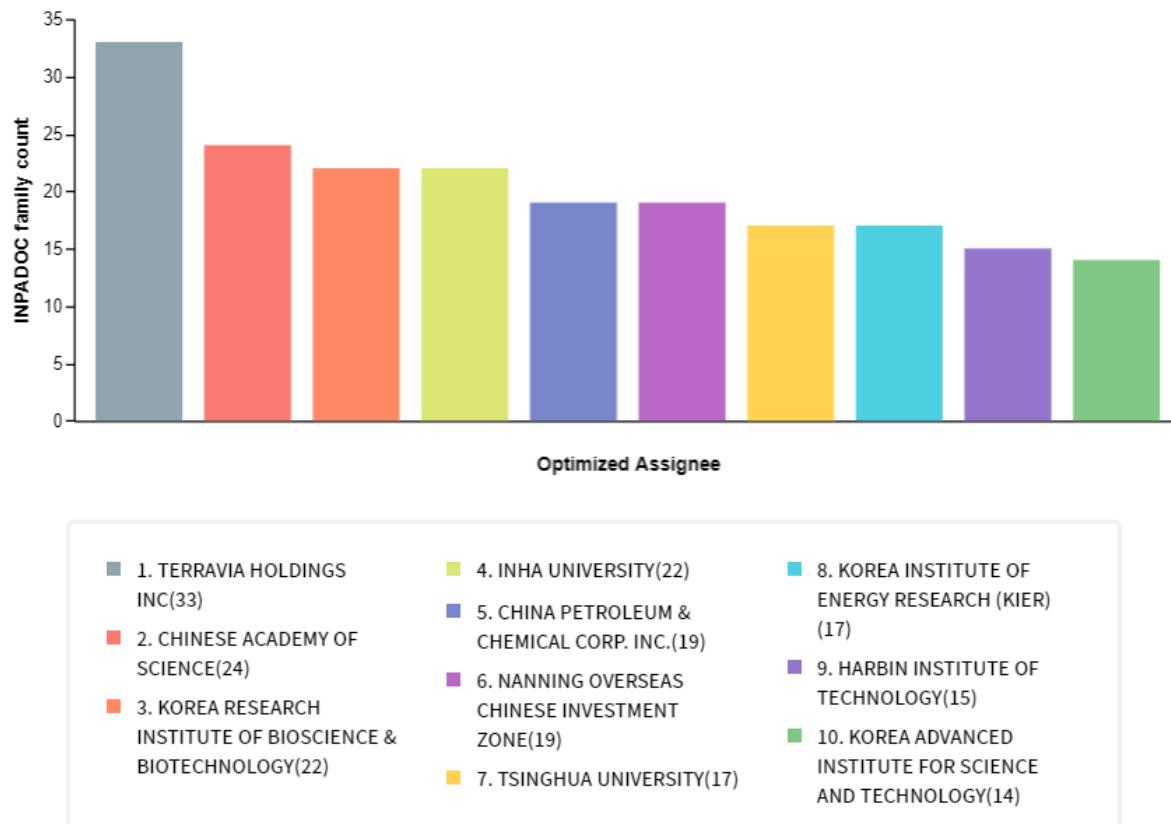


Figure 63 - Top assignees of patents concerning the production of biofuels from microalgae

The overall scenario in the field of microalgal biofuels is also confirmed by the patents distribution worldwide (Figure 64), where China, South Korea and United States present by far the highest number of registered patents in the considered timeframe (2005 – 2020).

Top countries/regions

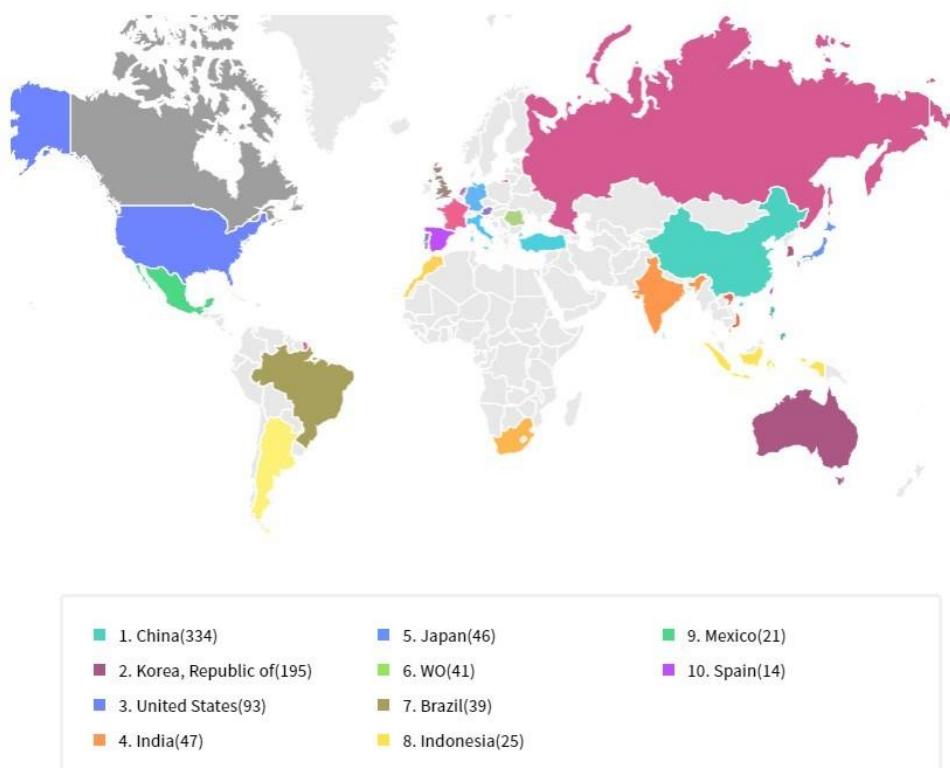


Figure 64 - Worldwide distribution of patents dealing with the production of biofuels from microalgae

One of the aims of this first 'generic' query was to identify the most represented IPC code among the ones registered in the field of microalgae-based biofuels. This allowed focusing the subsequent part of the analysis, with the related queries, on a specific IPC code, i.e. the one that seem to be the nearest to the focus of the present study. In particular, the following IPC code proved to be the most appropriate: C12N 1/12, dealing with "unicellular algae".

Top IPCs

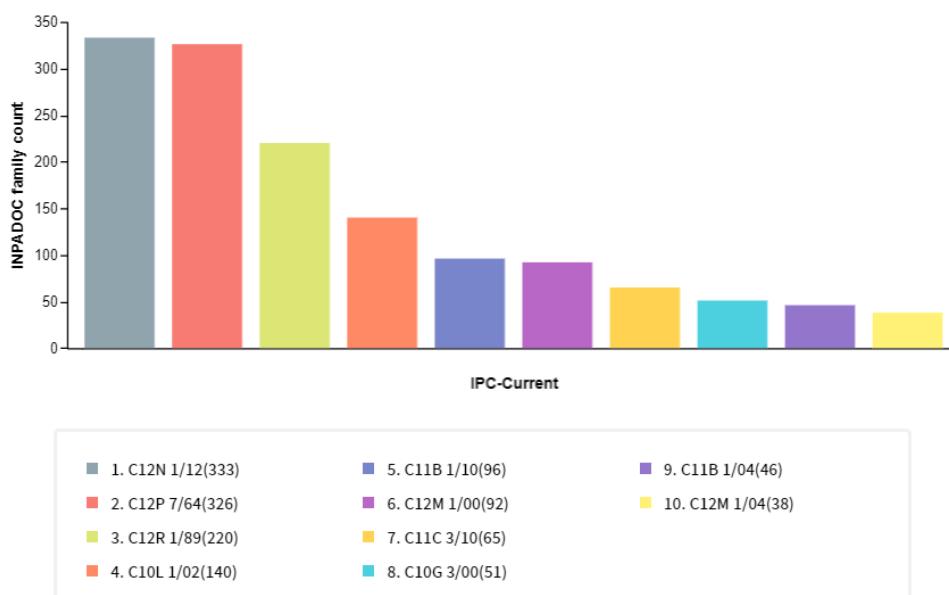


Figure 65 - Most represented IPCs among the patents linked to the production of biofuels from microalgae

Patent analysis aiming to investigate aspects linked to the cultivation phase

Starting from the IPC code specifically focusing on unicellular algae, a separate patent analysis has been carried out in order to further investigate a specific aspect of the value chain, i.e. the cultivation technologies, which currently represent one of the main technological constraints still preventing the sustainable and efficient deployment of microalgae-based pathway at higher scales.

Even though the technological concepts linked to microalgae cultivation do not directly depend on the final bioproducts that are targeted, the analysis focused on microalgae cultivation systems that do not explicitly address the production of proteins and/or ingredients for food and feed.

Figure 66 shows that the number of patents linked to microalgae cultivation systems have grown at least until 2012, when they have quadrupled. In the following year the patents application was almost stable, with a drop from 2015 to 2018: this decreasing trend may be associated with the parallel fall of oil prices which significantly affected the research and interest in the biofuels sector (including biofuels from microalgae). Even though 2019 and 2020 data are only partial, the graph shows a recovery in the publication of patents dealing with microalgae cultivation: it is worth considering that patents published in 2019 and 2020 have been developed and applied between 2017 and 2018, taking into account 18 months as timeframe between patent's application and publication.

Patent publishing trends

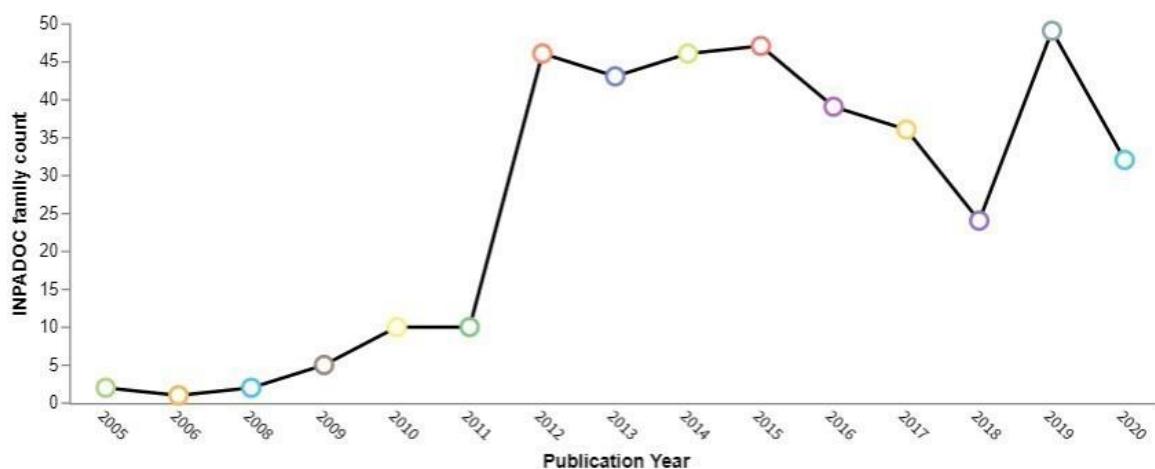


Figure 66 - Patent publication trend related to microalgae cultivation systems

As it can be seen in the following Figure 67 and Figure 68, the distribution of patents between countries mostly confirms the observation of the first analysis focused on the production of microalgal biofuels: China, South Korea, United States and India present the highest number of patents submitted, with assignees belonging both to the academia world and to the industry, including oil-based industry (see for example China Petroleum Chemical Corporation, i.e. Sinopec Group⁶⁹).

⁶⁹ <http://www.sinopecgroup.com/group/en/technologicalinnovation/Newenergy/>

Top Optimized Assignees

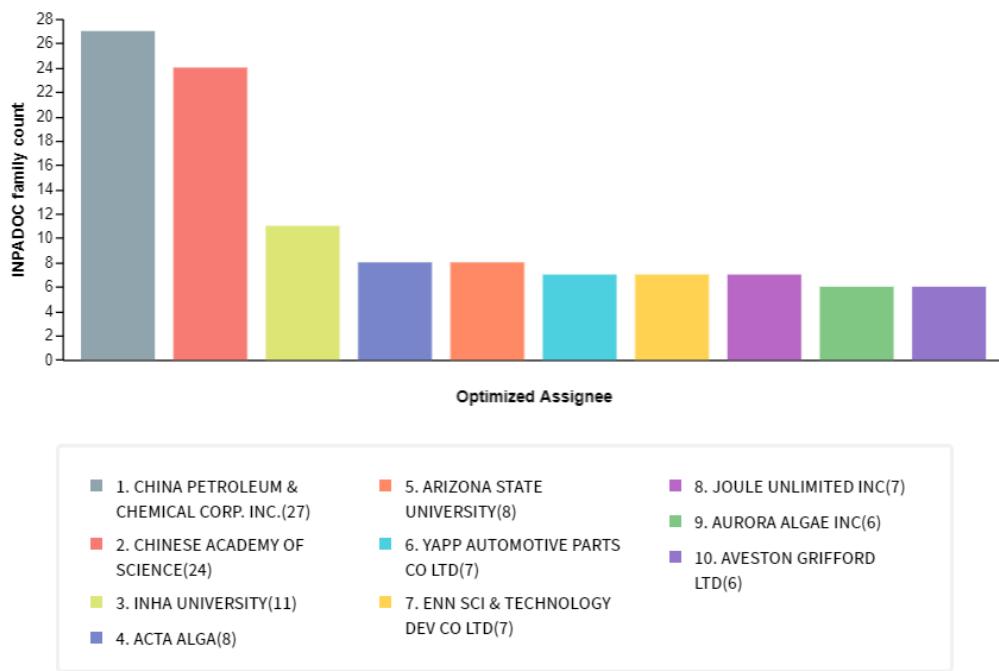


Figure 67 - Top assignees of patents concerning microalgae cultivation systems

Top countries/regions

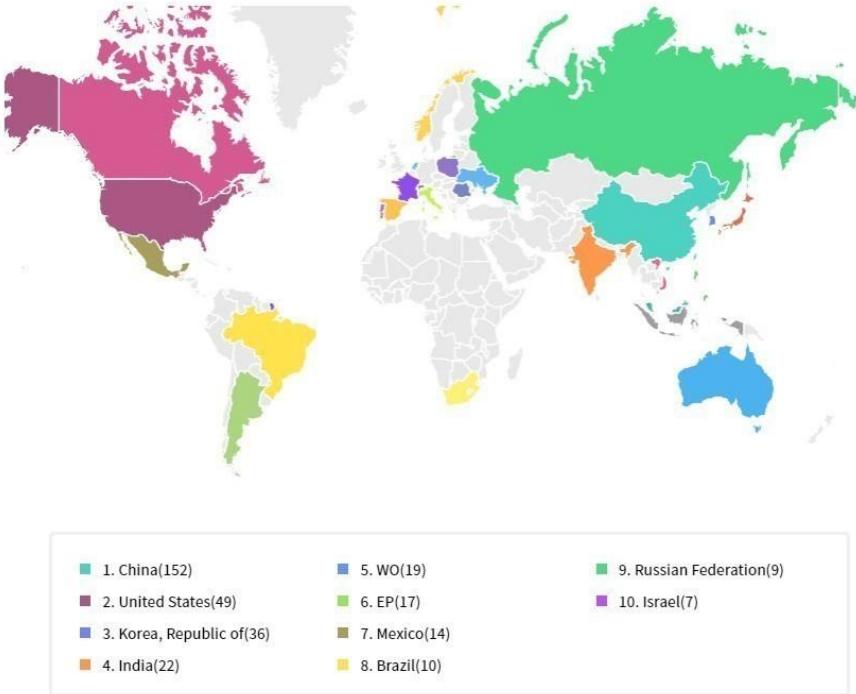


Figure 68 - Worldwide distribution of patents dealing with microalgae cultivation systems

In the framework of microalgae cultivation, the patents deal with several aspects and technological challenges, such as system design (both on open ponds and photobioreactors), CO₂ capture, mixing and distribution, harvesting.

Some examples of patents investigated by means of this second search query are reported in the Annexes.

Patent analysis aiming to investigate aspects linked to the harvesting and dewatering phases

Another specific aspect that has been investigated is related to the harvesting of microalgae from the cultivation medium and the dewatering phase of the harvested microalgal biomass. Most of the patents extracted through this query were already included in the analysis of the cultivation systems previously performed. However, additional patents have been identified (some examples are reported in the Annexes), specifically aiming to identify and develop solutions able to overcome the current challenges linked to these relevant stages within microalgae-based value chains.

Patent analysis aiming to investigate aspects linked to the engineering of microalgal strains

A further patents search focused on technological concepts associated with methods aiming to enhance microalgae efficiencies and productivities in the targeted bioproducts: this is the case for example of engineering approaches with the objective of increasing the production of lipids or other microalgal metabolites to be then converted to biofuels.

Figure 69 shows a fluctuating trend in terms of patent publication over the years: patents dealing with the engineering of microalgae to boost the production of biofuels started to be published just over 10 years ago, with a subsequent increasing and decreasing trend over the following years. In particular, after a drop from 2015 to 2018, a renewed interest in this field can be linked to the increase of the patents published in the last years (partial data for 2019 and 2020).

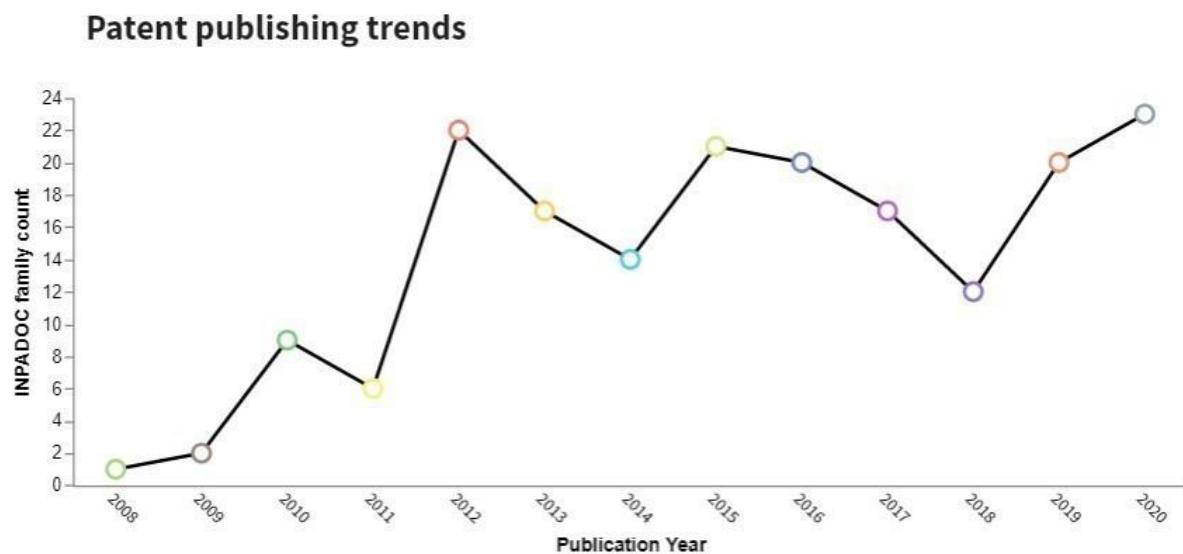


Figure 69 - Patent publication trend related to the engineering of microalgae targeting biofuels

Considering the top assignees identified by this search query (Figure 70), US entities are the most represented ones, along with Chinese and Japanese academia and industries. Most of the assignees reported in the graph are entities deeply involved in biotechnology, biofuels and alternative energy sources.

Top Optimized Assignees

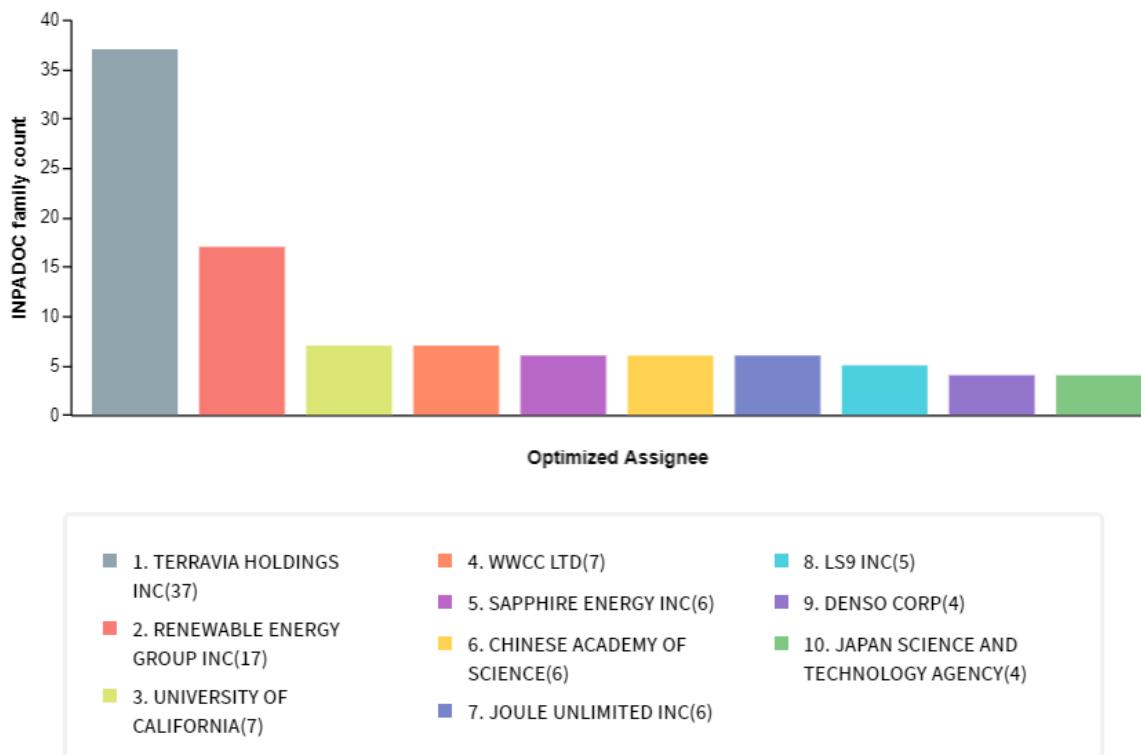


Figure 70 - Top assignees of patents concerning the engineering of microalgae targeting biofuels

Considering the patent distribution among the countries (Figure 71), it is worth noting that countries that were not in the driver's seat concerning patents on microalgal biofuels in general or microalgae cultivation, harvesting or dewatering system, are instead involved in this specific field dealing with engineering and advanced biotechnological approaches applied to microalgae: this is the case e.g. India, Japan, Mexico, Singapore, Indonesia, Australia.

Top countries/regions

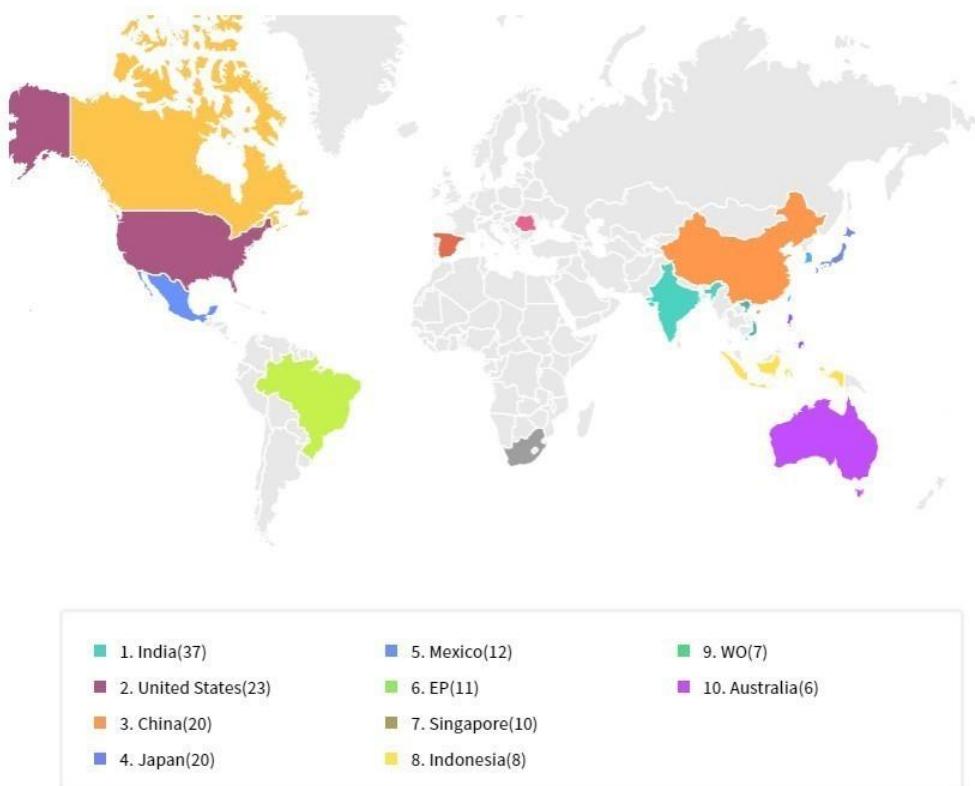


Figure 71 - Worldwide distribution of patents dealing with the engineering of microalgae targeting biofuels

Some examples of patents related the genetic engineering of microalgae for biofuels production are reported in the Annexes.

SWOT analysis

The main strengths, weaknesses, opportunities and threats associated with the microalgae-based value chains are summarised here below. They are mainly derived from literature analysis, patent analysis and direct stakeholders' consultation through surveys, workshops and dedicated calls.

Strengths

- Pressure on lands is lowered, especially in case of cultivation systems based on photobioreactors;
- Algal cultivation does not compete with food chain and can be implemented on lands (e.g. marginal lands) not suitable for food crops growing;
- Algae can be harvested more than once a year;
- CO₂ from other processes can be used to feed the microalgae;
- Nutrient-rich wastewater can be used for microalgae cultivation;
- Reuse of wastewater and CO₂, as well as recycling of water and nutrients, decreases needs for external inputs and reduces environmental impacts;
- Co-production of different products, including high added-value compounds, can increase the sustainability and economic feasibility of the process;
- Opportunity to obtain different solar fuels from microalgae value chains, such as bioethanol, biodiesel, biohydrogen, biogas and biomethane;
- Microalgae need CO₂ to grow, thus lowering GHG emissions;

- Although most terrestrial plants entail a solar energy-to-biomass conversion efficiency of 1%, microalgae can achieve light-to-biomass conversion efficiencies up to 4%⁷⁰.

Weaknesses

- Growth rate in some species needs to be improved;
- Production costs, as well as O&M costs, are still high;
- Plants need to be built close to CO₂ sources;
- High amounts of water, fertilizers/nutrients and energy (e.g. for pumping) are required;
- Effective penetration and distribution of light, CO₂ and nutrients in the culture medium represent an issue;
- The recovery of the targeted metabolites from algal cells is difficult;
- In case a multi-product approach is envisaged, investments are high and process configuration is more complex;
- Harvesting and downstream processes need to be improved;
- In case open ponds are used for large-scale cultivation, large areas are required and contamination risk is high;
- In case photobioreactors are used for large-scale cultivation, fouling can be an issue, as well as water/energy consumption for cooling;
- In the case of bioethanol production, the algal carbohydrates content has to be increased either by introducing stress conditions during cultivation or by applying genetic modifications for microalgae.

Opportunities

- Market opportunities exist both for fuels and for high-value compounds that can be derived from the same algal biomass;
- Genetic engineering can increase the yields in the target metabolites (e.g. lipids, carbohydrates);
- CO₂ and nutrients from other sources can be utilised (e.g. flue gases, wastewaters);
- High demand for bio-based products as sustainable alternatives for fossil-based counterparts;
- High fossil fuels prices can boost the development of alternative pathways for biofuels;
- Possibility of using water with less competitive uses, such as seawater, brackish water or wastewater;
- Possibility of recycling CO₂, water and nutrients within the value chain, thus lowering the resources consumption;
- Energy costs can be lowered in case solar energy is used also for electric energy generation;
- New sources for bioethanol are required, other than food crops or 1st generation bio-based feedstocks

Threats

- Competition with other production pathways for alternative fuels, including biofuels from other bio-based feedstocks;
- Market for the targeted co-products (other than solar fuels) can be hindered by the competition with alternative sources, including bio-based ones;
- Low or fluctuating oil and carbon prices can significantly affect the market deployment of biofuels;
- Low-cost sources for nutrients, water or CO₂ can be unavailable or entail logistics constraints (e.g. long distances from the cultivation site) ;
- Alternative uses for wastewaters (e.g. as soil improvers in the agricultural sector) can lower their availability as nutrients-rich sources for microalgae;

⁷⁰ Posten, C., & Schaub, G. (2009). Microalgae and terrestrial biomass as source for fuels - a process view. *Journal of Biotechnology*, 142 (1), 64–69.

- Potential environmental risks due to algae release;
- In case fresh water is used, high water footprint may be envisaged for large scale production;
- Harvesting and drying of microalgae biomass from high volume of water can represent energy-intensive processes.

Gap analysis

Although several developments, improvements and investments have been carried out concerning microalgae-based value chains, no industrial process specifically designed for biofuel production exists yet.

Indeed, despite microalgae entail some advantages compared with existing alternatives (both fossil fuels and other sources of bio-based fuels), different constraints are still preventing the implementation of microalgal biofuels production at commercial scale.

In particular, the main technological challenges are related to the enhancement of microalgae growth rate in the cultivation and productivity in the targeted metabolites, microalgae harvesting and dewatering, pretreatment of biomass (i.e. lysis of algal cells) and the yields in the biofuels production (e.g. fermentation of algal-derived carbohydrates to obtain bioethanol).

Here below, some of the most important aspects to be taken into account for the effective upscaling of microalgae-based solar fuels production are analysed, by highlighting **in bold** the main gaps to be overcome.

Cultivation

One of the most important advantages associated with microalgae production is that in most cases algae cultivation systems can be installed in non-arable lands, even in marginal lands, thus minimising the competition with food chain. Therefore, microalgal productivity does not depend on soil fertility and is able to reduce the pressure on arable lands, as well as on relevant forest ecosystems.

Two main solutions exist for microalgae cultivation, consisting in open ponds systems and closed photobioreactors.

Among the different configurations implemented as open ponds (e.g. unstirred ponds, inclined ponds, circular ponds, raceway ponds), raceways are the most used and the cheapest ones, where paddle wheel is utilised for agitation and mixing of the culture.

Open ponds can be built on non-arable lands and thus they do not compete with agricultural crops. Cleaning procedures are easier and **energy consumption** is lower compared with photobioreactors, as well as investment and maintenance costs⁷¹.

However, the control of the process parameters is more difficult for open ponds and several factors can significantly affect the microalgae growth rate and the subsequent biomass productivities, such as temperature, pH, light intensity and distribution, dissolved oxygen concentration, nutrients distribution. Moreover, open systems are more subjected to contamination by inhibitor compounds or external microorganisms coming from the air or the ground⁷². To overcome this issue, retention times are reduced, or **microalgal species able to grow under harsh conditions** such as high alkalinity, high salinity or high temperatures are employed⁷³.

⁷¹ Rodolfi, L., Zittelli, G. C., Bassi, N., Padovani, G., Biondi, N., Bonini, G., Tredici, M. R. (2009). Microalgae for oil: strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor. *Biotechnology and Bioengineering*, 102 (1), 100–112.

⁷² Harun, R., Singh, M., Forde, G. M., & Danquah, M. K. (2010). Bioprocess engineering of microalgae to produce a variety of consumer products. *Renewable and Sustainable Energy Reviews*, 14 (3), 1037–1047.

⁷³ Minhas, A. K., Hodgson, P., Barrow, C. J., & Adholeya, A. (2016). A Review on the Assessment of Stress Conditions for Simultaneous Production of Microalgal Lipids and Carotenoids. *Frontiers in Microbiology*, 7 (546).

Photobioreactors consist in closed systems with different possible configurations, such as column, annular, tubular or flat-panel reactors.

Column or annular PBRs are usually employed as bubble columns, airlift reactors or stirred tank reactors. This type of reactors allows for an easier control of algal growth conditions, an efficient mixing and a high volumetric gas transfer rates⁷⁴. In tubular reactors airlifts are able to provide the pumping force, while fostering the exchange of oxygen and carbon dioxide between the gas and the liquid medium⁷⁵. Flat-panel photobioreactors present the advantages of higher growth densities and higher **photosynthetic efficiencies** due to the larger illumination surface area⁷⁶.

Although photobioreactors generally entail higher costs compared with open ponds which currently prevent their upscaling for large scale production of biofuels like biodiesel, they present some benefits in terms of **control of algal growth** and processing parameters, process efficiencies and risk and **management of contamination** (although both open and closed systems can increase the risk for contamination if continuous cultivation is carried out for long periods).

In order to tackle the issues associated with contamination and improve the overall efficiency of the processes, **further research and better understanding of biological interactions and inhibition effects occurring among different microbial communities is required** (heteroinhibition and autoinhibition)⁷⁷.

Solar radiation

Solar light radiation and intensity are relevant factors directly influencing microalgae growth rate, as well as biomass yield.

Too low or too high light intensities affect algae growth and the photosynthetic CO₂ uptake, thus provoking photoinhibition: a **right balance between light and dark periods** is required to optimise algal growth and several studies have shown that 16h light/8h dark seems to be an optimal ratio to be targeted. Furthermore, in order to enhance biomass productivity little seasonal variations in terms of solar radiation are demanded⁷⁸.

Photoinhibition caused by the so-called 'self-shading effect' (i.e. algae at lower levels are shaded by the ones at upper levels) is also to be avoided, by targeting the right **penetration and distribution of light in the culture**.

In contrast to most plants having a solar energy-to-biomass conversion efficiency of 1%, microalgae can achieve light-to-biomass conversion efficiencies up to 4% in open ponds cultivation systems, while higher productivities have been reported for closed photobioreactors⁷⁹. Considering the theoretical maximum of photosynthetic efficiency for solar energy-to-oil conversion is about 8–12%⁸⁰, non-negligible improvements can be implemented to microalgae value chains, for example by applying **genetic modification** solutions to enhance lipids production in microalgae.

⁷⁴ Eriksen, N. T., Riisgard, F. K., Gunther, W. S., & Lønsmann Iversen, J. J. (2007). On-line estimation of O₂ production, CO₂ uptake, and growth kinetics of microalgal cultures in a gas-tight photobioreactor. *Journal of Applied Phycology*, 19 (2), 161–174.

⁷⁵ Hall, D. O., Acién Fernández, F. G., Guerrero, E. C., Rao, K. K., & Grima, E.M. (2003). Outdoor helical tubular photobioreactors for microalgal production: modeling of fluid-dynamics and mass transfer and assessment of biomass productivity. *Biotechnology and Bioengineering*, 82 (1), 62–73.

⁷⁶ Eriksen, N. T. (2008). The technology of microalgal culturing. *Biotechnology Letters*, 30 (9), 1525–1536.

⁷⁷ Stephens, E., Ross, I. L., Mussgnug, J.H., Wagner, L.D., Borowitzka, M.A., Posten, C., Kruse, O., & Hankamer, B. (2010). Future prospects of microalgal biofuel production systems. *Trends Plant Science*, 15(10), 554–564.

⁷⁸ Carvalho, A. P., Silva S. O., Baptista J. M., & Malcata, F. X. (2011). Light requirements in microalgal photobioreactors: an overview of biophotonic aspects. *Applied microbiology and biotechnology*, 89 (5), 1275–1288.

⁷⁹ Posten, C., & Schaub, G. (2009). Microalgae and terrestrial biomass as source for fuels - a process view. *Journal of Biotechnology*, 142 (1), 64–69.

⁸⁰ Melis, A. (2009). Solar energy conversion efficiencies in photosynthesis: Minimizing the chlorophyll antennae to maximize efficiency. *Plant Science*, 177 (4), 272–280.

Water

Large amounts of water are needed in microalgae-based process, especially for the cultivation stage, where water is not only used for the culture medium preparation, but it is also utilised to compensate evaporation in open pond systems or to cool photobioreactors. For these reasons, **water management** is one the main aspects to be considered in this pathway and the identification of **low-cost solutions for water supply** is essential for a commercial deployment of microalgal biofuels.

In this framework, some solutions aiming to reduce freshwater consumption can be considered:

- Use of **water entailing less competitive uses**, such as seawater, brackish water or wastewater, even though it is worth noting that in some cases (e.g. brackish water) additional pretreatments may be required in order to remove any potential inhibitors for microalgae growth;
- **Water recirculation** aiming also to reduce the consumption of nutrients, although particular attention should be paid on the fact that recycled waters often contain a higher concentration of inhibiting or infecting compounds (organic or inorganic) or organisms (bacteria, fungi, viruses), with the subsequent risk of introducing an increasing amount of such components into the culture;
- Identification of **water sources with limited distance from the cultivation sites**.

Carbon dioxide

Photoautotrophic organisms like microalgae can cover a relevant role for CO₂ emissions mitigation. However, due to the huge amount of CO₂ consumed in the process, the cost of CO₂ can entail a significant impact on the overall production costs.

One of the possible solutions to increase also the environmental benefits associated with the process consists in the **use of CO₂ coming from flue gas**. Considering that the separation of CO₂ from exhaust gases is often an energy-intensive process, the direct use of flue gas would be preferable, even though this route can be pursued only if microalgae are able to tolerate contaminating compounds in the gas supplied. Moreover, in case the use CO₂ from flue gas is targeted, the **cultivation site should be built nearby industrial sources from which the CO₂ can be retrieved in large quantities and almost continuously**.

Concerning CO₂ usage, the level of dissolved CO₂ into the medium culture has to be kept under control, also with the aim of maintaining the right pH levels. While outgassing is more relevant in open ponds systems, also in photobioreactors the control of CO₂ level can represent an issue: membrane-based solutions to foster **CO₂ transfer and distribution in the culture** seem to be a promising technology in the near future, even though where sparging is employed it entails also the advantage of boosting the mixing effect in the culture.

Finally, where possible, **CO₂ recirculation** to the cultivation phase can also enhance the overall feasibility and sustainability of the process: it is the case for example of the carbon dioxide deriving from the fermentation step in the bioethanol production, where carbohydrates are converted by fermentative microorganisms mainly into bioethanol and CO₂.

Nutrients

Algae cultivation requires a relevant amount of nutrients, such as nitrogen, phosphorus and potassium. Thus, there is the necessity to identify and develop solutions to lower the

costs for nutrients, especially in a general context where fertiliser pricing and phosphorous limitation⁸¹ can represent an issue in the future.

The use of **nutrient-rich wastewaters** in the cultivation step can aid in supplying at least part of the nutrients required, with the consequent benefits in terms of environmental and social aspects linked to the wastewater treatment.

Nutrient recycling after harvesting and dewatering of algal biomass is a fundamental concept in the process configuration in order to reduce the requirements of fresh fertilisers. However, a particular attention should be paid to the potential recycling, along with nutrients, of inhibitor compounds or contaminants.

Another solution for nutrients recycling can be represented by the **nutrient-rich residue coming from the anaerobic digestion of microalgal biomass**: other than producing biogas or biomethane that can be used to enhance the overall energy balance of the process, anaerobic digestion systems can indeed increase the sustainability and economic feasibility of microalgae-based value chain by providing an opportunity to recover and recycle nutrients for the cultivation phase.

Temperature

As mentioned above, **light intensity and** consequently **temperature** are important parameters to be properly controlled in order to achieve an effective microalgal growth rate. Moreover, in some cases **temperature can also be employed as parameter to create stress conditions** and induce microalgae to produce specific metabolites⁸².

Microalgae require a specific temperature range in order to grow optimally. While low temperatures reduce CO₂ uptake, high temperatures affect photosynthetic mechanisms e.g. by inactivating photosynthetic proteins, reducing cell size or respiration activities⁸³.

The evaporation that occurs in open ponds is able to effectively cool the system, thus usually limiting the maximum temperature to about 40 °C, while closed photobioreactors often need additional water for cooling, with a subsequent increase in terms of costs and complexity of the process.

Harvesting and dewatering

Considering the high amount of water used in the cultivation phase, the small size of microalgae cells and the subsequent low concentration of algae in the culture the **harvesting and drying processes** can represent a hotspot of the value chain in terms of energy consumption and production costs, thus affecting the overall sustainability of the microalgal value chains.

Harvesting process mainly consists in solid-liquid separation technologies and often more than one steps is required to achieve sufficient yields in terms of biomass recovery. Examples of the technologies used are: sedimentation, centrifugation, (ultra-)filtration, flocculation, floatation, electrophoresis. The choice of the implemented technologies can depend on several factors, such as the type of cultivation and the availability of low-cost energy.

⁸¹ Cordell, D., Drangert J. O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, 19 (2), 292–305.

⁸² Moller, A. P., Biard, C., Blount, J. D., Houston, D. C., Ninni, P., Saino, N., & Surai, P. F. (2000). Carotenoid-dependent signals: indicators of foraging efficiency, immunocompetence, or detoxification ability? *Avian and Poultry Biology Review*, 11 (3), 137–159.

⁸³ Atkinson, D., Ciotti, B. J., & Montagnes, D. J. S. (2003). Protists decrease in size linearly with temperature: ca. 2.5% degrees C (– 1). *Proceedings of the Royal Society of London, Series B: Biological Sciences*, 270 (1533), 2605–2611.

Environmental aspects

Apart from technological developments, sustainability aspects should also be considered in the framework of deployment of microalgae-derived solar fuels at commercial scale.

It is worth considering that no industrial microalgae plants specifically targeted biofuels yet exist, thus LCA estimation has to be made starting from laboratory or pilot scale systems, as well as commercial plants aiming to produce high value compounds such as ingredients for food or cosmetics.

Most of the impacts, especially in terms of GHG emissions linked to fossil fuel inputs, are associated with the **energy requirements**, mainly consisting in electricity for pumping and mixing in the cultivation step, heating energy for drying the microalgae and energy consumed in the harvesting phase. Moreover, temperature represents a fundamental parameter for algae growth and therefore it needs to be taken under control: for this reason, heating and cooling demand may entail additional fossil fuel inputs.

An **effective and sustainable energy balance** of microalgae-based systems is one of the main factors to be addressed in order to arrive at a full scale development of such value chains: in this framework, an efficient recovery and valorisation of all side- and wastestreams from the process (e.g. biogas from anaerobic digestion of microalgal residual biomass), coupled with the **integration of low-cost and sustainable energy sources** (e.g. PV panels, waste heat from other plants to dry algal biomass), should be targeted in the near future.

Another important aspect to be also improved in order to increase the overall sustainability of the value chain is represented by nutrients consumption and water management, where the latter has to be intended both in terms of water consumed within the process and in terms of liquid emissions potentially discharged in water courses.

Economic aspects

Considering the cultivation phase, raceway open ponds entail lower production costs for microalgae, compared with photobioreactors. While for open systems the highest costs are the ones linked to operation (i.e. labour, utilities and raw materials, especially CO₂ because of the lower CO₂ fixation performance of open ponds as compared to closed systems), for PBRs the costs are mainly due to the investment costs⁸⁴.

Significant enhancements are required **to lower the biomass production costs** and make algal-derived biofuels fully competitive with fossil-based fuels or other bio-based fuels.

For example, Slade et al.⁸⁴ report that **costs may be reduced by more than 50% if CO₂, nutrients and water can be supplied at low cost**: considering that **logistic aspects** mostly affect the supply cost of such raw materials, this requirement may significantly restrict the number of locations suitable for cultivating microalgae.

Moreover, the **production of different co-products** such as biofuels and added-value compounds, as well as the valorisation of residual streams targeting a 'zero-waste biorefinery', can further enhance the economic sustainability and feasibility of microalgal value chains.

Finally, it is worth considering that microalgal biofuels development is hugely affected by the petroleum price and its fluctuations (see also the decreasing patents' trend from 2015

⁸⁴ Slade, R., & Bauen, A. (2013). Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects. *Biomass and Bioenergy*, 53, 29–38.

onwards). For example, Gendy et al. reports that "oil from algae is likely to be financially viable in a scenario with crude petroleum sell for >USD100 per barrel"⁸⁵.

Genetic engineering

Synthetic biology and genetic engineering can represent a relevant boost for accelerate the deployment of microalgae biofuels production at large scale. The use of such techniques mainly aims at **improving the production of the targeted metabolites**, in particular by increasing the photosynthetic efficiency, lowering the effect of photoinhibition or enhancing the capacity of microorganisms to support stress conditions.

Co-production

One of the main factors still preventing the commercialisation of algal fuels is related to the high costs associated with the microalgae-based systems, in particular cultivation, harvesting and downstream processes.

Indeed, although most microalgae strains show a good potential for biodiesel production due to their high lipids content that usually varies between 20% and 50% and can reach up to 80%, the **low biomass concentration** makes the processes almost unfeasible⁸⁶.

Bioethanol production from microalgae is still to be enhanced too, considering the potential of such biofuel, in terms of GHG emissions reduction during burning (this is due to its higher oxygen content compared with other fuels) and linked to the fact that bioethanol can be directly used in the current automotive engines without any modifications needed. Moreover, during the fermentation process also CO₂ is obtained, which can be recycled as carbon source for microalgae cultivation, thus reducing greenhouse gas emissions as well.

Considering the bioethanol production carried out by microorganisms able to convert sugars through fermentation, several factors are to be taken into account, such as: the **selection of algae strains** with higher productivity in carbohydrates-rich biomass, **pretreatments of biomass** to recover the targeted metabolites and to convert starch and other polysaccharides into simple C5 and C6 sugars, **selection of microbial strains** able to reach sufficient yields in bioethanol during **fermentation**. In particular, in order to foster the feasibility of bioethanol production from microalgae, all the fermentable sugars (both pentoses and hexoses) should be converted to bioethanol, thus the **combination of different microorganisms able to tackle different substrates** should be pursued⁸⁷.

In order to further boost the productivity of microalgae in the targeted metabolites (e.g. lipids, carbohydrates), **genetic modifications** of algal metabolic pathways **or cultivation under stress conditions** can be applied. The latter may act for example on temperature, light intensity, pH, salinity of the growth media.

Considering that several challenges still have to be overcome to effectively make algal biofuels production competitive at commercial scale, the **co-production of high added-value compounds** such as pigments and proteins along with biofuels can significantly foster the development of microalgae-based value chains, thanks to the possibility to generate additional incomes.

Technological roadmap

In the following Figure 72 the main actions to be carried out in order to reach a large-scale deployment of solar fuels production from microalgae are summarised.

⁸⁵ Gendy, T. S., & El-Temtamy, S. A. (2013). Commercialization potential aspects of microalgae for biofuel production: An overview. *Egyptian Journal of Petroleum*, 22 (1), 43–51.

⁸⁶ Medipally, S. R., Yusoff F. M., Banerjee, S., & Shariff, M. (2015). Microalgae as Sustainable Renewable Energy Feedstock for Biofuel Production. *BioMed Research International*, 2015 (519513).

⁸⁷ Khan, M. I., Lee, M. G., Shin, J. H., & Kim, J. D. (2017). Pretreatment optimization of the biomass of *Microcystis aeruginosa* for efficient bioethanol production. *AMB Express*, 7 (1), 19.

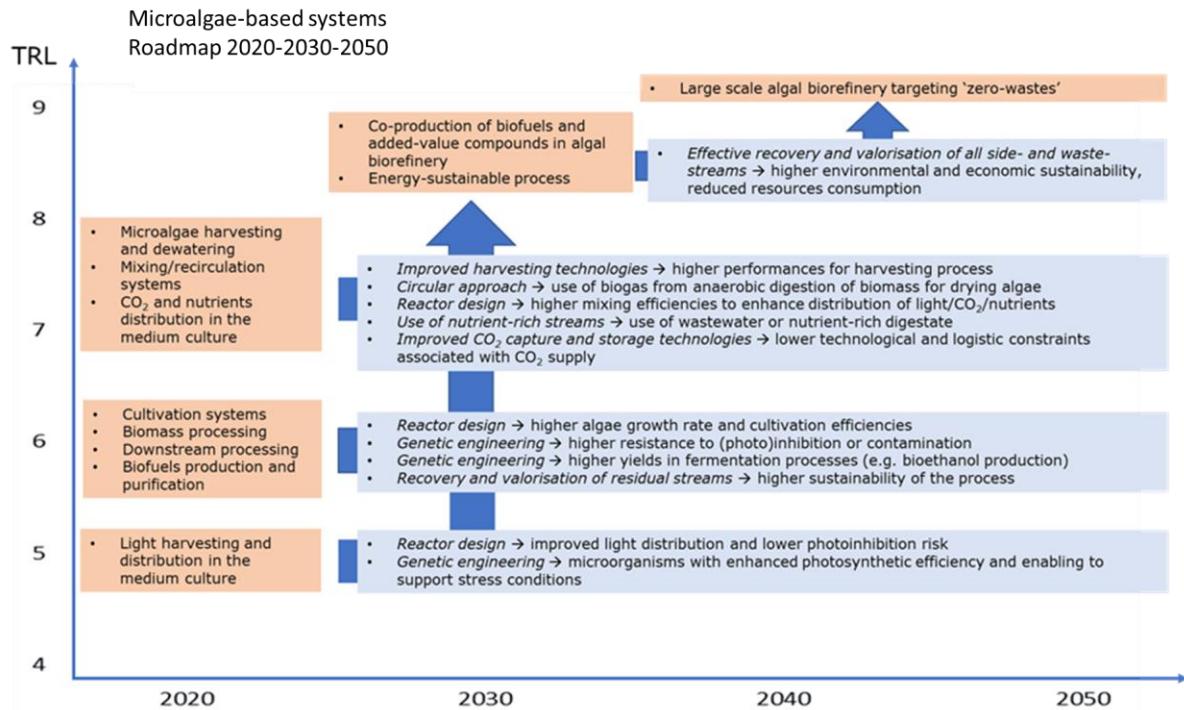


Figure 72 - TRL vs. Timing for biochemical pathway for solar fuels based on microalgae

Starting from several components ranging from TRL 5 to TRL 8, the objective would be to arrive at a TRL 8-9 by 2030. It is worth noting that the achievement in the medium term of a commercial scale for microalgal fuels production does not depend uniquely on technological developments. Indeed, also economic, social and political framework may accelerate or hinder the enhancements of such value chains in the coming years.

Political incentives aiming to reduce the use of fossil-based fuels, as well as an increase in taxation on CO₂ emissions may further boost R&D activities towards the development of alternative and sustainable (bio)fuels and/or the deployment of technological pathways based on CO₂ capture and utilisation.

Biofuels from microalgae can represent promising solutions to meet the demand for sustainable alternatives for fossil fuels: along with other environmental benefits, biofuels (including algal biofuels) entail an oxygen content of 10-45% and a lower sulphur content than fossil-based counterparts⁸⁸. Moreover, microalgae present also some advantages versus other biomass feedstocks (both 1st and 2nd generation feedstocks), mainly linked to their higher growth rate and the lack of competition with food chain.

This potentially favourable context for microalgal biofuels development may be hindered by the oil price trend: low oil prices, indeed, can decrease or at least delay the investments in the biofuels sector. In this framework, co-production of high added-value compounds other than biofuels can represent a means for fostering the development of microalgae-based value chains, by overcoming the economic and technical bottlenecks still related to them.

Finally, issues related to social aspects and public acceptance should be also considered. Indeed, people are often sceptical towards new or unknown technologies, use of bioengineering and land occupancy for industrial purposes instead of agricultural uses. Moreover, open ponds system can entail "NIMBY" phenomena that can prevent their installation at large scales.

⁸⁸ Khan, M. I., Shin, J. H., & Kim, J. D. (2018). The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. *Microbial Cell Factories*, 17 (36), 1-21.

In this context, along with technological improvements, specific campaigns should be also carried out with the aim of fostering public acceptance, as well as sensitising population and local communities on new, sustainable value chains.

2.2. Economic roadmap for solar fuels to 2100: key findings

Following the technology roadmap, the aim of the economic roadmap is to assess the cost competitiveness of the studied technologies over time. The groundworks of this analysis was laid out in the methodology section, presenting the structure of our LCOE economic model, used as basis for the economic roadmap. The comparison between the grey and solar technologies is the major point of attention, as it defines the key fuel tipping point: the moment when solar fuels have a cost advantage over their fossil counterparts. The analysis is structured by solar fuel for the base case scenario: Europe region, normal input/assumptions range and input energy from solar PV. We refer to our work in Power BI for further analysis.

2.2.1. Energy sources

The LCOE of energy sources is central to the analysis given that the entire range of solar fuel technologies' value chains depend on it. While the study focuses on the importance of solar energy to produce solar fuels, wind power can also be used as energy input to the production of such fuels and is therefore considered in our analysis. Figure 73 displays the LCOE evolution of solar PV and wind power in both the scale and stable scenarios outlined in the model's methodology (Table 1).

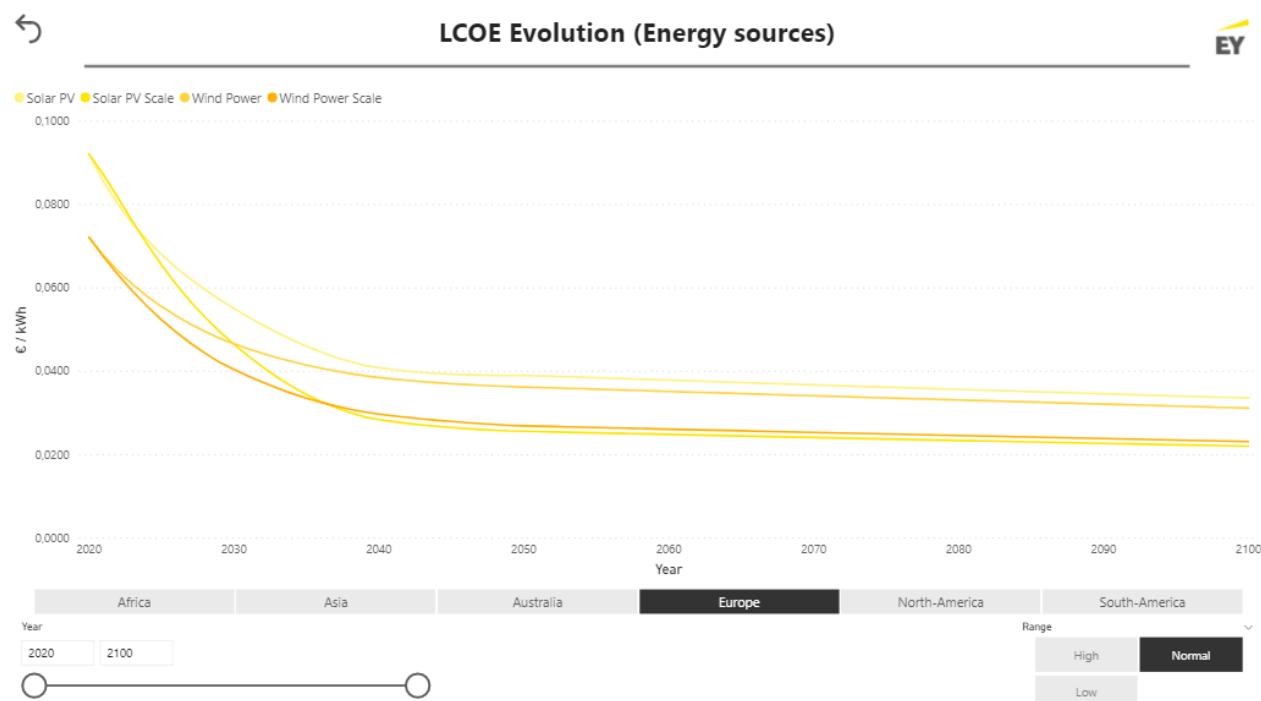


Figure 73 – Energy sources – LCOE evolution

Looking at the stable scenario for solar PV and wind power, we can observe a rapid evolution of the technologies' LCOE until 2040, especially for solar PV's LCOE which drops from 0,09 €/kWh in 2020 to 0,04 €/kWh in 2040. While wind power experiences a relatively less rapid decline until 2040, the two technologies level out at an almost steady rate until 2100. Under the stable scenario, wind power represents the most affordable energy source modelled in our study by a very small margin. Solar PV is nevertheless expected to become most competitive under a scale scenario, characterised by a higher investment push. The two technologies, and especially solar PV, see a rapid decline of their LCOE to reach 0,03 €/kWh in 2040 and a continued, steadier decline to 0,02 €/kWh in 2040. This expected decrease in the cost of solar power cost largely underpins our analysis, as it builds into the

LCOE of some of the studied technologies. This allows us to foresee solar fuels technologies becoming cost-competitive with comparable fossil fuel production processes.

2.2.2. Resources and commodities

The prices of resources and commodities are central to the analysis given that they underpin our technologies' LCOE and are also used as fossil-based benchmarks to assess the performance of the green solar fuel technologies against. Figure 74 below presents for all regions through 2100 the forecasted price evolutions of: CO₂ emissions, CO₂ as a resource from CCS/CCU, natural gas, electricity, H₂O and oxygen.

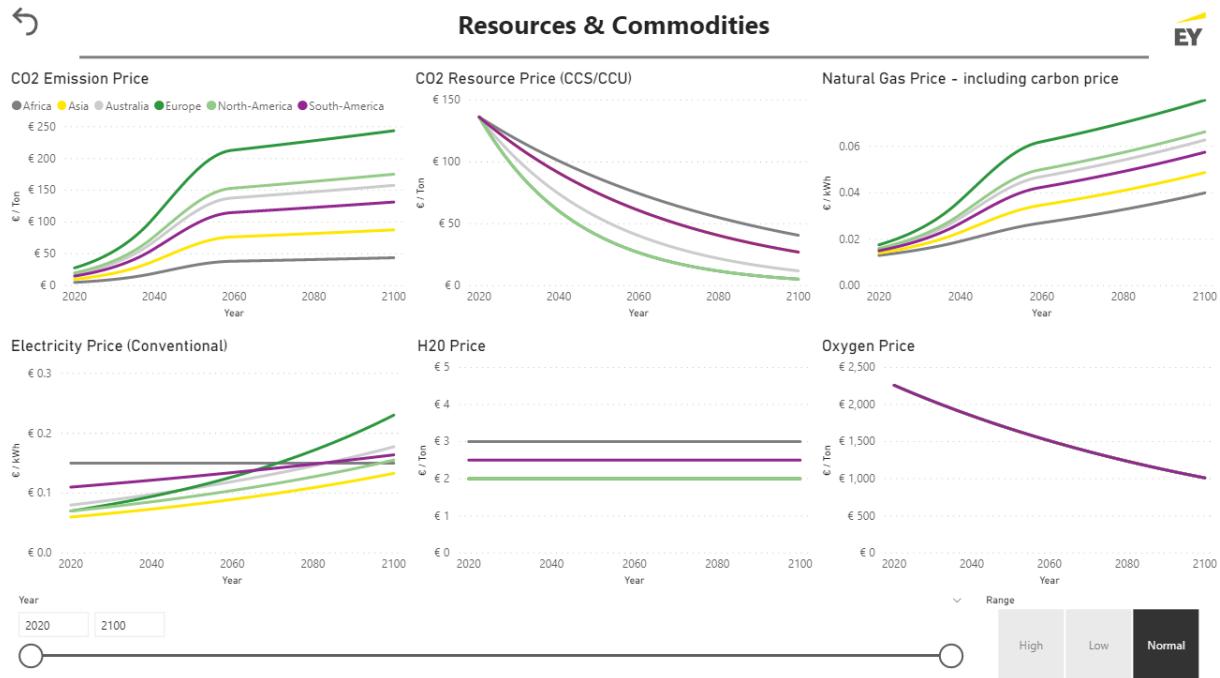


Figure 74 - Price forecasts for resources and commodities

Figure 74 above presents the rapidly growing price of CO₂ emissions, largely reflecting the political priorities of the studied regions towards decarbonisation. In this context, Europe sees the most rapid evolution of CO₂ emission price. In contrast, we can observe a slower increase in the price of natural gas, primarily due to the availability of the resource. Electricity prices are also forecasted to rise due to a greater push towards electrification worldwide and an associated increasing demand for electricity.

2.2.3. Hydrogen systems

The LCOE analysis for the hydrogen system is a key component of our study results, due to the already high maturity of some of the technologies. The technologies analysed as part of the hydrogen system are PEMEC, AEC, SOEC, and PEC, under stable and scale scenarios for Europe. The solar fuel produced by these technologies is referred to as green hydrogen. Conversely, the analysis also examines the grey hydrogen production method, namely, SMR. For AEC, PEMEC and SMR, data availability and a research and development environment characterised by low uncertainty provide for greater accuracy in the results and forecast. PEC, on the other hand, is at an early development stage characterised by a low TRL. It was therefore only modelled from 2050 onwards when, according to expert inputs, manufacturing PEC systems at commercial scale may become viable. Figure 75 presents the LCOE evolution of these hydrogen technologies under a stable investment scenario.

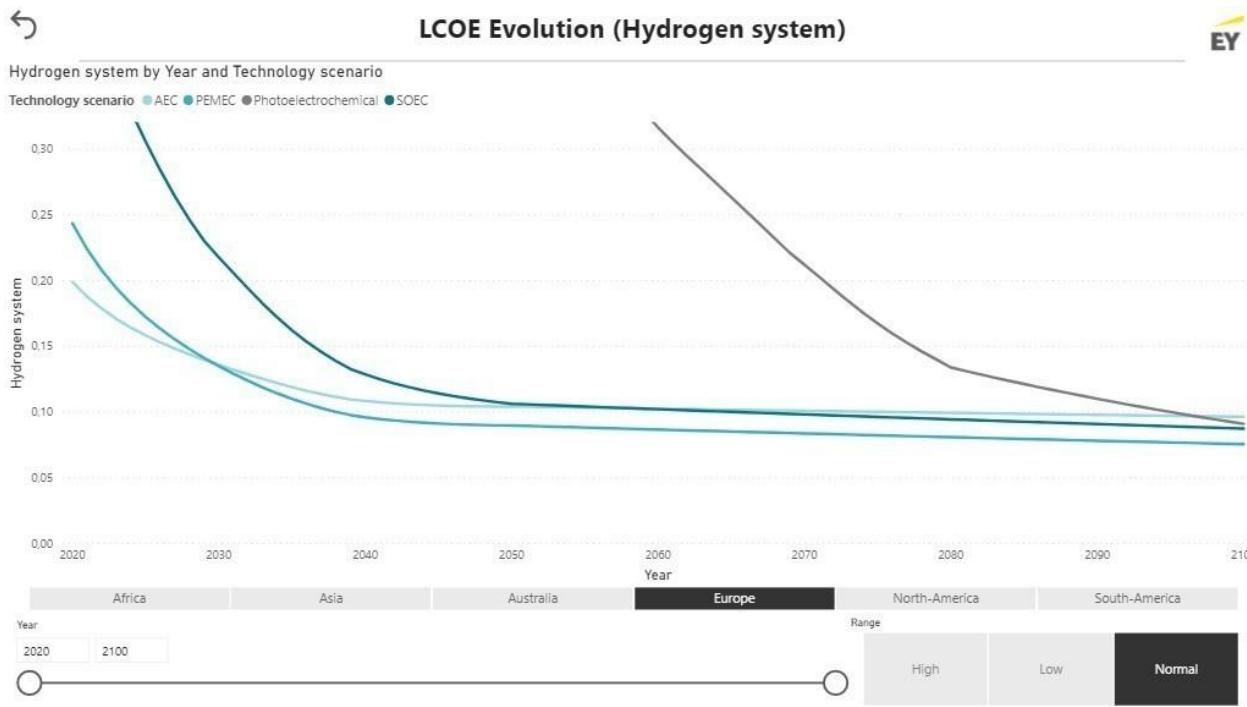


Figure 75 – Hydrogen systems – LCOE evolution (stable scenario)

Figure 75 highlights that AEC currently benefits from a cost advantage amongst the green hydrogen technologies. With that said, PEMEC is expected to become the most cost-competitive technology, with a rapidly declining LCOE surpassing that of AEC in 2030. This decline is due to reductions in PEMEC's CAPEX and energy input costs, as a result of declining solar power cost. SOEC also experiences significant LCOE and CAPEX improvements and reaches LCOE parity with AEC for about 20 years from 2055, before surpassing the latter in 2075. The figure also highlights developments in the PEC technology. Due to reductions in its CAPEX, PEC sees a significant decrease in its LCOE over the 50 year period of analysis, with a particularly important decline up to 2080. By a negligible margin, PEC becomes cost competitive with SOEC by 2100 under the stable scenario. AEC, which is currently characterised as the most competitive technology from a cost perspective, becomes the least affordable one just before 2100. Under a stable investment scenario, PEMEC is therefore expected to become the most competitive green hydrogen technology in the next ten years.

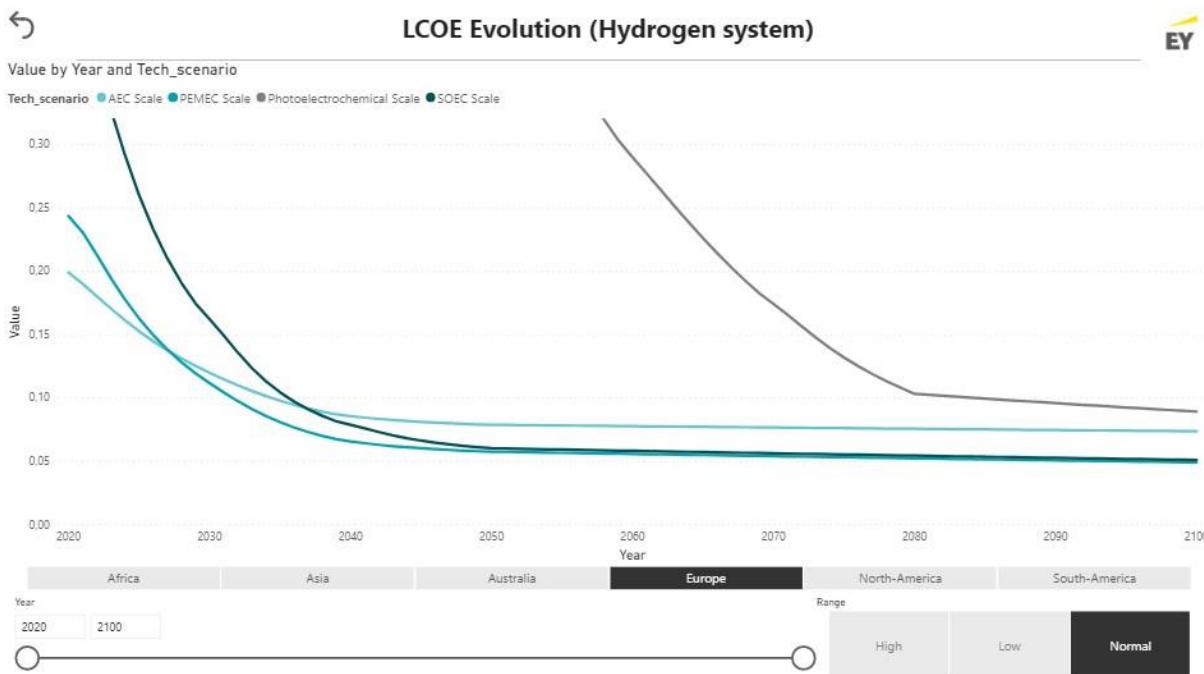


Figure 76 - Hydrogen systems – LCOE (scale scenario)

Figure 76 reports on the scale growth scenario for the same technologies. In this investment push scenario, PEMEC and SOEC become cost competitive with AEC in 2027 and 2037, respectively. While PEMEC benefits from an LCOE advantage until 2046, the two technologies then level out through 2100 to reach an LCOE of 0,05 €/kWh. Indeed, aggressive investment in SOEC would bring reductions in its CAPEX, eventually making the technology cost-competitive. Another key takeaway from this scenario analysis compared to the previous one is the lower performance of the PEC technology which, despite steep LCOE decline, remains the least affordable technology through 2100. An investment push scenario would therefore mostly benefit the PEMEC and SOEC technologies.

Drawing on this analysis for all green hydrogen technologies, PEMEC stands out as the most promising studied technology given its cost competitiveness in both scenarios. In this context, the following graph will dive into PEMEC's LCOE and compares it with its grey hydrogen equivalent, namely SMR.

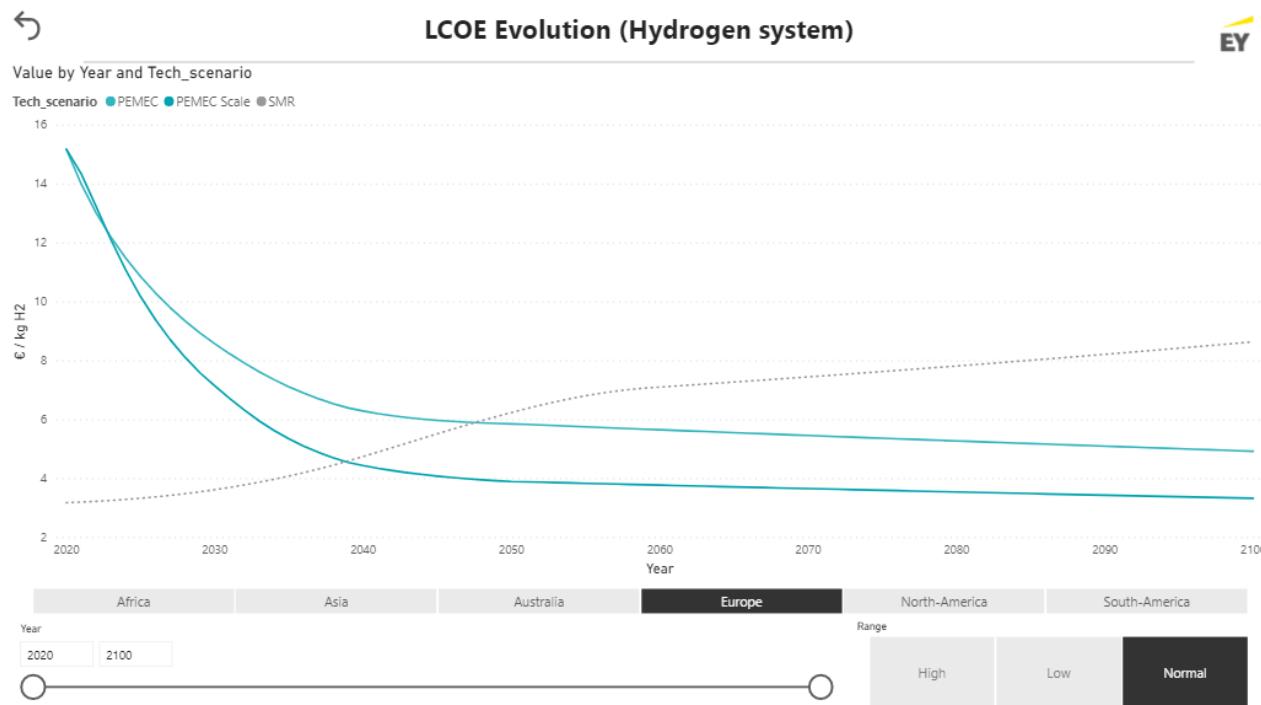


Figure 77 - PEMEC – LCOE evolution

Figure 77 reports on PEMEC's LCOE in both a scale and stable scenario, in relation with SMR's LCOE. While the LCOE results are presented throughout the study in terms of €/kWh of electricity produced in order to compare different technologies, this graph will present the PEMEC's results in terms of €/kg of hydrogen produced to focus on the fuel output.

From this graph, we can observe that in a stable investment scenario, PEMEC is expected to become cost competitive with SMR in 2048. This is the result of PEMEC's declining LCOE through 2100 together with a continuously rising LCOE for SMR, primarily due to the increasing cost of natural gas and CO₂ emission costs. Further, in an investment push scenario, PEMEC is foreseen to surpass its grey hydrogen equivalent as early as 2039, at 4,55 €/kg of hydrogen produced.

2.2.4. Methanol system

The methanol system pathway considers the CO₂ hydrogenation technology, which uses the green hydrogen produced by the PEMEC technology. Figure 78 below reports on CO₂ hydrogenation LCOE in scale and stable investment scenarios. The fossil benchmark used here to analyse CO₂ hydrogenation performance is gasoline. The wholesale price of gasoline was extended through linear forecast to 2100 to provide a benchmark to compare the price of methanol against that of liquid fossil fuels.



LCOE Evolution (Methanol System)

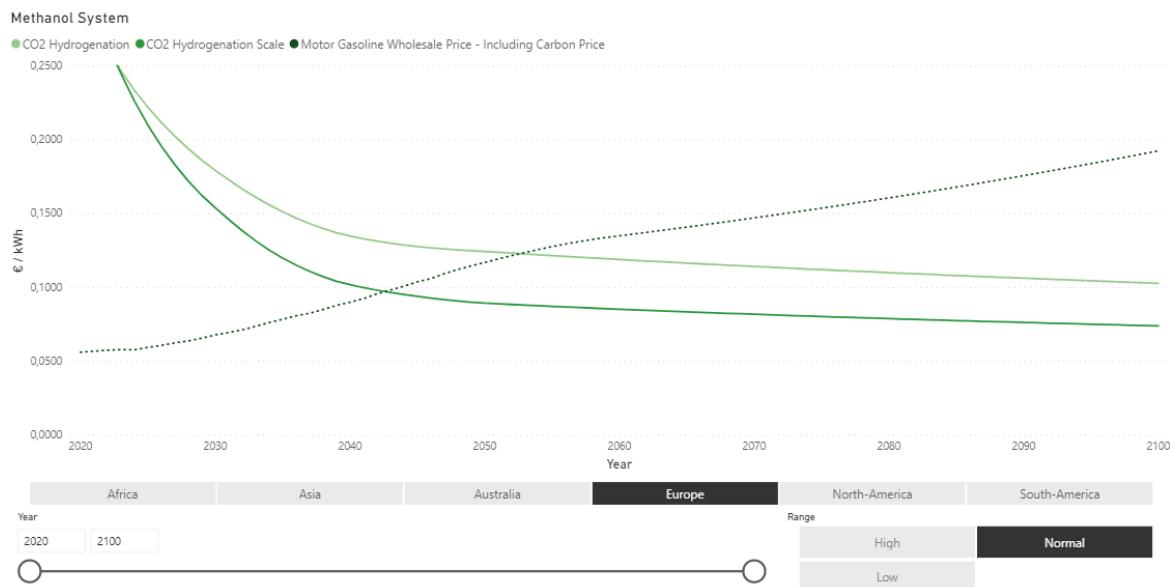


Figure 78 - Methanol systems – LCOE evolution

Figure 78 highlights that in a normal investment scenario, CO₂ hydrogenation could become cost competitive with gasoline in 2053. This decrease in CO₂ hydrogenation LCOE is primarily driven by the decline in the cost of green hydrogen resulting from PEMEC as well as a drop in the price of CO₂ as a resource captured from CCS/CCU. Against this, the cost of motor gasoline (including an expectedly rising carbon price in Europe) is foreseen to double to reach 0,13€/kWh in 2060. In this context and with the investment push of the scale scenario in the technology, CO₂ hydrogenation could become cost competitive against its fossil benchmark as of 2042.

2.2.5. Ethanol system

The technology considered for the ethanol solar fuel is the microalgae technology. Figure 79 below reports on microalgae's LCOE in scale and stable investment scenarios. Similar to methanol, the fossil benchmark used here is gasoline.

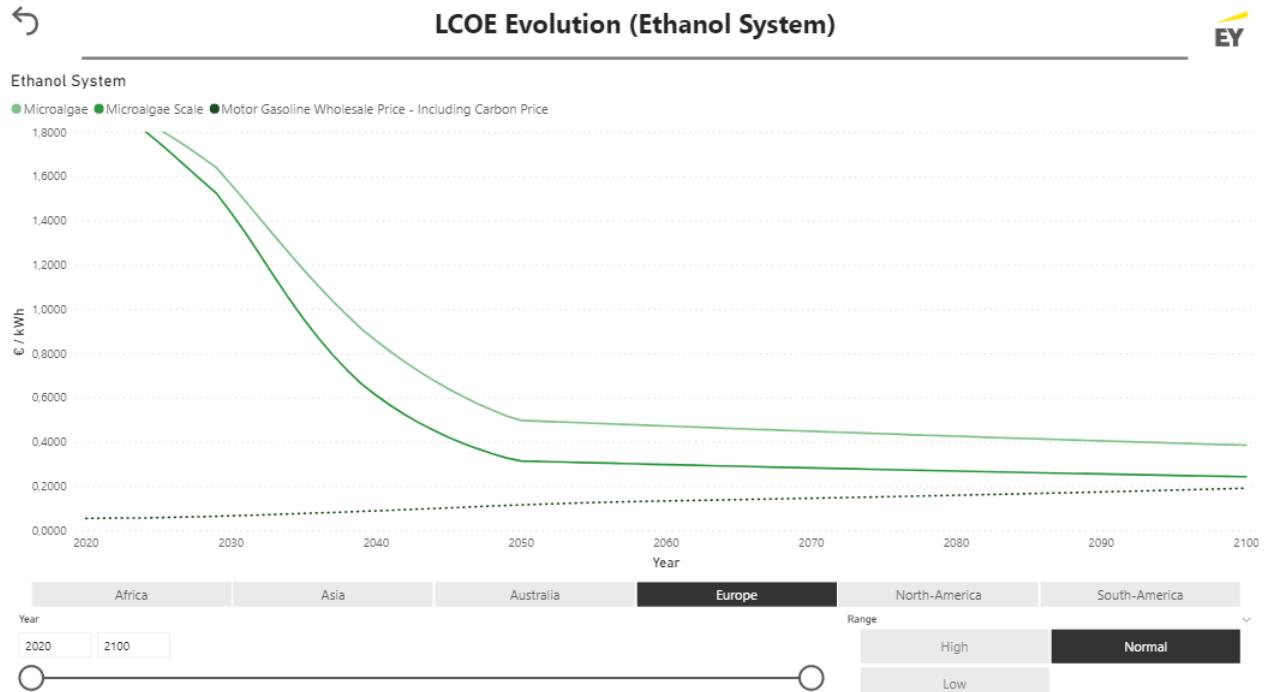


Figure 79 - Ethanol systems – LCOE evolution

The figure reports a high LCOE for the microalgae technology. Despite rapid decline of its LCOE until 2050, microalgae does not reach cost-competitiveness with gasoline in the studied period and for both investment scenarios. This graph reflects the technology's low maturity and relative inefficiency, characterised by continuously high CAPEX and overhead and maintenance costs through 2100. In a scale growth scenario, characterised by steadily declining LCOE of the microalgae and rising gasoline prices, we could envisage cost-competitiveness of the technology only post-2100. In 2100, gasoline still benefits from an important cost advantage over microalgae, with an LCOE of 0,24€/kWh against an expected price of 0,19€/kWh for gasoline. In a normal scenario, microalgae suffers from an even greater cost disadvantage to gasoline through 2100.

Nevertheless, microalgae cultivation has a number of other applications beyond fuel production, and a wide range of high-value compounds such as nutraceuticals can be extracted from microalgae, in parallel with fuels. Our calculations reveal that only approximately a third of the capital costs for the microalgal ethanol value chain, and 15 percent of the operating costs, are attributable to the downstream processing of microalgae into fuels. The remainder is incurred in the cultivation process. Should the downstream processing of microalgae into fuels be considered as a subsidiary process, considering null costs for the microalgal biomass whose cultivation costs would be offset by the sales of high value compounds, the LCOE for microalgal ethanol would be substantially lower. The production of microalgal ethanol would, therefore, be subjugated to market demand for nutraceuticals and high value compounds, and would likely remain limited. Additionally, given the energy intensiveness of the cultivation and downstream processing, any fuels produced would likely be re-utilised, applying circular economy principles.

This analysis indicates that, on the short-term, microalgae is unlikely to be considered a promising solar fuel technology, given the stronger performance of peer electrolyser technologies, and the negative energy balance of microalgal ethanol production.

2.2.6. Methane system

The study analyses power-to-methane technology for methane production. Figure 80 looks at the technology in both scale and stable investment scenarios using natural gas as benchmark.

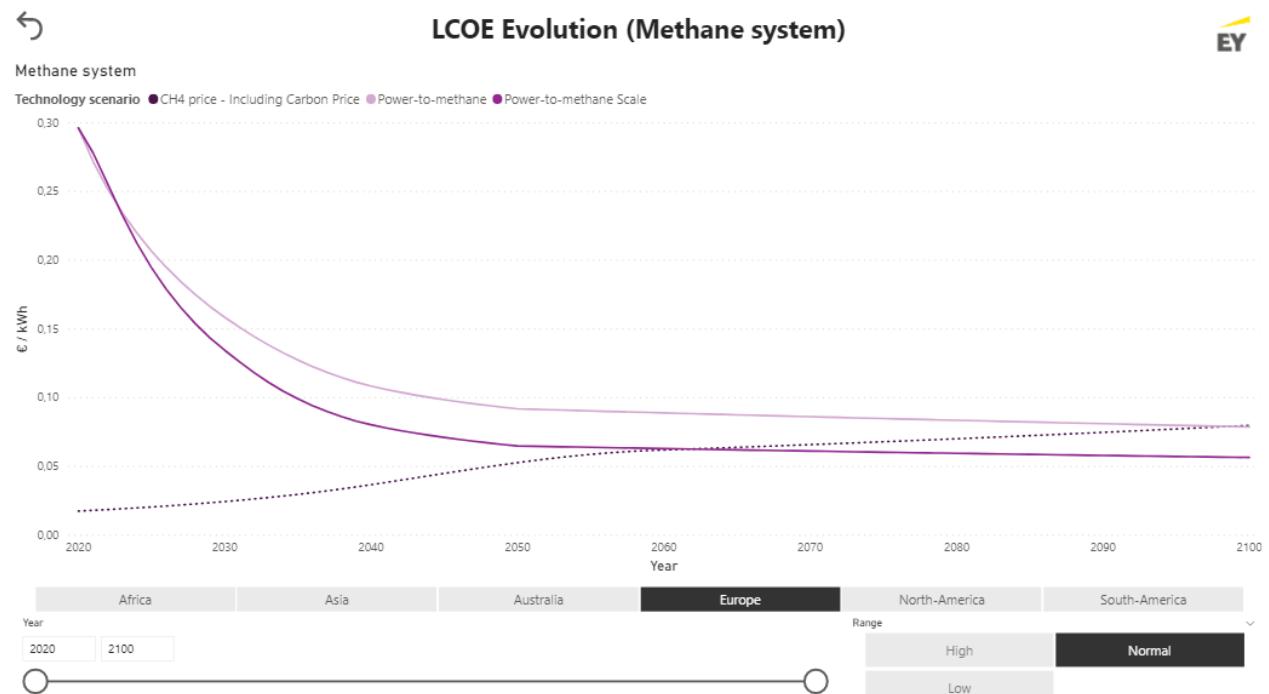


Figure 80 - Methane systems – LCOE evolution

The figure demonstrates significant LCOE improvements for the power-to-methane technology in both scenarios, where we can observe a clear decline to 2050. This is primarily explained by decreasing CAPEX and green H₂ costs resulting from the hydrogen technologies. In a scale investment scenario, power-to-methane reaches cost parity with natural gas in 2060. Due to its availability and lower carbon footprint compared with oil products, natural gas experiences a rather slow price increase. Within this, carbon pricing actually represents the main driver of CH₄ rising prices, expected to account for half of natural gas' price by 2060. Based on this, power-to-methane is not expected to reach cost competitiveness with natural gas before 2060 in a scale scenario. In a normal investment scenario, power-to-methane is foreseen to attain cost parity with natural gas in 2091.

2.2.7. LCOE decomposition for all technologies

This section provides a decomposed overview of the studied technologies' LCOE at different points in time. This analysis allows us to look at the different technology and economic components of the LCOE and assess which are key drivers or bottlenecks to generating cost reductions. The below graph presents the decomposed LCOE of all studied technologies for 2020 in Europe, under a stable investment scenario.

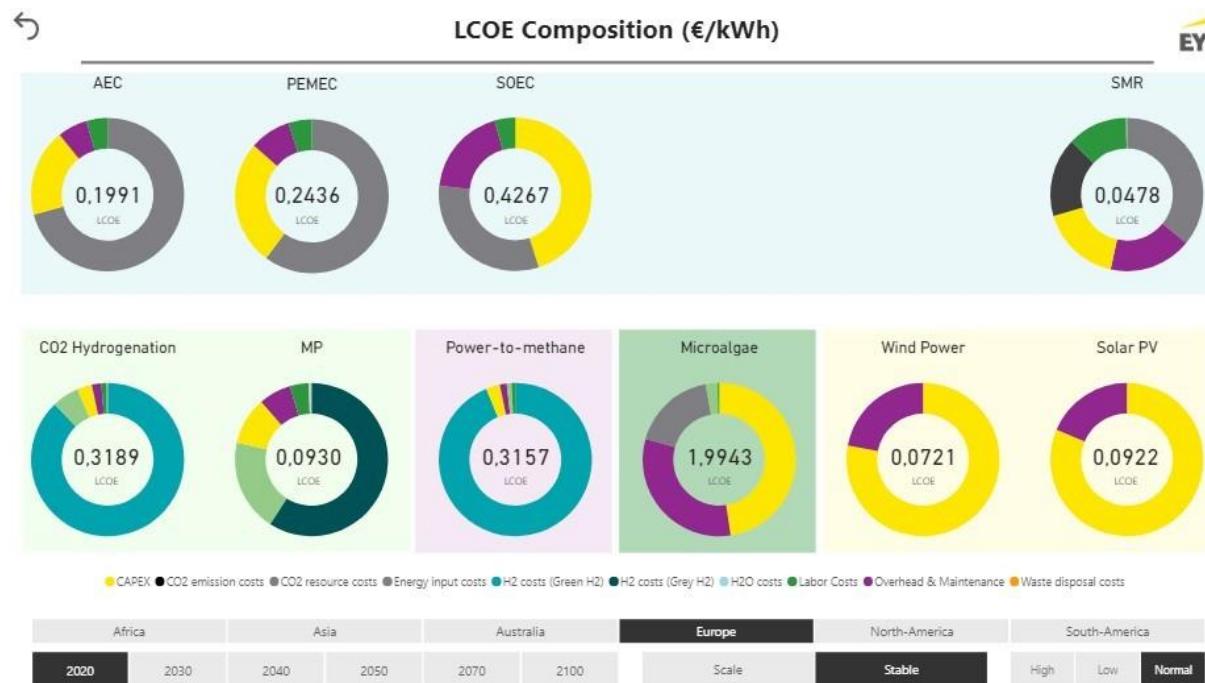


Figure 81 – LCOE composition for 2020 – all technologies

Figure 81 highlights that production costs and most specifically energy input costs are key drivers of the hydrogen system technologies' LCOE, namely AEC, PEMEC, SOEC and SMR. We can observe the high share of CO₂ emission costs of the SMR technology relative to its green counterparts. In contrast, CO₂ hydrogenation and power-to-methane incur high green hydrogen input costs, as they rely on the H₂ produced from the hydrogen system technologies. The MP technology, as fossil-benchmark, incurs high costs for grey hydrogen. For energy sources, both wind power and solar are driven mostly by capital expenditure costs, as they require no additional energy inputs and have relatively low operating costs. Similarly, microalgae faces high a CAPEX as well as high overhead and maintenance costs, which largely reflect the low maturity of the technology.

Looking at the technologies' LCOE levels, this figure highlights that the fossil-based technologies, namely SMR and MP, currently benefit from a cost advantage over their green counterparts. Amongst the green technologies, AEC displays the lowest LCOE, followed by PEMEC, power-to-methane and CO₂ hydrogenation.

The following figure will present the same analysis for 2050 to assess the change in technologies' LCOE performance and composition.

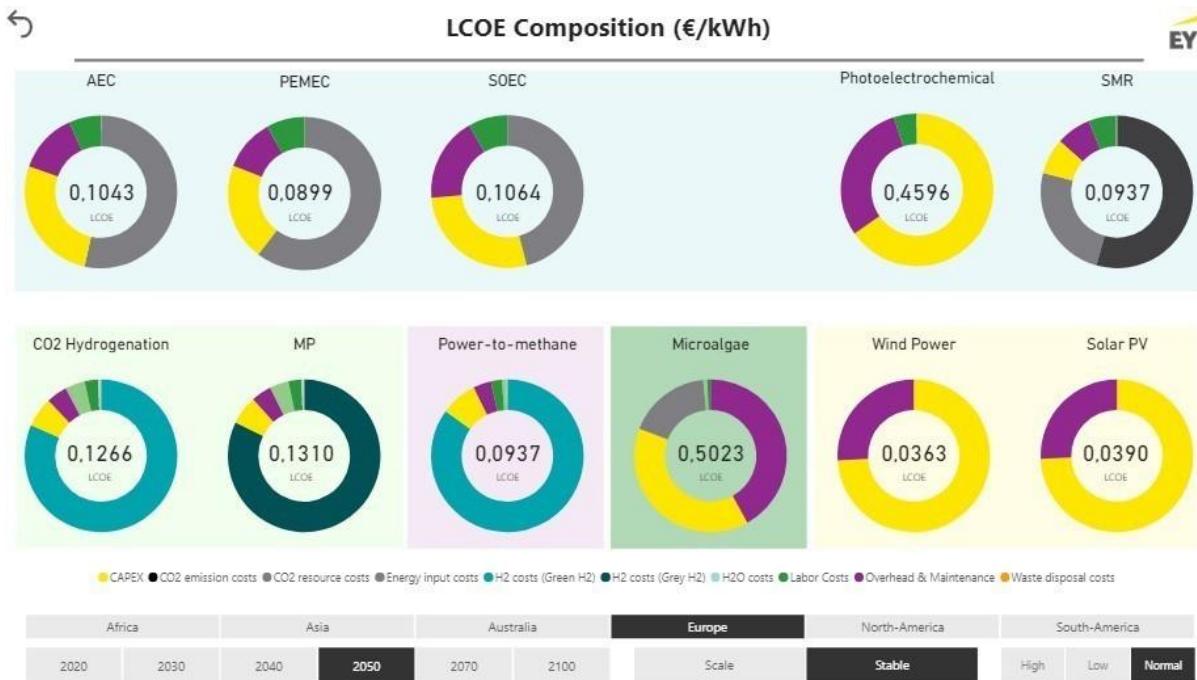


Figure 82 – LCOE composition for 2050 – all technologies

Figure 82 highlights that although decreased, energy input costs remain the largest cost driver of the hydrogen electrolyser technologies' LCOE. Although they are reduced in share for AEC, they remain an equal share of PEMEC's LCOE and increased for SOEC compared to 2020. PEMEC and SOEC display noticeable reductions in their CAPEX. PEC is now modelled, based on expected developments in the technology from 2050. The figure presents the high CAPEX and overhead and maintenance costs incurred by PEC, representing 63% and 30% of the technology's LCOE, respectively. Another key takeaway from the figure is the increased cost of CO₂ emissions for SMR, which represent 35% of the technology's LCOE against 16% in 2020. This plays a key role in the technology's cost performance overtime. We can also observe that green H₂ costs remain important for CO₂ hydrogenation and power-to-methane, while grey H₂ costs have strongly grown for MP, representing 82% of the technology's LCOE. MP also displays a notable decrease in the cost of CO₂ as a resource. Regarding ethanol production, microalgae displays decreased CAPEX levels in 2050 which are surpassed by overhead and maintenance costs now representing 41% of microalgae's LCOE. This demonstrates the increasing maturity of the technology in 2050, although still faced with challenges linked to efficiency. Wind power and solar PV benefit from decreased CAPEX in 2050 which, in terms of LCOE share, still represent around 75% of the technologies' cost structure.

Compared with 2020, the technology benefiting from a cost advantage is PEMEC, followed by SMR and power-to-methane which display equal LCOEs in 2050. AEC and SOEC are next, followed by CO₂ hydrogenation and MP. Microalgae and PEC still are at a cost disadvantage in 2050 under a stable scenario. One key takeaway from this figure is therefore that PEMEC became cost competitive with its fossil counterpart, SMR.

2.3. Market Outlook for solar fuels

Following the technology and economic roadmaps outlined in the following sections, the chapter will present a market outlook for solar fuels, aiming at forecasting potential future solar fuel demand through 2100 by region, sector and fuel, and based on a set of scenarios modelling different levels of climate action. The chapter provides an investment outlook identifying necessary levels of investment to meet the forecasted solar fuel demand and looks at the African continent in more detail in the form of a case study.

2.3.1. Forecasted solar fuel demand

2.3.1.1. Forecasted worldwide energy demand

Figure 83 to Figure 85 below show total final consumption worldwide from 2000 to 2100, broken down by region, for the Reference, 2°C, and 1.5°C scenarios. Historical values are shown from 2000 to 2017, with our forecasted estimates appearing going forward. All scenarios foresee a rising energy demand for Africa through 2100, despite a steep decline in the modelled energy intensity of the economy. Indeed, the sharp rise in GDP in Africa, due to the combination of strong population growth and growing GDP per capita, neutralises the decline in Africa's energy intensity per unit of GDP.

Asia's continuing strong economic growth drives a growing demand for energy in all scenarios as well, although the decline in the energy intensity of Asian economies leads to a reduction in their collective energy demand in 2050, 2035 and 2031 in the Reference, 2°C and 1.5°C scenarios.

Australia and New Zealand's contribution to worldwide energy demand is small, relative to other regions. Compared to Europe and North America, whose total final consumption is expected to peak in the current decade in the Reference scenario, total final consumption in Australia and New Zealand continues to grow, albeit at a moderate pace, to 2070. Only in the 1.5°C scenario does Australia and New Zealand's total final consumption begin declining as of 2020.

The total final consumption in Europe is approximately stable to 2025 in the Reference scenario, unlike the other regions where energy demand continues to rise, at least initially. Europe's steep drop in forecasted total final consumption in the 2°C and 1.5°C scenarios show a marked difference between historical trends prior to 2020, and pathways required to achieve decarbonisation by 2050.

Finally, South America's forecasted total final consumption rises through 2090 in the Reference scenario, and peaks in 2048 and 2035 in the 2°C and 1.5°C scenarios respectively. Relative to the other regions, South America's GDP growth is modest, particularly compared to Africa and Asia. However, the decoupling of South American economies from energy consumption is not expected to reach the same levels as other regions, thereby leading to relatively substantial growth in the region's total final consumption.

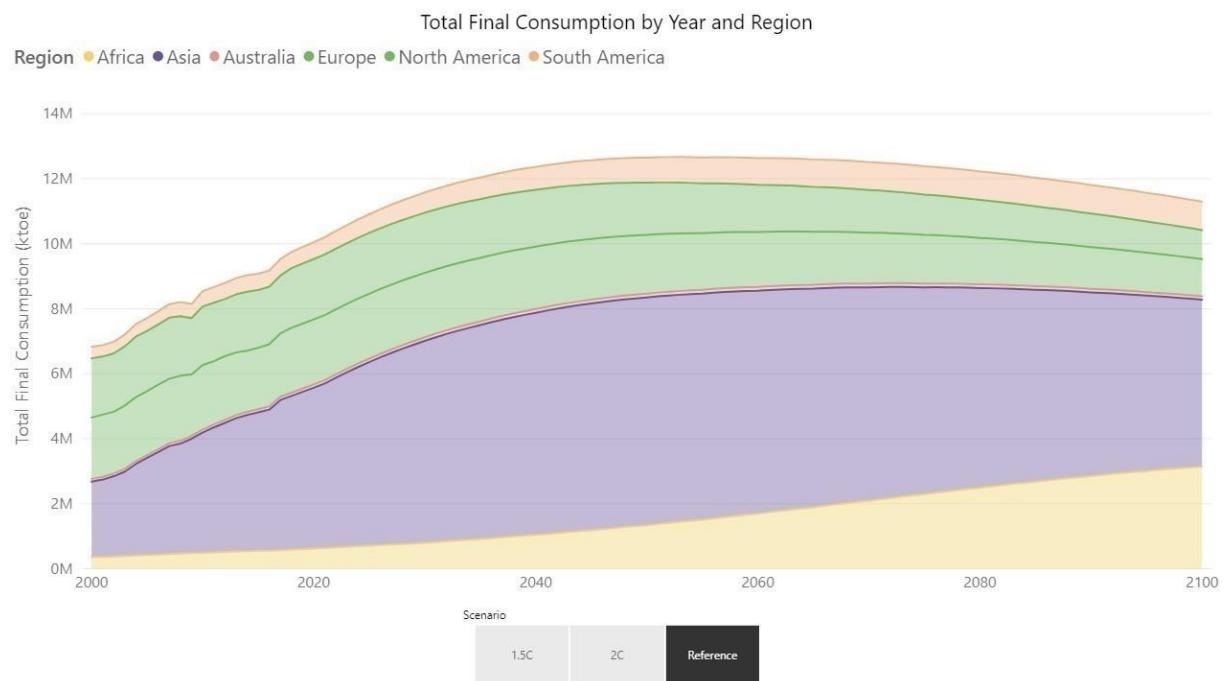


Figure 83 - Total Final Consumption by region, Reference Scenario

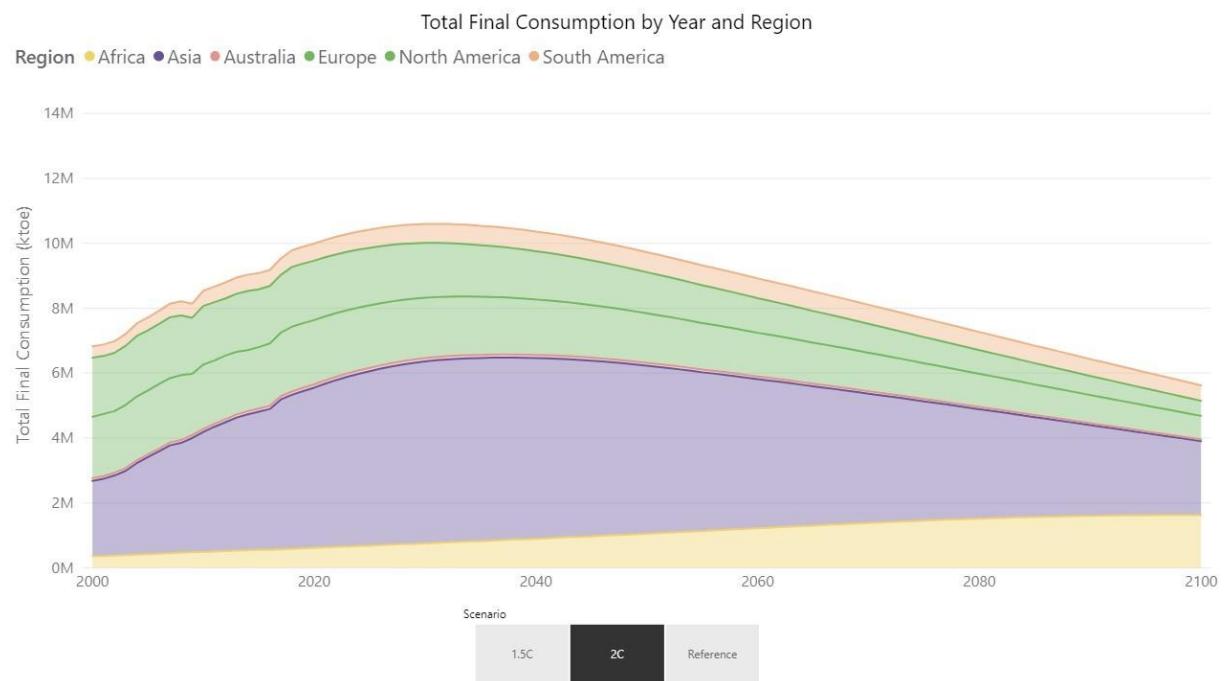


Figure 84 - Total Final Consumption by region, 2°C Scenario

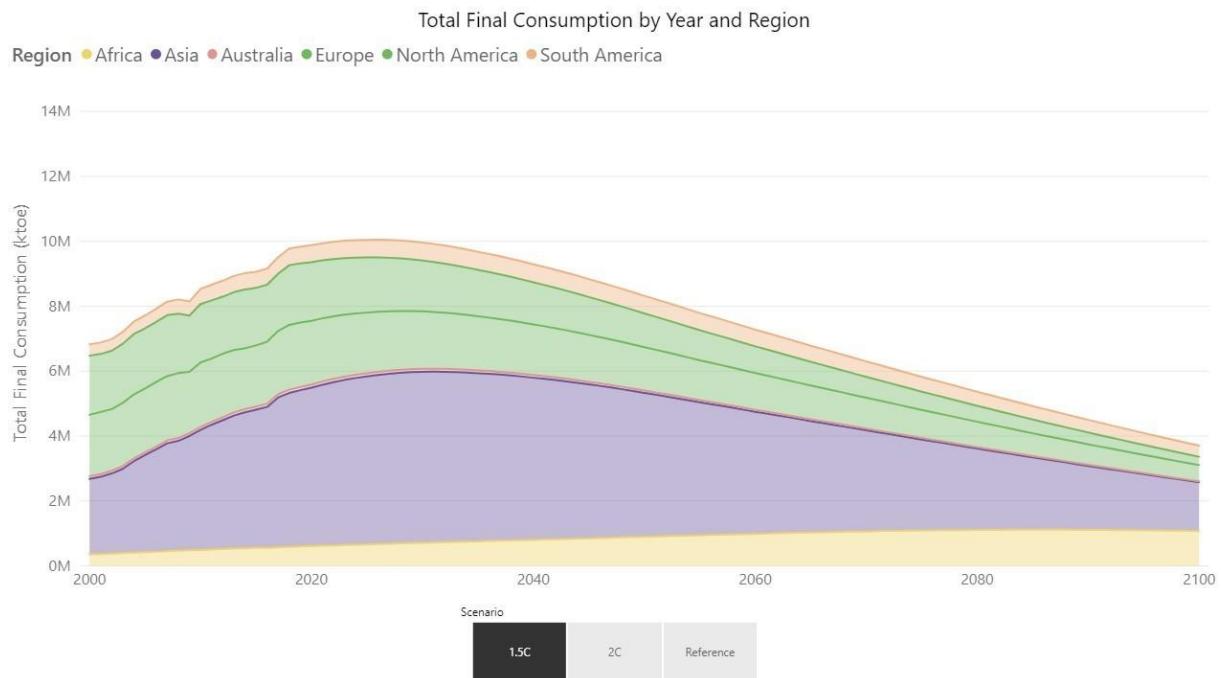


Figure 85 - Total Final Consumption by region, 1.5°C Scenario

2.3.1.2. Forecasted energy demand by sector

Figure 84 to Figure 86 below show the forecast for total final consumption worldwide from 2050 to 2100, broken down by sector, for the Reference, 2°C, and 1.5°C scenarios.

Sectoral shares of total final consumption remain fairly stable throughout the forecast for the Reference scenario, with the share attributable to buildings nevertheless rising from 30.9 percent in 2017 to 33.1 percent in 2100. In the 2°C scenario, the share attributable to industry falls from 30.3 percent in 2017 to 24.8 percent in 2100, whereas the share attributable to buildings rises from 31.8 percent to 34.4 percent. In the 1.5°C scenario, the share attributable to industry declines from 30.3 percent in 2017 to 23.5 percent, whereas the share attributable to buildings grows from 31.8 percent in 2017 to 38 percent in 2100.

It appears that the Reference scenario does not foresee great changes in the average worldwide shares of total final energy consumption broken down by sector. A middle-of-the-road scenario is expected to bring about some level of change, with industry's share of total final consumption declining in favour of buildings. In the 1.5°C scenario, this tendency is exacerbated, and buildings end up representing a substantial share of an admittedly lower final energy consumption. This points to greater difficulties in achieving energy efficiency gains, relative to other sectors.

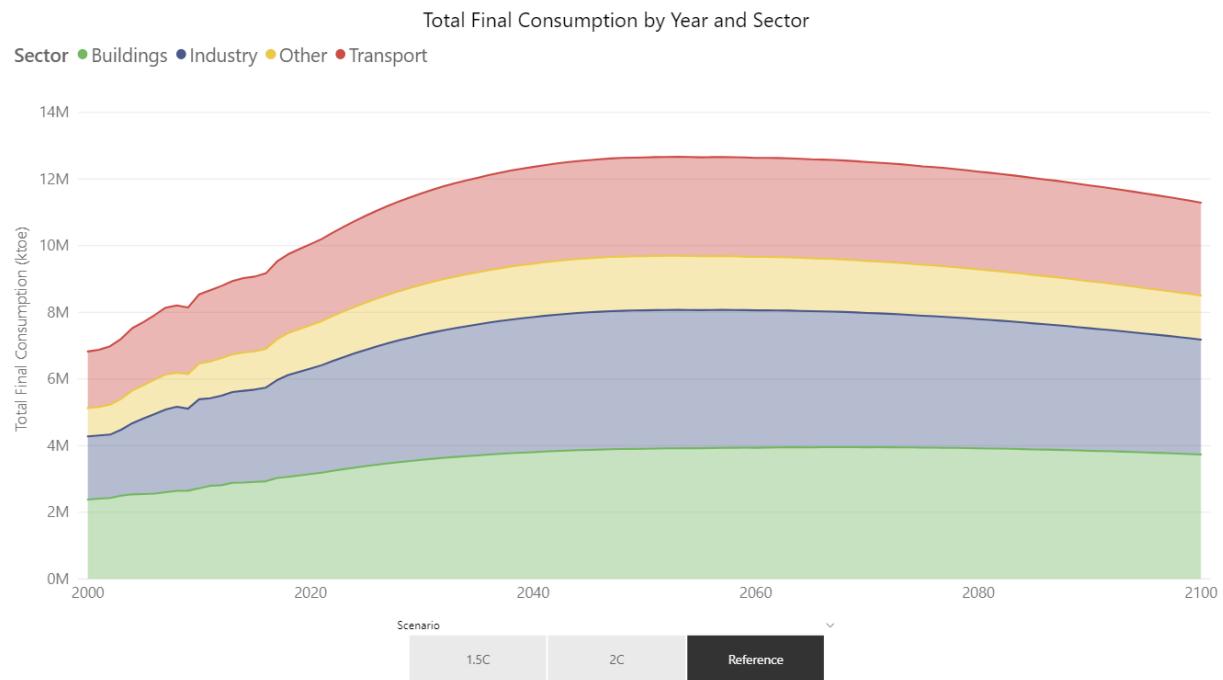


Figure 86 - Total Final Consumption by sector, 2°C scenario

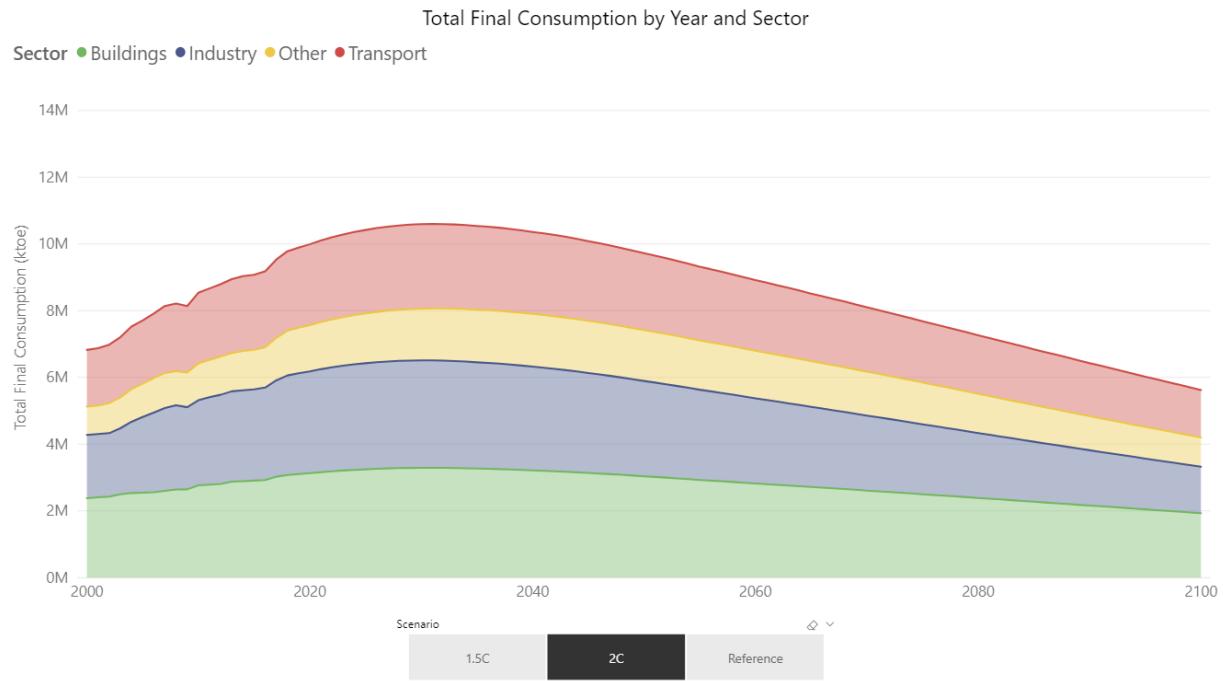


Figure 87 - Total Final Consumption by sector, 2°C scenario

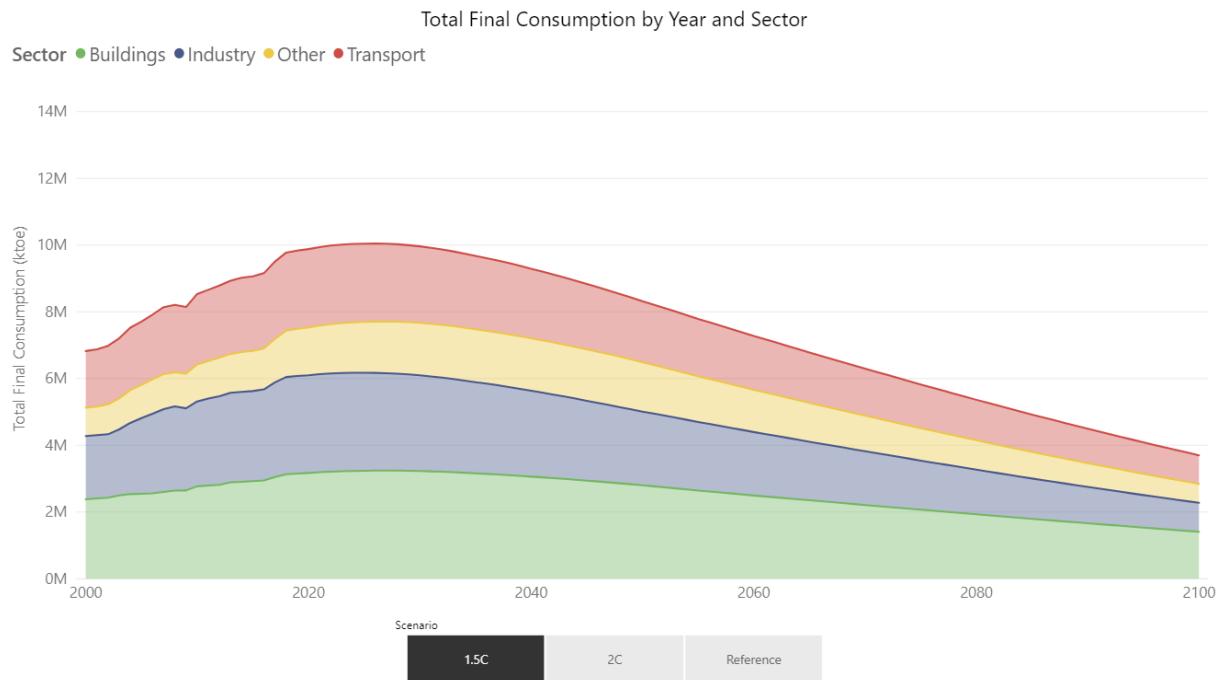


Figure 88 - Total Final Consumption by sector, 1.5°C scenario

2.3.1.3. Forecasted energy demand by fuel type

While the absolute amount of final consumption of oil worldwide stays relatively stable through 2100 in the Reference scenario, its share of total final consumption does decline, as the majority of the growth in total final consumption, relative to 2017, is driven by a rise in the consumption of electricity and, to a lesser extent, of natural gas. The major difference between the three scenarios appears to be the role of oil, which goes from representing 38 percent of total final consumption in 2017, to 22 percent in 2050 and 14 percent in 2100 in the 2°C scenario. In the 1.5°C scenario, the decline is sharper yet, and oil is expected to contribute to 18 percent of total final consumption in 2050, and down to under 7 percent in 2100.

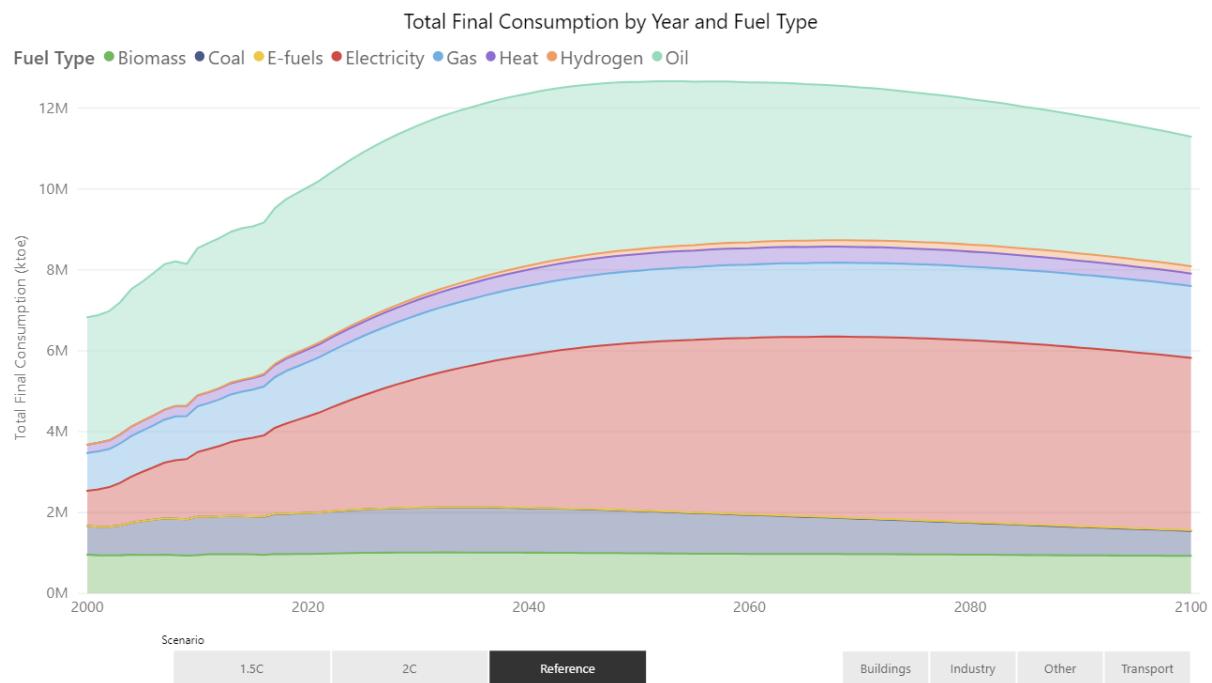


Figure 89 - Total Final Consumption by fuel type, Reference scenario

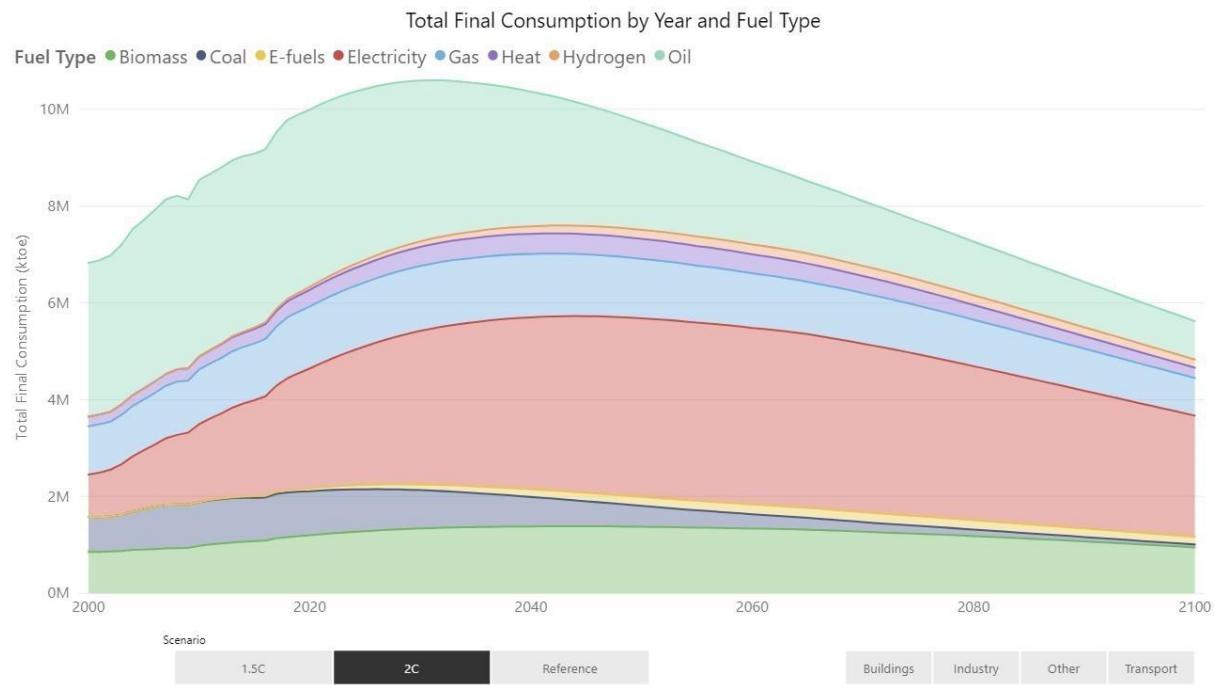


Figure 90 - Total Final Consumption by fuel type, 2°C scenario

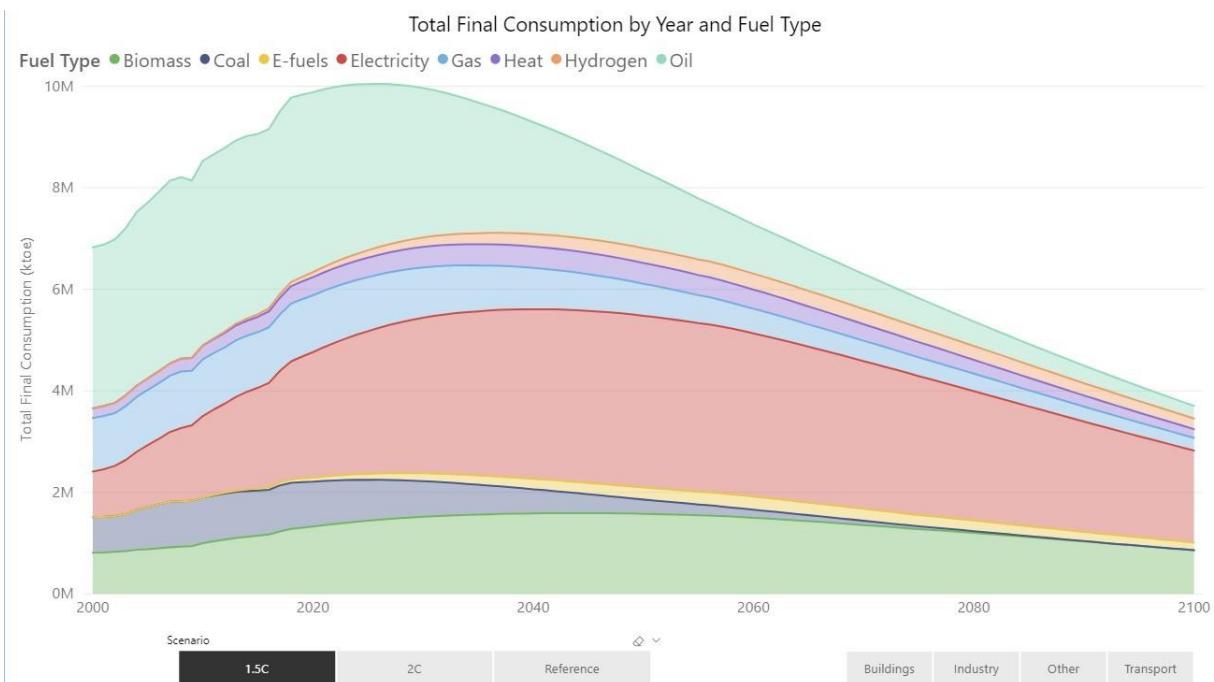


Figure 91 - Total Final Consumption by fuel type, 1.5°C scenario

2.3.1.4. Forecasted solar fuel demand by scenario

As discussed in the methodological note in Section 0.3, we have considered that forecasted demand for hydrogen in 2050 and 2100 will be met by green hydrogen, i.e. hydrogen produced through electrolysis coupled with renewable energy, and can therefore be considered a solar fuel⁸⁹. The fuel types considered in our market exercise also include e-

⁸⁹ While approximately 95 percent of hydrogen produced worldwide in 2020 was manufactured through steam methane reforming, our forecast of the LCOE of steam methane reforming, compared to electrolysis technologies coupled with solar PV, shows that hydrogen is expected to become market competitive by 2040 to 2050, depending on the jurisdiction and on assumptions

fuels, defined as synthetic hydrocarbon fuels in either liquid or gaseous form, and derived from the reaction of hydrogen with CO₂. In order to be fully carbon-neutral, without CO₂ capture at the point of combustion, the CO₂ used to produce these e-fuels must be harvested from the atmosphere using direct air capture ("DAC"). While DAC technologies have been making inroads, including through innovative start-ups such as Carbon Engineering⁹⁰ and Climeworks⁹¹, they remain costly. As a compromise, e-fuels may be produced using CO₂ derived from carbon capture and utilisation ("CCU"), for instance by harvesting CO₂ from process emitters such as cement factories. Such a scheme would mitigate, if not negate, the net CO₂ emissions from e-fuels.

Figure 92 to Figure 94 below illustrate the potential demand for solar fuels up to 2100, for all three scenarios. In the Reference scenario, solar fuels are not expected to meet a substantial share of worldwide energy needs, contributing just one percent of total final consumption in 2050, and 1.7 percent in 2100.

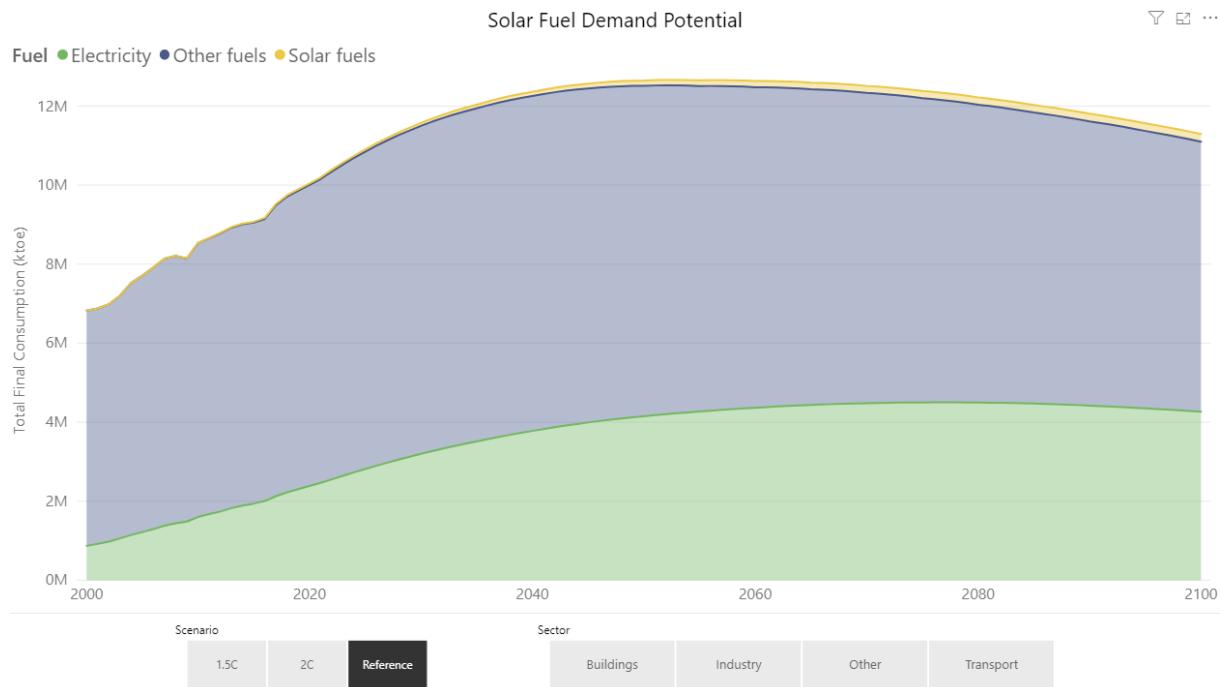


Figure 92 - Solar Fuel Demand Potential, Reference scenario

In the middle-of-the-road 2°C scenario, solar fuels become a real key part of energy systems worldwide, contributing to 3.8 percent and 5.8 percent of worldwide energy needs in 2050 and 2100.

regarding the level of investment in electrolysis technologies, among others. We believe it reasonable to assume that electrolysis, coupled with solar PV, can produce practically all of the expected hydrogen demand in 2050.

⁹⁰ <https://carbonengineering.com/>

⁹¹ <https://climeworks.com/>

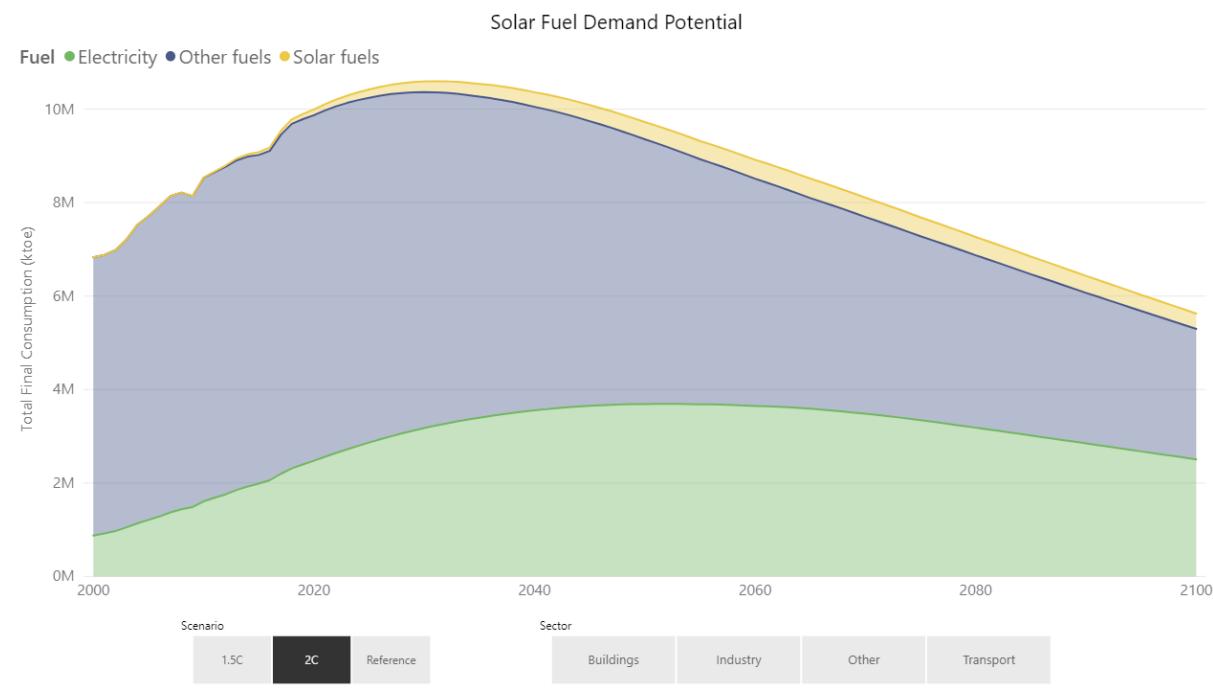


Figure 93 - Solar Fuel Demand Potential, 2°C scenario

In the 1.5°C scenario, finally, solar fuels would contribute to 6.3 percent and 9.8 percent of energy needs worldwide in 2100.

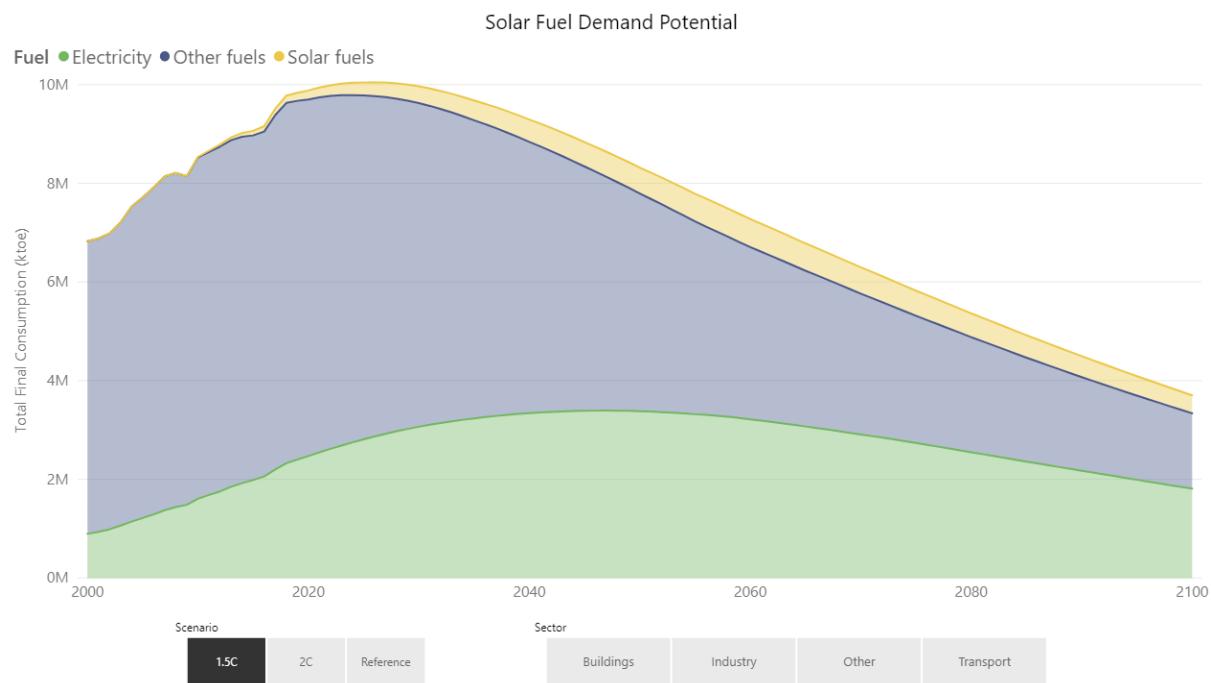


Figure 94 - Solar Fuel Demand Potential, 1.5°C scenario

2.3.1.5. Solar fuel demand factors

Ultimately, the demand for solar fuels depends on a wide variety of factors endogenous and exogenous to the energy system, including:

- Costs of solar fuels, which are primarily driven by the price of solar electricity at first vs. costs of comparable fossil fuels,
- Costs of adapting end-use systems to solar fuels, such as changing from coal to hydrogen in steel manufacturing,
- Infrastructure costs,

- Demand for carbon-neutral industrial products, vehicles and transportation services, and heating and cooling technologies in buildings, and
- Supportive regulations and policies such as those implementing carbon pricing mechanisms.

The expected decline in the costs of solar fuel technologies, in turn, depends on a broad range of factors including efficiency gains, declining capital expenditures as the technology matures, and declining costs of solar PV electricity itself.

In our LCOE forecast model, whose results were presented in section 2.2 of this report, we have assumed two scenarios for the level of investment in solar fuel technologies: the stable scenario models a stable growth, driven by incremental innovation that could potentially make the technology market competitive in the long run. The second scenario, labelled “scale”, models aggressive investments in solar fuel technologies, resulting in quicker cost reductions.

Under stable conditions, the time to market for these technologies could be as long as 30 to 60 years, depending on the jurisdiction. Therefore, under stable conditions comparable to those underlying the Reference scenario for our market outlook exercise, we do not expect solar fuels to supply a substantial share of worldwide energy needs.

On the other hand, the time to market for green hydrogen under aggressive scale conditions, implying heavy investments in early-stage technologies, could be as little as 20 years. These heavy investments would result in the production of solar fuels in the very near term, as portrayed in the 1.5°C scenario in our market outlook exercise.

Hydrogen is proven to be an efficient energy carrier in a wide variety of applications in industry, transport and buildings. The potential for hydrogen demand in each sector is discussed in greater detail in the sections below, presenting results by sector. Beyond its suitability to a number of end-use cases, hydrogen is also being considered as a promising means of energy storage. Stored hydrogen can address the impacts of fluctuating renewable energy production at all time horizons, from intra-day to inter-seasonal⁹².

On top of addressing the temporal distribution of renewable energy, hydrogen and solar fuels in general can help address imbalances in the geographical distribution of renewable energy production, relative to consumers. Solar PV plants require inexpensive land, as well as plentiful sun, to make them as cost-efficient as possible. This implies building solar PV capacity far away from population centres. Japan is a mountainous country and is relatively limited with regards to locations suitable for the development of solar PV. Australia, however, has high average annual solar irradiation and vast areas of land suitable to solar PV plants. The development of solar fuel supply chains emanating from Australia could help address Japan’s growing demand for hydrogen. Japan and Australia have already established a hydrogen supply chain based on hydrogen production from coal gasification⁹³. Given Australia’s favourable conditions for solar PV, and further expected cost reductions in solar PV technologies, this supply chain could potentially be decarbonised in the medium term.

The benefits of solar fuels discussed above apply at large scales, implying centralised energy production. Solar fuels can be produced at small scales, thereby enabling innovative solutions for decentralised energy production. Decentralised, also labelled distributed production of hydrogen could help introduce hydrogen in the short term, as it

⁹² Guerra, O., Zhang, J., Eichman, J., Denholm, P., Kurtz, J., Hodge, B., 2020, The value of seasonal energy storage technologies for the integration of wind and solar power, *Energy Environ. Sci.*, 2020, **13**, 1909-1922

⁹³ FuelCellsWorks, 2019, Japan-Australia Hydrogen Energy Supply Chain Pilot Begins, Available online at <https://fuelcellsworks.com/news/japan-australia-hydrogen-energy-supply-chain-pilot-project-begins/>

would not require the development of extensive distribution infrastructure. For instance, hydrogen could be produced directly in hydrogen fuelling stations. Fraunhofer ISE developed such a facility in Freiburg, Germany in 2012, and Honda has been installing its Smart Hydrogen Stations throughout Japan. There are trade-offs between decentralised and centralised production of hydrogen. Centralised production allows for economies of scale, lowering production costs. However, the costs of distribution infrastructure can be high, and decentralised production helps address these costs.

The development of electrolyser capacity coupled to industrial plants, including both hydrogen users such as refiners and CO₂ emitters such as cement plants, could help reduce the challenge of infrastructure needs. As industries are increasingly considering carbon capture and storage schemes, CO₂ may become more readily available, and could serve as an input to solar fuel production. These solar fuels could be produced and used on-site to power the same CO₂-emitting industrial processes, thereby closing the carbon loop. Such schemes, with the right incentives, could prove attractive to industries, driving them to invest in early-stage technologies.

Figure 95 below illustrates an example of such a process, where CO₂, emitted by e.g. a cement plant, could be captured by a base such as OH⁻, which would be fed to an electrolyser powered by solar PV. The resulting products would be evaporated to yield liquid fuels such as methanol and the base, which would be recycled for CO₂ capture. The resulting fuel could be used to power the cement plant, or used as a means of energy storage, or shipped to users through existing infrastructure.

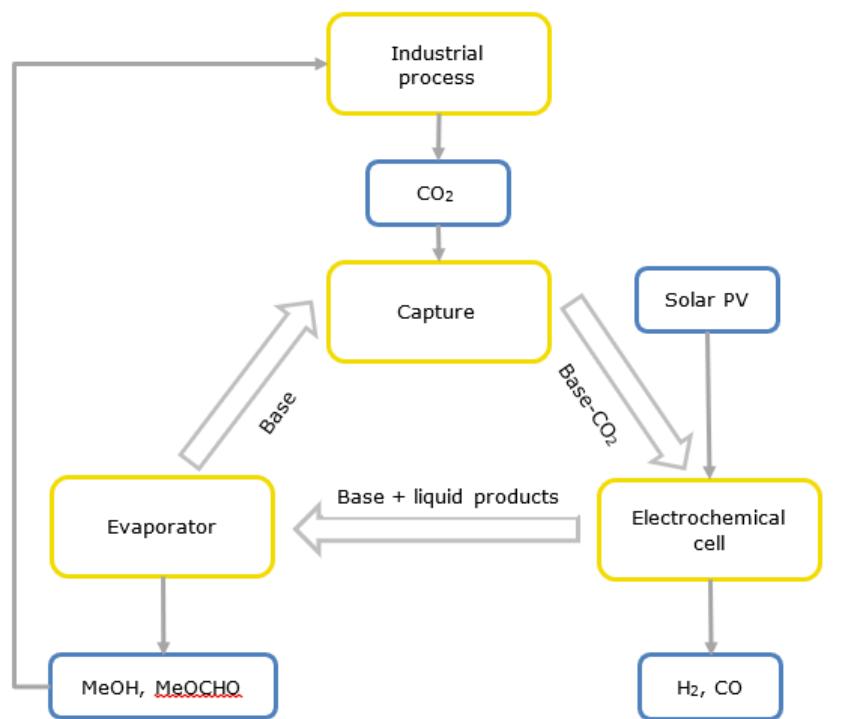


Figure 95 - Example of a cyclical process coupled to a CO₂ emitting plant⁹⁴

Given the long time horizon, it is difficult to estimate the potential contribution of solar fuels to worldwide energy needs with much precision. We have deliberately chosen a conservative approach to account for the possibility that unexpected challenges make solar fuels more costly to develop, such as raw materials limitations. Our conservative approach is also based on the expected limitations of solar fuels, including hydrogen.

Based on discussions with energy experts during the stakeholder workshops held as part of this project, it appears that hydrogen alone cannot fulfil the entirety of our energy needs

⁹⁴ Adapted from Crabtree, R., 2020, Alternative strategies for solar fuels from carbon dioxide, Available at <https://pubs.acs.org/doi/pdf/10.1021/acsenergylett.0c01359>

for use cases where electrification does not apply. There is a clear need, for instance in the transport sector, for hydrocarbon energy carriers. The expected low price of natural gas through 2050⁹⁵ lengthens the time to market for solar-based power-to-methane technologies relatively lengthy. Our LCOE forecast models a time-to-market of 40 years for power-to-methane in the best conditions, with natural gas remaining the cheaper alternative up to 2060, despite factoring in relatively high anticipated carbon prices⁹⁶.

Nevertheless, e-liquids in particular could become market competitive sooner than e-gases, given the expected high prices for oil products through 2050⁹⁷. Our LCOE model anticipates that the production of methanol through CO₂ hydrogenation could compete with the price of motor gasoline as early as 2040, under aggressive scale conditions. The advantage of methanol is that it can be blended with motor gasoline for use in road transport with minimal changes to existing powertrains. However, while we have selected it as a representative benchmark indicating a potential pathway for e-liquids, methanol cannot be directly applied in all use cases. Many applications consuming oil products, such as aviation or maritime transport, would require subsequent refining, or the development of parallel technologies producing different hydrocarbon fuels. These alternatives could potentially result in greater costs. We have attempted to factor in these potential challenges in our estimates, thereby explaining why solar fuels have not entirely replaced fossil fuels in any of our market outlook scenarios by 2100.

2.3.2. Potential solar fuel demand by sector

The following sections present and discuss estimates of solar fuel demand by sector. The results are presented for the 2°C scenario, as it represents an average between the Reference scenario, which does not reflect expected commitments towards climate change mitigation in many jurisdictions, and the 1.5°C scenario, whose ambitious targets may not be fulfilled in all jurisdictions. As our analysis does not anticipate solar fuel demand in the “other” sector, we focus here on industry, transport, and buildings.

2.3.2.1. Potential solar fuel demand in industry

Figure 96 below shows estimates of forecasted total final consumption of energy in industry, in the 2°C scenario, broken down by fuel type, i.e. electricity, other fuels and solar fuels. The contribution of solar fuels to energy needs in industry remains relatively modest in this scenario, amounting to just 0.8 percent in 2050 and 1.5 percent in 2100. Green hydrogen can contribute to industrial processes both as a fuel and as a feedstock, although the latter use case is outside of the scope of this market outlook exercise, given the focus on solar fuels as energy carriers.

Our estimates of potential solar fuel demand in industry, in particular, are relatively conservative and are highly dependent on a number of exogenous variables, including the rate of adoption and costs of CCU technologies, as the latter could facilitate synergies enabling the production of solar fuels directly on-site at industrial facilities. Estimates of the contribution of solar fuels to industry’s final consumption of energy in 2050 in the EU28, in scenarios modelling ambitious pathways for reaching carbon neutrality, exceed 10 percent of industry’s final energy consumption⁹⁸.

⁹⁵ As evidenced in a number of forecasts, including DG JRC’s GECO and the US Energy Information Agency’s 2020 Annual Energy Outlook.

⁹⁶ Our LCOE model anticipates carbon prices reaching 178 € per tonne of CO₂ in 2050 in Europe, for instance.

⁹⁷ As evidenced in a number of forecasts, including DG JRC’s GECO and the US Energy Information Agency’s 2020 Annual Energy Outlook.

⁹⁸ European Commission, 2018, In-depth analysis in support on the COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate

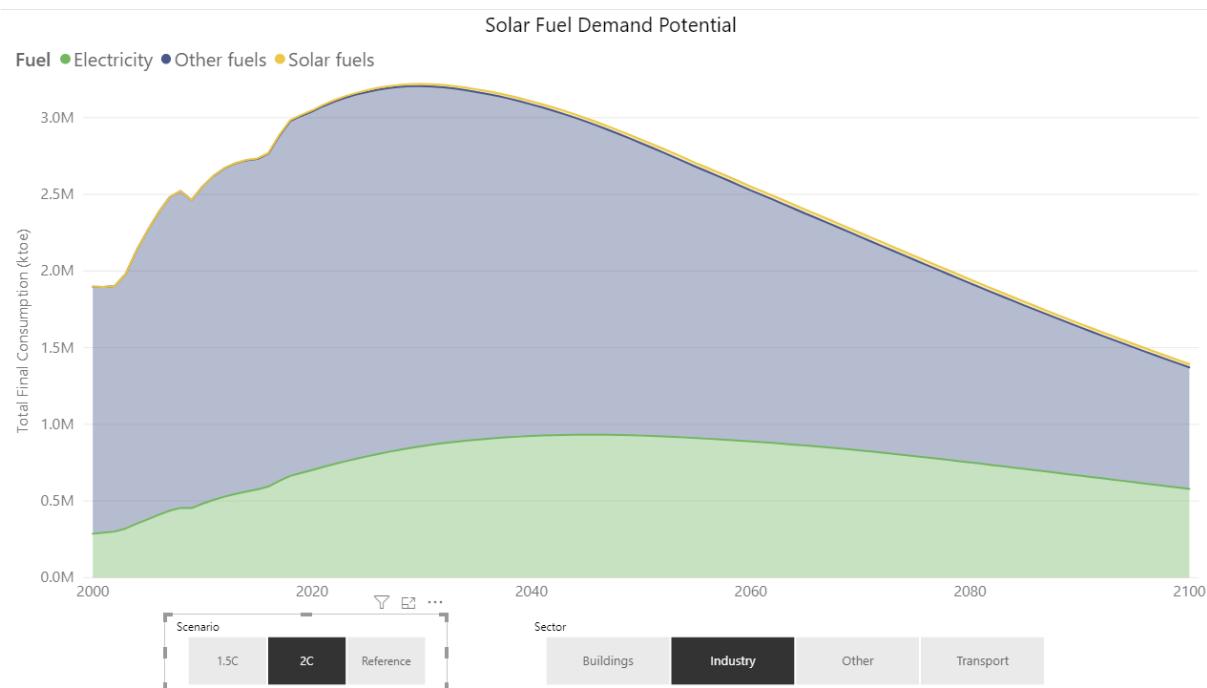


Figure 96 - Potential solar fuel demand in industry, 2°C scenario

Hydrogen's suitability as a fuel for industrial processes is already being trialled in a number of processes, including steelmaking⁹⁹. The blending of green hydrogen into the existing natural gas infrastructure, powering industrial processes currently using pure natural gas, could contribute to partially decarbonising industry's fuel consumption. Estimates of the upper limit of the blending rate vary, but it appears that hydrogen could be blended with natural gas at a rate of 15 to 20 percent, using existing natural gas infrastructure. However, this blend may not be suitable to all end use cases—existing gas turbines, for instance, may only accept one to two percent hydrogen, albeit with the potential to increase to 10-15 percent¹⁰⁰.

As discussed in section 2.3.1.4 above, our analysis shows that hydrogen is expected to become market competitive by 2040 to 2050, depending on the jurisdiction and on assumptions regarding the level of investment in electrolysis technologies, among others. The share of hydrogen consumption in industry total final consumption, ultimately, will depend on a number of factors including:

- Cost of green vs. grey¹⁰¹ hydrogen,
- Cost of green hydrogen vs. other fossil fuels currently used in industrial processes, and
- Energy efficiency gains or losses when adapting industrial processes to use hydrogen fuels, relative to currently used fossil fuels.

⁹⁹ neutral economy, Available online at https://ec.europa.eu/knowledge4policy/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en

¹⁰⁰ International Renewable Energy Agency, 2019, Renewable Power-to-Hydrogen – Innovation Landscape Brief, Available online at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Power-to-Hydrogen_Innovation_2019.pdf?la=en&hash=C166B06F4B4D95AA05C67DAB4DE8E2934C79858D

¹⁰¹ Ibid.

¹⁰² i.e. hydrogen produced through steam methane reforming.

While hydrogen is indeed expected to become market competitive relative to the steam methane reforming in the second half of the century, it will not necessarily be competitive with the direct use of natural gas until the end of the century, based on our analysis of the LCOE of solar and fossil fuel technologies, and expectations for the costs of natural gas and carbon pricing. Therefore, its ability to compete with fossil fuels in industry remains largely dependent on exogenous market conditions set by e.g. demand for carbon-neutral industrial products, public policy, and innovation.

Call-out box: Accelerating industry demand for solar fuels

As discussed above, industry's demand for solar fuels could far exceed our conservative estimates under the right conditions—including increased demand for carbon-neutral industrial products, support to investments for re-tooling industrial processes, and support to innovative means of leveraging CCU from energy-intensive industries to produce solar fuels to be re-used directly to power these very industries.

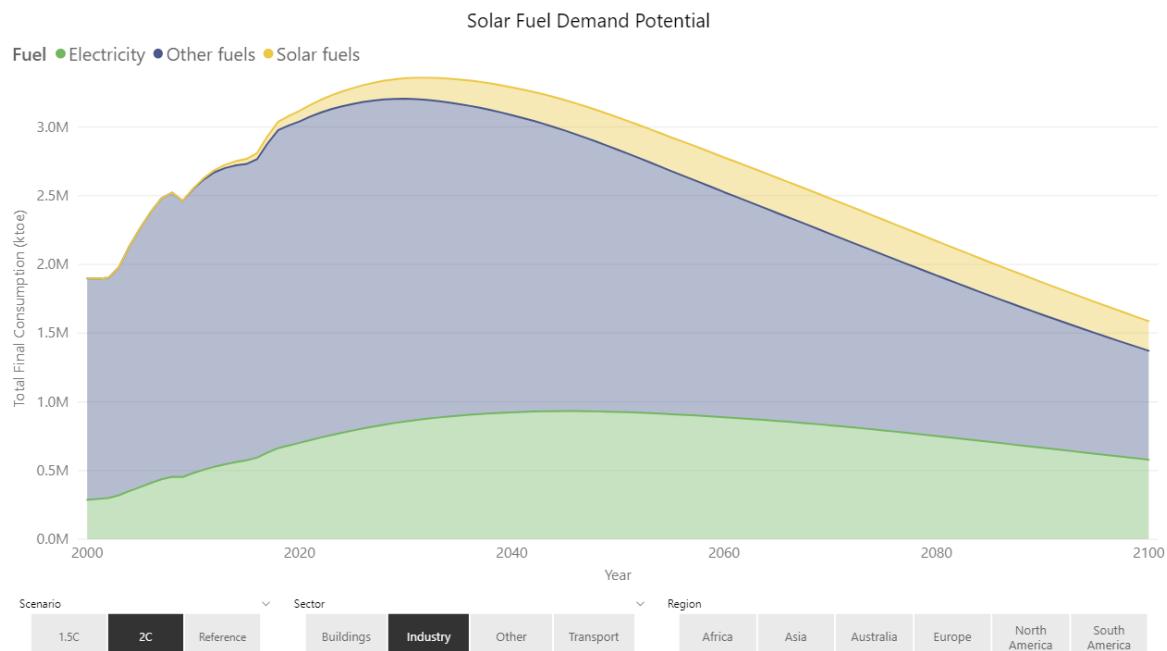


Figure 97 - Potential solar fuel demand in industry under an accelerated demand scenario

Under this accelerated demand scenario, solar fuels could potentially contribute to between 7 and 8 percent of industry's energy needs worldwide in 2050, and between 13 and 14 percent in 2100.

The total investment required to achieve the targets identified above for solar fuel production to meet demands by industry in 2050 amount to €4 to 5 trillion. The additional investments required in the second half of the century amount to €6 to 7 trillion, for a grand total of €10 to 12 trillion. On an annual basis, this would require yearly investments of €145 to 155 billion until 2050, and between €120 and €130 billion from 2050 to 2100, to meet industry's demand for solar fuels.

2.3.2.2. Potential solar fuel demand in transport

Figure 98 below shows estimates of forecasted total final consumption of energy in industry, in the 2°C scenario, broken down by fuel type, i.e. electricity, other fuels and solar fuels. Of all four sectors considered in our analysis, transportation sees the greatest share of solar fuels out of total final consumption. We expect that, in the 2°C scenario, solar fuels could contribute to 11 percent of energy demand in transport in 2050, rising to 15.2 percent in 2100.

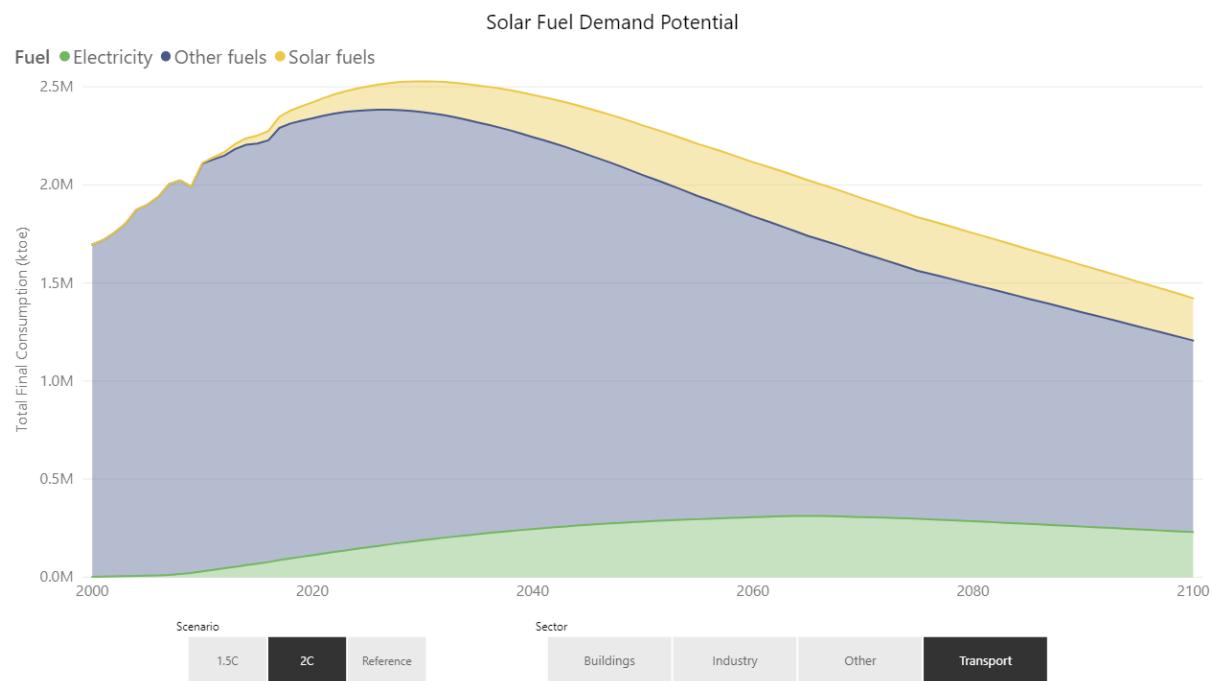


Figure 98 - Potential solar fuel demand in transport, 2°C scenario

Transport accounted for 24.5 percent of worldwide energy use in 2017. More specifically, road transport alone accounted for nearly half of worldwide oil demand in 2018¹⁰². Road transport is also the use case for which widespread electrification appears most likely within the first half of the century. The 2°C scenario builds on the assumption that battery electric vehicles would represent 16 percent of the vehicle fleet worldwide in 2050. As discussed previously, this scenario does not necessarily reflect expected pathways for all jurisdictions. In the case of EU-27 countries, battery electric vehicles are expected to make up, at a minimum, 35 percent of the EU-27 vehicle fleet in 2050 in a baseline scenario, reaching nearly 60 percent in a scenario modelling high electrification across all sectors¹⁰³. Drilling down to look at results of our market outlook analysis for just Europe, in the 1.5°C scenario, reveals that electric energy would make up 24 percent of total final consumption in transport, with other fuels contributing to 50 percent, and solar fuels to the remaining 26 percent. This appears to be broadly consistent with targets for high electrification of road transport specifically¹⁰⁴.

Our analysis of the LCOE of solar fuel technologies to 2100, and of comparable fossil fuel technologies and prices of fossil fuel resources indicate that e-liquids, and more specifically solar methanol, could become competitive with expected motor gasoline prices by the first half of 2040 in Europe, assuming aggressive levels of investment in early stage solar fuel technologies. This benchmarking analysis includes carbon pricing at the source in the wholesale price for motor gasoline, which is expected to reach € 178 per tonne of CO₂ in 2050 in Europe per our analysis. Methanol is nearly a drop-in replacement for motor

¹⁰² International Energy Agency, 2019, World Energy Outlook 2018, Available here: https://webstore.iea.org/download/direct/2375?fileName=World_Energy_Outlook_2018.pdf

¹⁰³ European Commission, 2018, In-depth analysis in support on the COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, Available online at https://ec.europa.eu/knowledge4policy/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en

¹⁰⁴ The definition of Europe, within our market outlook analysis, extends to a number of non-EU countries. Additionally, the transport sector comprises a number of sectors that are not expected to be as adaptable to electrification as road transport, such as aviation and maritime transport. Therefore, our results are not incompatible with the ambitious targets for electrification of road transport set by the EU.

gasoline and is therefore expected to contribute substantially to phasing out fossil fuels in road transport for the share of remaining internal combustion engine ("ICE") vehicles.

Nevertheless, fossil fuels can still be expected to continue contributing to energy needs in aviation, inland navigation, maritime transport, sectors that are considered more difficult to electrify, and for which methanol may not be a suitable fuel. Most scenarios considered in the European Commission's "A Clean Planet for All" Communication¹⁰⁵ anticipate that in most scenarios achieving 80% of emission reductions in the EU¹⁰⁶, fossil fuels still represent 75 percent of energy demand in aviation¹⁰⁷. However, aviation is only expected to represent 18.4 percent of the EU's energy demand in transport in 2050, compared to 75% percent for private passenger road transport, motorcycles, and heavy goods and light commercial vehicles¹⁰⁸—all of which are suitable to electrification, conversion to hydrogen fuel cell powertrains, or can readily accept hydrocarbon solar fuels expected to become market competitive by 2050. Therefore, despite potential challenges in aviation and maritime transport, the potential solar fuel demand in the transport sector is expected to be high.

2.3.2.3. Potential solar fuel demand in buildings

Figure 99 below shows estimates of forecasted total final consumption of energy in industry, in the 2°C scenario, broken down by fuel type, i.e. electricity, other fuels and solar fuels. The contribution of solar fuels to buildings' energy needs is estimated to reach 3.1 percent and 4.7 percent of total final consumption by buildings in 2050 and 2100, respectively.

¹⁰⁵ European Commission, 2018, In-depth analysis in support on the COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, Available online at https://ec.europa.eu/knowledge4policy/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en

¹⁰⁶ The scenarios are built to model pathways where the EU's GHG emissions decline by 80% by 2050, relative to levels in 1990.

¹⁰⁷ The remaining 25 percent of energy demand could be fulfilled by hydrocarbon solar fuels, as well as hydrogen, as anticipated by e.g. Airbus' recently announced concept aircraft deploying hybrid-electric turbines fuelled by a combination of hydrogen combustion and hydrogen fuel cells.

¹⁰⁸ European Commission, DG ENER, 2018, Energy modelling - EU Reference Scenario 2016, Available online at <https://data.europa.eu/euodp/en/data/dataset/energy-modelling>

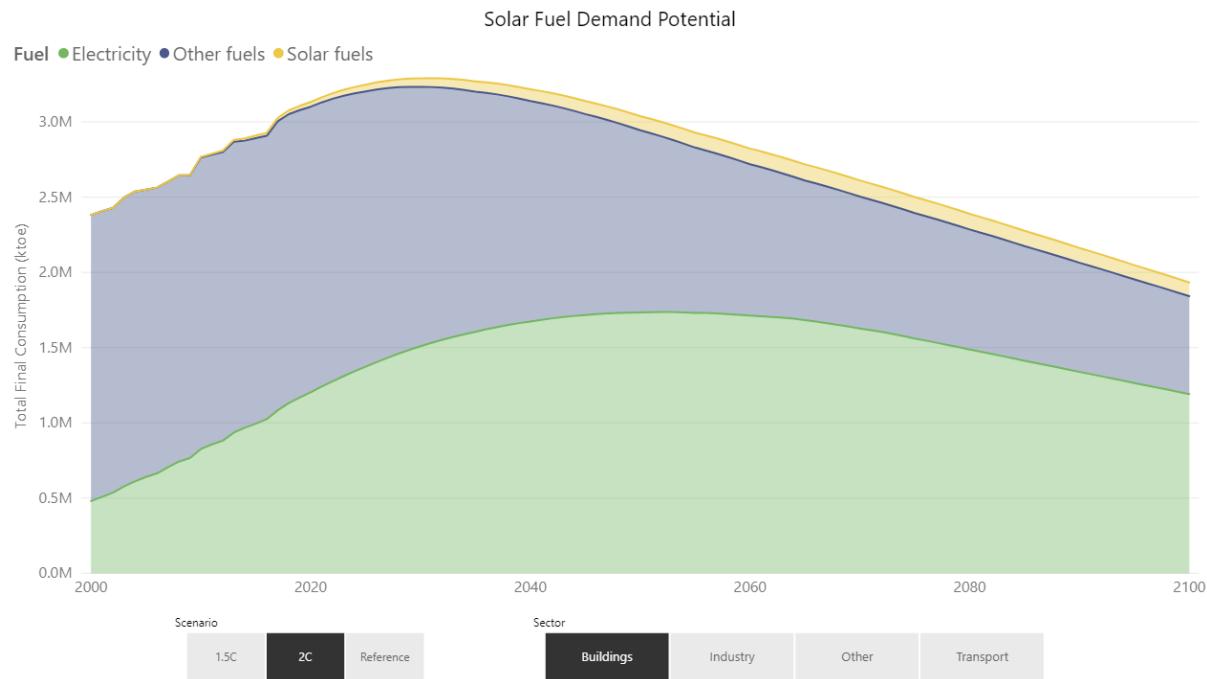


Figure 99 - Potential solar fuel demand in buildings, 2°C scenario

Our estimates of buildings' energy consumption by type of fuel show a decline in the shares of biomass, coal, gas, and oil, with a substantial increase in the share of electricity, as well as growth in the shares of heat and hydrogen. The expected sharp rise in electricity consumption in buildings is enabled by technologies such as heat pumps. In the 2°C scenario, the percentage of dwellings with heat pumps is expected to rise from zero in 2015 to 16 percent in 2050. Over 35 percent of buildings' energy consumption worldwide is applied to space heating and cooling¹⁰⁹, and is currently largely powered by fossil fuels including natural gas and heating oil. Heat pumps are highly adaptable, function in all climates, and are able to be retrofitted to existing buildings. They are therefore expected to contribute substantially to the decarbonisation of buildings' energy use, by enabling the use of renewable energy for space heating and cooling.

As regards solar fuels, a number of innovations are driving increased demand for hydrogen in buildings. This includes micro-combined heat and power ("micro-CHP") units for domestic applications. These micro-CHP units comprise a fuel cell set up to produce both heat and electricity and to supply these for domestic uses. In Japan, for instance, approximately 300,000 micro-CHP units have been installed by 2019¹¹⁰, and the government of Japan is targeting 5.3 million cumulative sales by 2030. Micro-CHP units can reduce or altogether eliminate buildings' dependencies on electricity grids, and are therefore a very attractive solution to help decarbonise energy consumption in remote and isolated areas. Micro-CHP units in grid-connected applications can also help with the integration of renewable energy into grids. With smart meters, micro-CHP units can be switched on or off at will, depending on the current grid load.

¹⁰⁹ Keramidas, K., Diaz Vazquez, A., Weitzel, M., Vandyck, T., Tamba, M., Tchung-Ming, S., Soria-Ramirez, A., Krause, J., Van Dingenen, R., Chai, Q., Fu, S. and Wen, X, 2020, Global Energy and Climate Outlook 2019: Electrification for the low-carbon transition, available here: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC119619/kjna30053enn_geco2019.pdf

¹¹⁰ Arias, J., 2019, Hydrogen and Fuel Cells in Japan, Available online at https://www.eu-japan.eu/sites/default/files/publications/docs/hydrogen_and_fuel_cells_in_japan.pdf

2.3.3. Investment outlook

This section presents estimates of the annual investment, captured in Figure 100 below, required to reach targets for the production of solar fuels meeting the forecasted demand, in the 2°C scenario, modelling scale growth conditions.

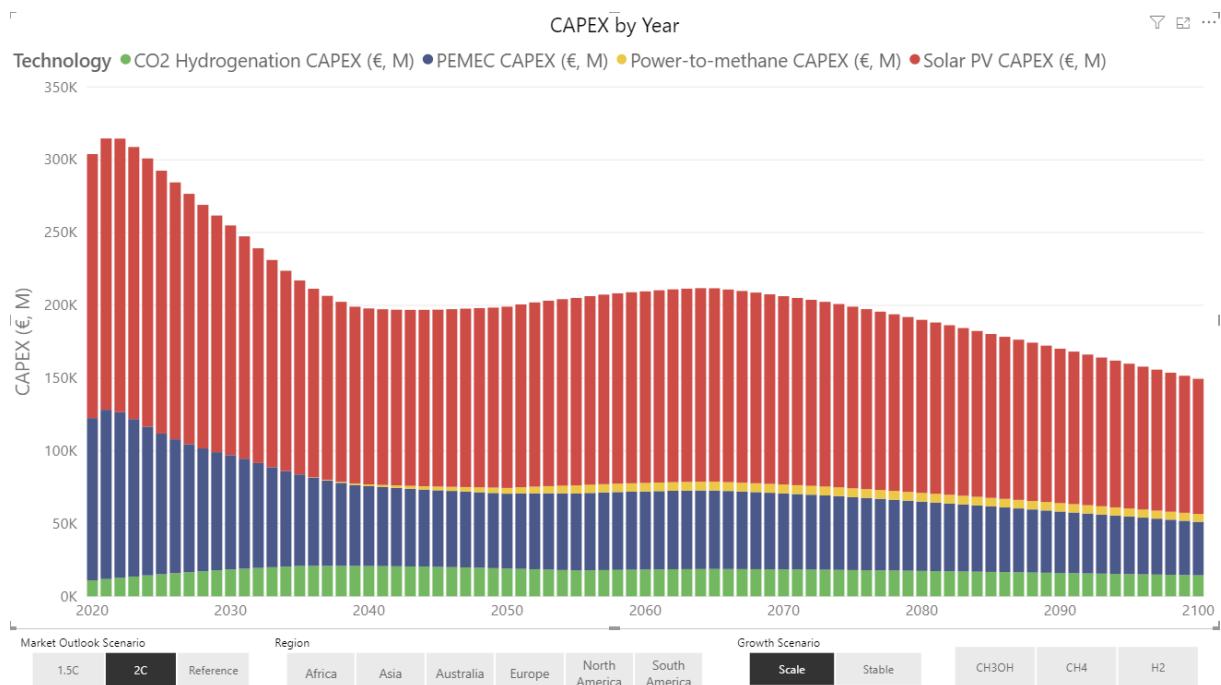


Figure 100 - Investment outlook for solar fuels worldwide, 2020-2100

The total investment required to achieve the targets identified above for solar fuel production by 2050 amount to €7.3 trillion. The additional investments required in the second half of the century amount to €9.5 trillion, for a grand total of €16.8 trillion.

In the period from 2020 to 2050, despite a relatively low annual demand for solar fuels, the high capital costs of solar fuels require substantial annual investments. Averaged from 2020 through 2050, these amount to annual investments across the entire solar fuel value chain of €236.5 billion. This includes €145.2 billion of annual investments in the solar PV capacity required just to produce electricity for the solar fuel supply chain. Annual investments in electrolyzers in the first half of the decade amount to €72 billion. The third-stage technologies, CO₂ hydrogenation and power-to-methane, require relatively low levels of additional CAPEX, calling for €18.4 and €1 billion in annual investments respectively.

In the period from 2050 to 2100, average total annual investments decline slightly thanks to substantial reductions in capital expenditure costs. The total annual investment required amounts to €190 billion. Annual investments in solar PV capacity for the solar fuel supply chain amount to €119.2 billion. Electrolyzers require €48 billion in annual investments to feed the demand for hydrogen, both for final consumption and for further transformation into hydrocarbon fuels. Annual investments in CO₂ hydrogenation fall very slightly compared to the first period, amounting to €17.4 billion. Power-to-methane, on the other hand, is expected to require substantial investments as the technology reaches parity with natural gas prices in the second half of the century, resulting in annual investments of €5.8 billion.

2.3.4. Interaction with UN Sustainable Development Goals

The United Nations' ("UN") Sustainable Development Goals ("SDGs"), established in 2015, set a vision for improved living conditions worldwide by 2030, achieving "a better and more

sustainable future for all”¹¹¹. The UN SDGs number 17 across a variety of themes, including the environment, energy and climate, as well as economic development, education, and social justice. The development of solar fuels are expected to contribute to all sustainable development goals to different extents. Expectedly, solar fuels are expected to contribute mostly to the SDG related to energy, environment and climate. They could nevertheless have an indirect impact on other goals as well. In this context, the below table summarises the potential role that the development of solar fuels could play in reaching the 17 goals and associates a level of impact to each goal.

Table 29 – Interaction of solar fuels development with UN SDG

SDG	Impact of solar fuels development on SDG	Comments
1. No poverty	Low	The development of solar fuels in regions blessed with abundant average solar irradiation could lead to economic growth, which could, in the long term, contribute indirectly to eradicating poverty. Nevertheless, the benefits of solar fuel projects developed in poverty-stricken regions are also expected to accrue mostly to project developers, likely from more developed nations, in the short term at least. In the medium and long term, the development of local solar fuel value chains would be expected to contribute to economic growth, and indirectly to the eradication of poverty.
2. Zero hunger	Low	As above, the development of solar fuels could contribute to economic growth in the medium and short term, indirectly helping to eradicate hunger.
3. Good health and well-being	Low	As above, the development of solar fuels could contribute to economic growth in the medium and short term, indirectly helping to improve health outcomes.
4. Quality education	Low	As above, the development of solar fuels could contribute to economic growth in the medium and short term, indirectly helping to improve education outcomes.
5. Gender equality	Low	In terms of employment, renewable energy employs 32% of women against 22% in the energy sector overall according to IRENA. While this figure remains low, solar fuels research and development could follow this trend towards greater women employment ¹¹² .
6. Clean water and sanitation	Low	Most solar fuel pathways, and in particular water electrolysis coupled with solar PV, require a source of freshwater, an increasingly scarce resource. Nevertheless, research is underway to achieve

¹¹¹ United Nations, 2017, Resolution adopted by the General Assembly on 6 July 2017, Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development, Available online at https://ggim.un.org/documents/A_RES_71_313.pdf

¹¹² International Renewable Energy Agency, IRENA (2019). Renewable Energy: a gender perspective. <https://www.irena.org/publications/2019/Jan/Renewable-Energy-A-Gender-Perspective>

		<p>electrolysis using seawater, thereby negating the potential negative impacts on access to clean water.</p> <p>Additionally, microalgal ethanol production can utilise wastewater, helping to address sanitation problems.</p>
7. Affordable and clean energy	High	The development of solar fuels could strongly contribute to the goal of providing clean energy. Regarding affordability, as demonstrated in our study, some of the studied technologies and notably PEMEC is expected to reach cost parity with fossil counterparts as early as 2039 in Europe, with an investment push. In a normal investment scenario, affordability of the technologies will be achieved on the longer-term.
8. Decent work and economic growth	Medium	The development of solar fuels is expected to lead to economic growth and job creations, notably in the fields of project development, manufacturing, construction and installations as well as operations and maintenance.
9. Industry, innovation and infrastructure	High	The development of solar fuels represent an important innovation, generated by strong efforts in research and development. The production and application of solar fuel will require the development of appropriate sustainable infrastructure.
10. Reduced inequalities	Medium	The development of local solar fuel value chains notably in regions blessed with high solar irradiation could participate in reducing inequalities in terms of energy poverty, by providing for greater energy access, distribution and storage at the local level.
11. Sustainable cities and communities	High	The development of local solar fuel value chains could strongly participate in the development of sustainable communities and cities by providing for greater independence in energy supply. They would also participate in making cities more sustainable through their applications in the transport sector and buildings, often concentrated in cities.
12. Responsible consumption and production	High	The development of solar fuels could strongly participate in generating more responsible consumption and production. This is especially true in the case of circular economy loops that could be generated by industry through innovative means of leveraging CCU from energy-intensive industries to produce solar fuels to be re-used directly to power these very industries.
13. Climate action	High	The development of solar fuels would contribute to climate action by reducing our reliance on fossil fuels and limiting GHG emissions into the atmosphere.
14. Life below water	Medium	By acting towards the reduction of GHG emissions, the development of solar fuels would contribute towards reducing the effects of climate change on ocean life, including mitigating ocean temperature rises and marine ecosystems impacts.

15. Life on land	Medium	As above, the development of solar fuels could contribute to mitigating the impacts of climate change on nature and land ecosystems.
16. Peace, justice and strong institutions	Low	The development of solar fuels could participate in providing for peace and justice by limiting conflicts linked to control over fossil energy sources and by participating in mitigating risks and crises generated by climate change.
17. Partnerships for the goals	High	The development of solar fuels requires strong international cooperation as exemplified by initiatives such as Mission Innovation Challenge 5. Similarly, concerted efforts between energy industries, consumers and policy-makers worldwide will be required to ensure solar fuels efficient and large-scale development.

2.3.5. Africa case study

2.3.5.1. Solar Fuel market size in Africa: potential demand by sector

The following sections present and discuss estimates of solar fuel demand by sector in Africa. As is the case for the worldwide average presented above, the results are presented for the middle-of-the road 2°C scenario. As our analysis does not anticipate solar fuel demand in the “other” sector, we focus here on industry, transport, and buildings.

Our analysis foresees a demand for solar fuels in Africa that is relatively lower than the worldwide average, across all sectors. Due to a number of factors including higher expected capital costs, and lower expected carbon pricing in Africa, our economic roadmap for solar fuels, presented in section 2.2 of this report, anticipates a longer time to market for solar fuels in Africa, relative to the worldwide average. Additionally, on the demand side, it is expected that the high costs of adapting energy end uses to solar fuels may prove to be a constraint to the adoption of solar fuels in Africa. Indeed, while green hydrogen, for instance, is being put to the test as a potential fuel and reducing agent in the steel industry in Europe, it remains highly expensive due to both greater capital costs and fuel costs, relative to coal-based steel production. The future of green hydrogen-based steel production depends on many factors, including the existence of a demand for carbon-free steel, and expectations of rising carbon prices¹¹³. As these factors are expected to materialise later in Africa than in most other jurisdictions, Africa’s demand for solar fuels is expected to be relatively lower than the worldwide average.

Nonetheless, there are two main factors counterbalancing the above. The first is Africa’s relatively low investment in legacy fossil fuel infrastructure, and its concomitant predisposition towards adopting new technologies¹¹⁴. The second is Africa’s competitive advantage with regards to solar irradiance, coupled with large areas of land available for the development of solar PV plants. This results in low expected costs for solar energy in Africa. Regarding the latter, experts foresee a role for North Africa in supplying Europe

¹¹³ Simon F., Euractiv.com, 2018, Swedish steel boss: ‘Our pilot plant will only emit water vapour’, Available at <https://www.euractiv.com/section/energy/interview/hybrit-ceo-our-pilot-steel-plant-will-only-emit-water-vapour/>

¹¹⁴ Most countries in Africa have been quicker to adopt mobile payments and other cell phone-based technologies, due to, among others, a lack of investment in legacy payment systems and fixed-line telephony.

with affordable decarbonised fuels¹¹⁵. Coupled with investment capital coming from Europe as well¹¹⁶, this could catalyse the development of a solar fuel industry in North Africa. The local availability of these fuels could contribute to the acceleration of local demand. Therefore, the estimates presented and discussed below can be considered relatively conservative, and the right combination of early investment by international stakeholders, and the development of a local industry, can help capitalise on the significant potential for solar fuels in Africa.

2.3.5.2. Potential solar fuel demand in the industry sector in Africa

Figure 101 below shows estimates of forecasted total final consumption of energy in the industry sector in Africa, in the 2°C scenario, and broken down by type of energy, i.e. electricity, other fuels and solar fuels. Similarly to the worldwide average, the contribution of solar fuels to industry's energy needs in Africa remain relatively modest in this scenario, amounting to just 0.3 percent in 2050 and 0.5 percent in 2100.

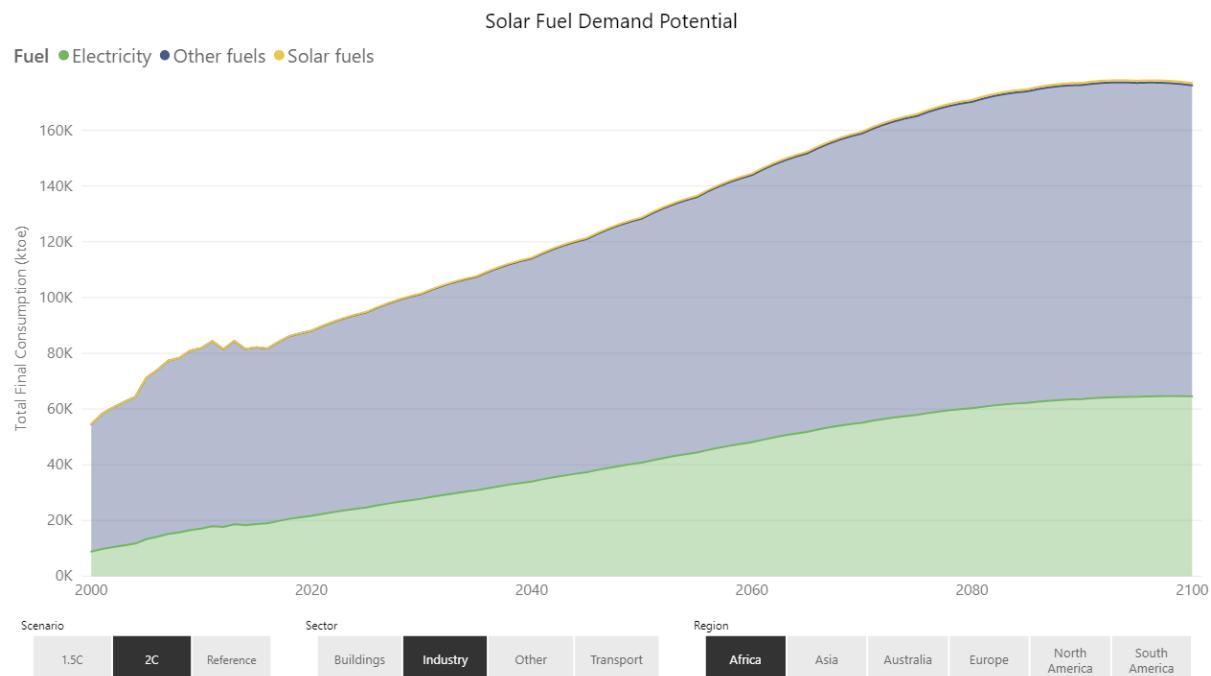


Figure 101 - Potential solar fuel demand in the industry sector in Africa, 2°C scenario

2.3.5.3. Potential solar fuel demand in the transport sector in Africa

Figure 102 below shows estimates of forecasted total final consumption of energy in the transport sector in Africa, in the 2°C scenario, and broken down by type of energy, i.e. electricity, other fuels and solar fuels.

Similarly to the worldwide average, transportation sees the greatest share of solar fuels out of total final consumption. We expect that, in the 2°C scenario, solar fuels could contribute to 9.5 percent of energy demand in transport in 2050, rising to 11.7 percent in 2100.

¹¹⁵ Chatzimarkakis, J., 2020, Green gases from sun and wind are a new opportunity for North Africa, Available online at <https://www.neweurope.eu/article/green-gases-from-sun-and-wind-are-a-new-opportunity-for-north-africa/>

¹¹⁶ Including for instance the €2 billion earmarked for green hydrogen investments by Germany in third countries, such as North Africa in particular.

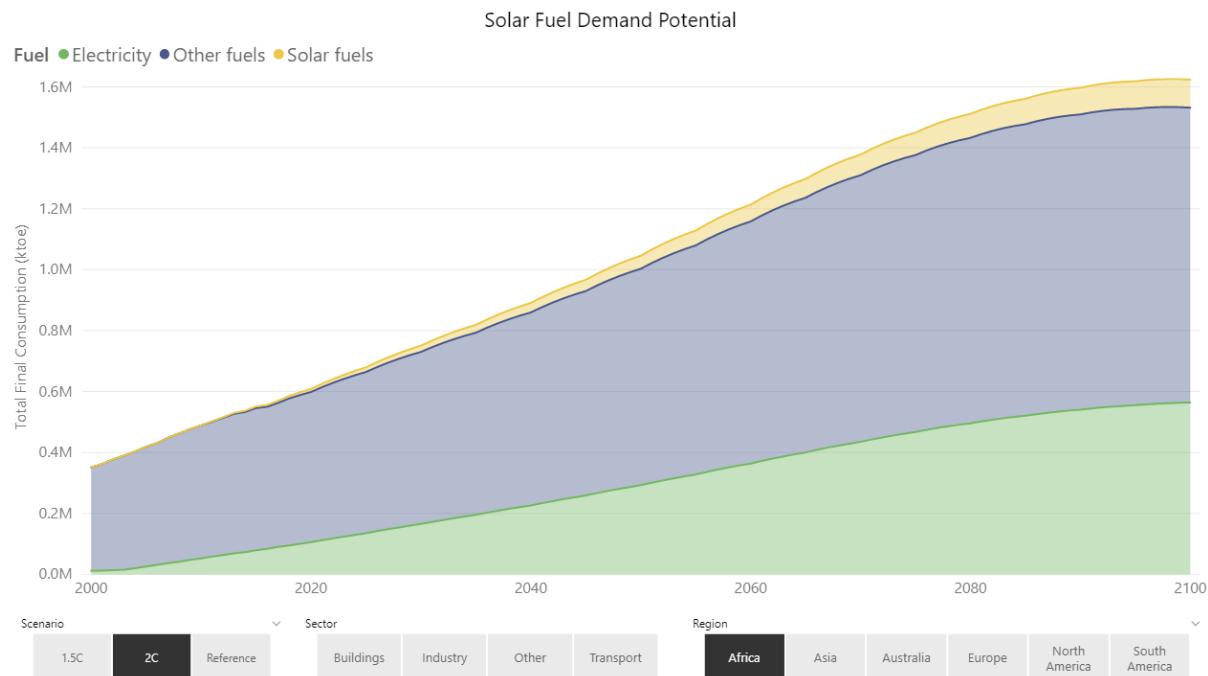


Figure 102 - Potential solar fuel demand in the transport sector in Africa, 2°C scenario

2.3.5.4. Potential solar fuel demand in the buildings sector in Africa

Figure 103 below shows estimates of forecasted total final consumption of energy in the buildings sector in Africa, in the 2°C scenario, and broken down by type of energy, i.e. electricity, other fuels and solar fuels.

The contribution of solar fuels to buildings' energy needs is estimated to reach 2.5 percent and 3.7 percent of total final consumption by buildings in 2050 and 2100, respectively.

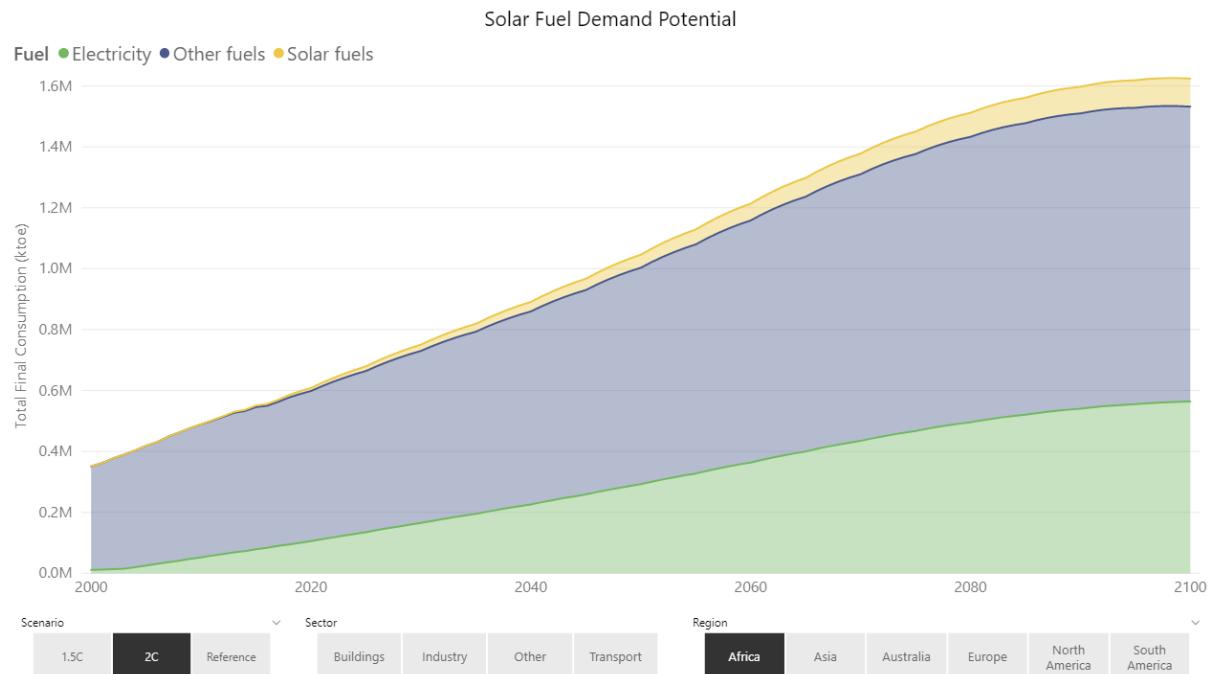


Figure 103 - Potential solar fuel demand in the buildings sector in Africa, 2°C scenario

2.3.5.5. Solar Fuel market size in Africa: investment outlook

This section presents estimates of the annual investment, captured in Figure 104 below, required to reach targets for the production of solar fuels meeting the forecasted demand in Africa, in the 2°C scenario, modelling scale growth conditions. These figures reflect the investment required to fulfil the energy demand in Africa. The introduction to this section discussed Africa's comparative advantage with regards to solar fuel production, due to the high solar irradiance and low cost of land enjoyed by many African countries. Africa is expected to be able to supply other world regions with carbon-neutral solar fuels, and the investments required to develop Africa's solar fuel production capacity for export are not reflected here.

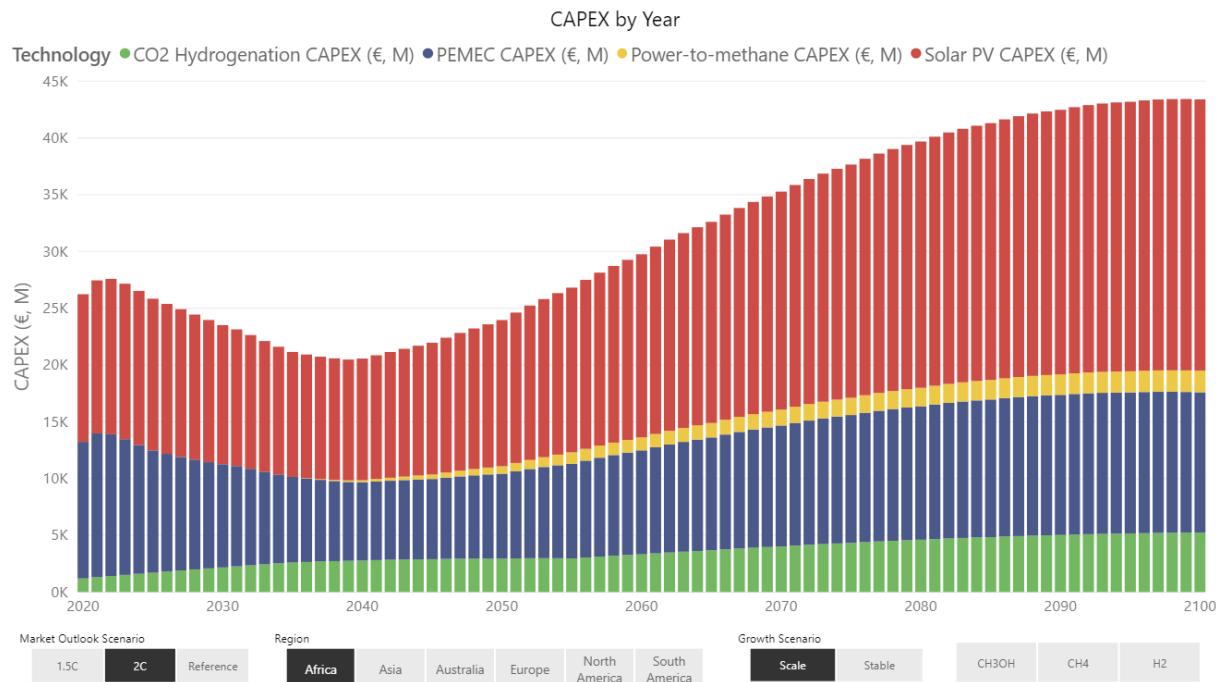


Figure 104 - Investment outlook for solar fuels in Africa, 2020-2100

In the period from 2020 to 2050, Africa's low demand for solar fuels, relative to the worldwide average, results in lower required investments. Nevertheless, the high cost of solar fuels drive up the capital expenditures required to develop the capacity needed to fulfil expected solar fuel demand in Africa. Averaged from 2020 through 2050, these amount to annual investments across the entire solar fuel value chain of €24 billion. This includes €12.5 billion of annual investments in the solar PV capacity required just to produce electricity for the solar fuel supply chain. Annual investments in electrolyzers in the first half of the decade amount to €8.9 billion. The third-stage technologies, CO₂ hydrogenation and power-to-methane, require relatively low levels of additional CAPEX, calling for €2.5 billion and €161 million in annual investments respectively.

In the period from 2050 to 2100, average total annual investments rise substantially, due to Africa's growing energy demand, and despite substantial reductions in capital expenditure costs. The total annual investment required amounts to €36.5 billion. Annual investments in solar PV capacity for the solar fuel supply chain amount to €19.9 billion. Electrolyzers require €10.9 billion in annual investments to feed the demand for hydrogen, both for final consumption and for further transformation into hydrocarbon fuels. Annual investments in CO₂ hydrogenation grow to €4.2 billion. Power-to-methane is expected to require substantial investments as the technology reaches parity with natural gas prices in the second half of the century, resulting in annual investments of €1.5 billion.

2.3.5.6. Supply-side constraints

Africa being composed of many different countries and local contexts, it is difficult to analyse the continent as a whole in a general analysis. With that said, this section of the

report aims at providing a description of the main common features that can be identified in Africa in the context of solar fuels development.

To complement this analysis, we have developed country-specific case studies aiming at assessing the potential for solar fuels in specific markets, building on our own experience in those countries and taking into consideration the specificities of their local contexts.

Both in the general overview and in the country factsheets, we look at possible supply-side constraints in Africa which could hinder the development of solar fuels. In this context, the following topics are covered:

- Raw materials;
- Network infrastructure issues;
- Investment barriers;
- Political instability.

Raw materials

Africa is one of the richest continents for raw material supply in the world with many developed countries relying on Africa for their supply of energy resources and materials for industrial production. On the other hand, local value chains for the production of renewable energy technologies are underdeveloped, primarily due to the lack of public and private investments that will be discussed in the following sections.

In this context, we have identified the following barriers hindering the supply of raw materials and energy-related equipment in Africa, preventing the development of renewable energy systems:

Africa suffers from the absence of local producers of energy-related equipment and lack of know-how for devices operation and maintenance. This generates the need to import technology and knowledge from outside Africa (e.g.: Europe, North America, China and Far East), for example "importing" technicians for technology operations and maintenance. Depending on the country, this issue can apply to photovoltaic/solar thermal components and other devices for energy production from renewable or conventional sources (including diesel generators amongst others), but also to highly efficient lighting and HVAC systems (heat pumps, chillers, etc.).

The presence of high custom duties may strongly increase the final cost of equipment compared to that in developed countries (up to double the cost). Similarly, lengthy and complex custom procedures may significantly delay the delivery of the purchased devices and materials.

In a limited number of countries, the presence of an embargo or other international limitations prevents import/export and trade. This impacts the availability of materials and equipment in two different ways: on one hand it generates difficulties to physically deliver the materials from foreign countries to the project location and on the other hand difficulties in carrying out international bank transfers to pay for the equipment.

In a few African countries, the import of equipment and materials can only be done from certain countries, due to geographical or geopolitical reasons. This limits the range of technologies that can be imported to those that are present in a single country and may lead to an increase in equipment prices. This issue applies for instance to Lesotho, E-Swatini and neighbouring countries in the southern region that need to import technologies from South Africa, as well as to Djibouti and Eritrea that need to import from Ethiopia (or from the Gulf countries).

Network infrastructure issues

The unreliability of network infrastructure in many African countries poses barriers to the development of sustainable energy systems. For example, the unreliability of the electricity grid constitutes an important barrier to the development of African countries: at least 50% of the population has no access to electricity in Sub-Saharan Africa, with over 90% in least developed areas.

This leads to two main issues:

In rural areas, energy uses are reduced to the minimum required for subsistence, e.g. water pumping from wells, limited lighting, food conservation and communication devices. Even in cold mountain areas, heating is not used other than through wood or small propane heaters.

In urban areas, the electricity grid is generally more developed but not always fully reliable, especially in the main cities. Electricity demand is higher due to all the energy uses typically found also in developed countries, including cooling, which is typically based on split-type air conditioners. Due to the unreliability of the grid, modern office buildings, hotels, hospitals, etc. are generally provided with backup diesel generators (or even as primary choice).

Moreover, the infrastructural weakness of the national grids provides for limited possibilities to feed the grid with electricity produced by scattered solar farms, since the connection of a new power generator along the grid may generate further instability to already unstable networks.

In addition to the issues related to the electricity grid, infrastructural issues that impact the development of sustainable energy systems are those related to the insufficient availability of roads and other transport infrastructures (e.g. railways are scarcely used for goods) and of fuel distribution. Regarding transport infrastructures, the lack of roads implies on one hand the formation of significant traffic jams in urban areas (especially in capital cities and large cities) and on the other hand difficulties in reaching remote areas, even if served by national roads. The accessibility to sites is therefore a limiting barrier to the implementation of new energy systems, from surveys through design and procurement, to maintenance.

Regarding fuel distribution, natural gas pipelines are virtually inexistant, whereas diesel/gasoline distribution is carried out by trucks. The latter are negatively impacted by the above-mentioned road-related barriers and this negatively impacts the final price of fuels, which in rural areas can reach double of the price typically found in cities.

Investment barriers

The main investments in the energy sector in Africa currently primarily driven by the public sector. This includes national and local governments, state enterprises (TSO/DSO/national electricity or oil company), and international financial institutions or donors. The latter typically operate through bilateral/multilateral cooperation projects or through credit facilities and support energy transition both as a tool for limiting climate change and to contribute to the improvement of living conditions and the increase of economic development.

For private entities, several barriers to investing in African countries exist – both in the energy sector and in general:

The political instability, which is discussed in more detail in the following section, leads to uncertainty in the regulatory framework and constitutes a risk factor for all kinds of investments. In many countries, no specific provisions exist for the connection to the grid or for the acknowledgment of a feed in tariff or other types of incentive on renewable energy production. Political and social unrest represent another major risk factor for foreign private investments, together with high corruption rates and lengthy judiciary trials of uncertain duration.

Regarding financial and economic aspects, lack of local know-how, the need to import technologies from foreign countries, high custom duties and long custom procedures constitute a strong barrier to investing in export-oriented businesses, only partially compensated by low manpower costs.

Even stronger barriers exist in countries subject to an embargo or international limitations to trade or transfers of funds. In a few countries – in addition to international restrictions – national restrictions also apply, such as the obligation to keep revenues from businesses in the local currency and not to convert them into currencies like the Euro or US Dollars.

The lack of energy and non-energy infrastructures also hinders foreign investments, especially those in industrial fields that require security of supply to guarantee the continuity of the production. Introducing backup fossil fuel-based power generation systems is considered an expensive and insufficient temporary fix, and these issues make investments in renewables for power generation purposes in industrial sites an unattractive proposition.

Therefore, investors face a number of rigid barriers preventing foreign investments in Africa in general as well as in renewable energy systems.

Political instability

A number of African countries are characterized by high levels of political instability. Such instability largely affects the development of renewable energy systems in the continent primarily by preventing or disincentivizing private and foreign investments.

As discussed earlier, investments in the energy field (and not only) in African countries are mainly driven by the public sector, either directly – i.e. through public spending – or indirectly, through the impact that policies and government regulations have on private investments, especially coming from foreign countries.

Based on this, it is clear how political instability constitutes a barrier to the economic and sustainable development of African countries, especially in the context of social unrest and civil wars. This constitutes a vicious circle: political instability leads to low economic growth (through mechanisms related to government spending, fiscal policies, creation of deficit, decrease of local competitiveness, devaluation of local currency and consequent increase of inflation) and low economic growth leads to even more political instability. In addition, corruption rates are very high in many African countries, hindering economic development and companies' growth. High corruption also generates illegal money flows and leads to uncertain and potentially unfair, as well as long, judiciary trials.

Therefore, businesses are faced with strong uncertainties and high-stake investment decision-making resulting from the lack of political stability in Africa. This creates significant barriers for the investments of international companies in many African countries, most of which could be related to the energy field, such as the development of large utility-scale solar power plants, wind farms, hydropower or biomass power plants.

2.3.5.7. Demand-side constraints

Keeping in mind the considerations from the previous chapter regarding difficulties in analysing the African continent as a whole, the aim of this section is to provide a general overview of common characteristics regarding demand-side constraints.

Both in the general overview and in the country factsheets, we look at possible demand-side constraints in Africa which could hinder the development of solar fuels. In this context, the following topics are covered:

- Underdeveloped distribution infrastructure;
- Socio-political willingness to convert to green energy.

Underdeveloped distribution infrastructure

The topics related to the lack of reliable infrastructures have already been mentioned in the previous paragraph focusing on network issues. The reasons why these issues constitute a constraint on the demand-side are clear, since they hinder the continent's economic and sustainable development and prevent the improvement of living conditions in both urban and rural areas of African Countries.

Indeed, the introduction of renewable-based power generation or fuel production systems could generate significant benefits for end-users in terms of reduced dependency on the grids and infrastructures, increased security of supply and reduction of energy poverty.

The security of energy supply aspect is of particular interest with reference to the economic development of countries through the creation of new businesses. This is demonstrated for instance by the launch of programmes for the creation of industrial parks – with the aim to attract foreign investments – only minimally relying on the supply of electricity from the national grid, thanks to the adoption of renewable power generation systems. Unfortunately, this is of interest only to urban areas and their surroundings, characterized by a certain level of industrial development. On the other hand, the increased availability of cheap and reliable electricity in rural areas could support the improvement of living conditions (higher water availability, better food conservation, lighting, communication, etc.) but also the creation of workplaces and related income thanks to micro- and small-sized activities ranging from handcraft manufacture to enhancement of agriculture and processing of products from agriculture to animal growing.

Socio-political willingness to convert to green energy

Despite the clear benefits that could be derived from converting to green energy, concrete steps towards decarbonisation have been limited in some African countries, despite the clear benefits of embracing clean energy. The lack of project experience in renewable energy technologies, scarcity of available capital, and a number of other factors impact the development of renewable energy technologies in Africa. From the perspective of African Countries, renewable energy could support both the improvement of living conditions and the development of African economies. This is mainly due to a twofold increase of the security of supply:

For countries relying on import of fuels from abroad, the reduction of the dependency on potentially unstable foreign markets is a significant benefit at macro-economic level;

For final users relying on power supply from unstable grids, the availability of owned renewable-based power plants, possibly coupled with storage systems, would allow for the continuity of operation (for industries and companies in general), improvement of living conditions (for households) and reduction of supply costs – compared to the purchase of electricity from the grid and the use of backup diesel generators. Since most of the population living in rural areas has a very limited access to energy for basic living needs, the adoption of state-of-the-art renewable energy systems (PV and solar thermal for hot water) would constitute a notable enhancement of living conditions. This constitutes a benefit also at national level since this kind of private plants does not require an enhancement of the power grid and, on the contrary, improves its reliability for other grid-connected users. With that said, concrete steps towards decarbonisation have been limited in some African countries, despite the clear benefits of embracing clean energy.

As concerns climate change mitigation, an important instrument for the development of green energy in Africa is the Clean Development Mechanism (CDM) created by the Kyoto Protocol in 2005. Although not exploited at its full potential, this instrument allows developed countries to implement emission-reduction projects in developing countries, including African ones, to earn certified emission reduction (CER) credits, each equivalent to 1 tCO₂, which can be used to meet part of their emission reduction targets.

E-Swatini

Country: E-Swatini

Region: Southern Africa

Area: 17,364 km²

Population: 1,104,000 (July 2020 est.)

Capital: Mbabane

Notes: landlocked, almost completely surrounded by South Africa, predominantly rural territory, highest HIV/AIDS rate in the world, consequently high mortality and low life expectancy and median age.

Climate: varies from tropical to near temperate; solar radiation fairly available, with global horizontal irradiation typically in the range 1,700 – 1,800 kWh/m²/y.

Economy: E-Swatini depends on South Africa for most of exports and imports. Its currency (lilangeni) is anchored to the South African Rand and customs duties are managed by the Southern African Customs Union (SACU). The main economic activities are related to agriculture, whereas industrial manufacturing is concentrated in the sugar and soft drink concentrate production. The mining sector has recently declined in importance. The Country's national development strategy up to 2022 prioritizes the improvement of infrastructures, agriculture production and economic diversification.

Natural Resources: asbestos, coal, clay, cassiterite, hydropower, forests, small gold and diamond deposits, quarry stone, talc.

Energy prices:

- Electricity: 0.90 – 2.05 SZL/kWh (i.e.: 0.045 – 0.105 EUR/kWh);
- Natural gas: not present in the Country;
- Diesel: 12 – 15 SZL/l (0.60 – 0.75 EUR/l);
- Coal: 1,000 – 1,600 SZL/t (i.e.: 50-80 EUR/t).

Energy mix: about 70% (1 TWh/y) of electricity imported from South Africa and 30% (0.4 TWh/y) self-produced through four hydropower plants; out of the total, 61% of electricity is produced by renewables (mainly hydro, wind and solar) and 39% by fossil sources (mainly coal); thermal energy needs are covered by coal and biomass only (mainly internally produced). Diesel and other liquid fuels (fully imported) are used for vehicles and backup power generation purposes.

Market for energy technologies: completely dependent on South Africa except for limited number of local importers of commercial technologies (e.g.: air conditioning, lighting).

Infrastructural issues: main roads are generally well kept and safe and connect the main cities with South Africa and Mozambique. The Country has no access to coasts and therefore no ports. The airport has only daily connections to South Africa. The electricity grid is generally reliable in urban areas and less reliable in rural areas. The overall rate of access to electricity is 66% (61% in rural areas and 83% in urban ones).

Socio-political issues: the political situation is generally stable, with occasional political demonstrations. E-Swatini is an absolute monarchy and some political parties have been banned and designated as terrorist organizations.

Potential for solar technologies:

The country presents a good potential for the implementation of energy from solar source, being characterized by an average global horizontal irradiation around 1,800 kWh/m²/y. For this reason, solar energy has been inserted among priority technologies to be exploited in the coming years by the local Ministry of Tourism and Environmental Affairs when carrying out the Technology Need Assessment (TNA) as part of the UNEP DTU initiative.

Utility-scale photovoltaic is suitable for integration in the national grid to reduce dependency from electricity import from South Africa as demonstrated by the 10 MW plant that will be commissioned by the end of 2020 and by the 40 MW project recently awarded to potential independent power producers, which constitute a significant achievement towards meeting the targets expressed in the TNA.

On the other hand, distributed generation based on small-scale photovoltaic (not connected to the grid) and solar thermal can improve living conditions and reduce energy supply costs for households and larger size buildings (public and private offices, hospitals, hotels, small manufacturing sites, etc.). In this context, it is worth highlighting that the Portuguese GoParity Impact Investment Platform is supporting a photovoltaic power plant to support the Good Shepherd Mission Hospital in Siteki whereas the Italian Ministry for Environment is supporting Raleigh Fitkin Memorial Hospital in Manzini for its conversion to almost zero GHG emissions, thanks to a photovoltaic plant among other technologies. In addition, the Government foresees to complete by 2024 the installation of 13,000 small domestic-scale photovoltaic plants (typical size: 1.5 kW) and 15,000 business-scale photovoltaic plants (typical size: 50 kW).

The potential for solar fuels is promising, especially for the replacement of fossil fuels currently used for backup power generation and in the transport sector. In this context, it is highlighted that the two local sugar companies, Ubombo Sugar Limited and Royal Swaziland Sugar Corporation, have declared their potential interest in investing in cogeneration plants, which would increase the demand of fuels suitable for this purpose, like solar fuels – in addition to biomass feedstocks.

Ethiopia

Country: Ethiopia

Region: Eastern Africa

Area: 1,104,300 km²

Population: 108,113,000 (July 2020 est.)

Capital: Addis Ababa

Notes: landlocked, territory constituted by a high plateau (Average elevation 1,300 m a.s.l.) with central mountain range, highest population density around the Capital, with remote regions sparsely populated

Climate: tropical with large variations due to topography; good solar radiation availability, with global horizontal irradiation typically in the range 1,800 – 2,400 kWh/m²/y

Economy: Ethiopia is a one-party state with a planned economy, characterized by a very high GDP growth rate (8% to 11%), mainly due to public investments in infrastructures, agriculture and services. The State directly controls most sectors of the Ethiopian economy and 70% of the population is employed in the agricultural sector. The industrial sector is less developed and is concentrated around the following sectors: textiles, leather, processed agricultural products; these are also the main drivers of Ethiopian export, in addition to available raw materials like precious metals. The services sector is limited to national investments, whereas international funding (from China, Turkey, EU) is supporting projects in the field of infrastructures, construction, agriculture.

Natural Resources: small reserves of gold, platinum, copper, potash, natural gas.

Energy prices:

- Electricity: 1.0 – 3.0 ETB/kWh (i.e.: 0.03 – 0.09 EUR/kWh);
- Natural gas: not used in the Country;
- Diesel: 20 – 32 ETB/l (0.60 – 1.00 EUR/l);
- Coal: not used in the Country.

Energy mix: 100% of electricity (11 TWh/y) is self-produced in the country, mainly from hydropower plants (86%), other renewables – mainly wind (11%) and fossil fuel-fired power plants (3%). The limited thermal energy needs are covered by biomass (internally produced). Diesel and other liquid fuels are used for vehicles and backup power generation purposes. The country is characterized by not negligible reserves of natural gas, which however is not used as fuel in Ethiopia.

Market for energy technologies: local importers of almost all types of energy technologies are available and they mainly refer to China and other Asian countries for the import of devices.

Infrastructural issues: main roads in central areas, around Addis Ababa, are generally well maintained and connect the Capital with the main nearby cities. Many other roads, in other regions and in rural areas, are unpaved and not well kept, thus implying logistic issues especially in the rainfall season. The country has no access to coasts and therefore no ports. There are two international airports (Addis Ababa and Dire Dawa) and additional 16 airports served by the national airline, plus minor airports not served by commercial airlines. The electricity grid is generally reliable in urban areas and less reliable in rural areas. The overall rate of access to electricity is 43% (26% in rural areas and 85% in urban ones).

Socio-political issues: the political situation is relatively stable, except for civil unrest sometimes occurring in regions far from the Capital where ethnic conflicts are also present. Ethiopia is a parliamentary republic that however is based on a single party and therefore not fully democratic.

Potential for solar technologies:

The country presents a good potential for the implementation of energy from solar source, being characterized by an average global horizontal irradiation higher than 1,800 kWh/m²/y. For this reason, solar energy is one of the fields with maximum support by international cooperation projects.

Utility-scale photovoltaic would be suitable for integration in the national grid, but this potential is largely unexploited; so far, no large sized photovoltaic plant is present in Ethiopia and only one tender was launched in 2019 for two 125 MW plants, which however have not been awarded yet.

On the other hand, distributed generation based on small-scale photovoltaic, not connected to the grid, is much more widespread (with an estimated cumulated power of 5 MW) and also solar thermal systems are present (estimated area of 10,000 m²), especially in Oromia region, close to the Capital. A large programme for the electrification of rural areas through micro-grids fed with solar power was launched in the recent years with funds of the Italian government, and solar water pumping systems have been in place since more than 20 years. Moreover, the major user of small-sized photovoltaic systems in the Country is Ethiopian Telecom, which uses this kind of systems, coupled with batteries for energy storage, to supply power to rural installations for telecommunications. There are also projects for solar cooking in remote areas and for lighting in urban contexts.

The potential for solar fuels is promising, especially for the replacement of fossil fuels currently used for backup power generation and in the transport sector. This could be particularly of interest in rural areas not served by the national electricity grid and where also the supply of liquid fuels is problematic for logistical reasons. As concerns power generation, this could support the realization of micro-grids, constituting a suitable alternative to conventional energy storage solutions in the support to other renewables including traditional solar power plants.

Ghana

Country: Ghana

Region: Western Africa

Area: 238,533 km²

Population: 29,340,000 (July 2020 est.)

Capital: Accra

Notes: a democratic republic rich in natural resources but suffering of public spending-related issues,. It is characterized by a high GDP growth thanks to the oil and gas industry and a strong agricultural sector.

Climate: tropical; warm and dry along the south-eastern coast; hot and humid in south-western area; hot and dry in north; solar radiation fairly available, with global horizontal irradiation typically in the range 1,600 – 2,000 kWh/ m²/y

Economy: Ghana has a market-based economy, it is rich in natural resources and has relatively low policy barriers to investments and trade. The national economy is growing at a high annual rate but is contemporarily suffering of high public spending and deficit, linked with high inflation and currency devaluation. Most of the population is employed in agriculture but the core sector for the recent development of the economy is oil and gas production followed by mining and industrial manufacturing in the metals and agri-food sectors.

Natural Resources: gold, timber, industrial diamonds, bauxite, manganese, fish, rubber, oil, silver, salt, limestone.

Energy prices:

- Electricity: 0.40 – 0.80 GHS/kWh (i.e.: 0.06 – 0.12 EUR/kWh);
- Natural gas: not used in the Country;
- Diesel: 4.8 – 5.5 GHS/l (0.70 – 0.80 EUR/l);
- Coal: not used in the Country.

Energy mix: about 50% (6 TWh/y) of electricity is produced by hydropower plants and 50% (6 TWh/y) by oil- and gas-fueled power plants, built in the recent years to support the strongly increasing electricity demand (10-15% per year) due to economic growth. Thermal energy needs are covered by internally produced/harvested biomass. Diesel and other liquid fuels are used for vehicles and backup power generation purposes.

Market for energy technologies: local importers of almost all types of energy technologies are available and they mainly turn to Europe or China for the import of devices.

Infrastructural issues: main roads in urban areas are generally well kept whereas logistical issues arise in remote areas where roads are not reliable and often unpaved. The Country has two main ports in Tema (Accra) and Takoradi, two main international airports

(Accra and Kumasi) and seven other airports served by national commercial airlines. The electricity grid is generally reliable in urban areas and less reliable in rural areas. The overall rate of access to electricity is 79% (66% in rural areas and 89% in urban ones).

Socio-political issues: the political situation is generally stable. Ghana is a democratic presidential republic. political demonstrations sometimes occur but they are usually peaceful.

Potential for solar technologies:

The country presents a good potential for the implementation of energy from solar source, being characterized by an average global horizontal irradiation higher than 1,600 kWh/m²/y.

Utility-scale photovoltaic is suitable for integration in the national grid to reduce the dependency from fossil fuels and increase environmental and economic sustainability of the power generation sector. At the end of 2018, the total installed capacity for utility-scale photovoltaic plants in Ghana was of 64 MW. In recent years, it is highlighted that German KfW supported the development of 12 MW of photovoltaic plants at three sites in the Upper West Region, the first of which (2.5 MW) was commissioned in 2013. In addition, Ghana's largest power supplier, VRA, has started building two photovoltaic power plants for a total power of 17 MW in Kaleo (13 MW) and Lawra (4 MW).

On the other hand, distributed generation based on small-scale photovoltaic (not connected to the grid) and solar thermal can improve living conditions and reduce energy supply costs for households and larger size buildings (public and private offices, hospitals, hotels, small manufacturing sites, etc.). In this context, many projects supported by international donors and sponsors have focused on the development of solar water pumping systems to support agricultural production and solar cooking systems to replace biomass in rural areas.

The potential for solar fuels is promising, especially for the replacement of fossil fuels currently used for backup power generation and in the transport sector, but it shall be highlighted that in a country like Ghana, characterized by a significant production of oil and its derivatives, the competition from conventional fossil fuels would be very high and could strongly hinder the switch to solar fuels.

Lesotho

Country: Lesotho

Region: Southern Africa

Area: 30,355 km²

Population: 1,969,000 (July 2020 est.)

Capital: Maseru

Notes: landlocked, completely surrounded by South Africa, mountainous territory (80% of the country is 1,800 m above sea level), second highest HIV/AIDS rate after Eswatini, consequently high mortality and low life expectancy and median age.

Climate: temperate; cool to cold, dry winters; hot, wet summers; solar radiation fairly available, with global horizontal irradiation typically in the range 1,800 – 2,100 kWh/ m²/y.

Economy: Lesotho depends on South Africa for most of its exports and imports. Customs duties are managed by the Southern African Customs Union (SACU) and represent a relevant share of the national GDP. The main economic activities are related to agriculture and animal growing, whereas industrial manufacturing is mainly focused on textile production. The Government is the largest employer in the Country, which leads to a high public spending rate.

Natural Resources: diamonds, sand, clay, building stone.

Energy prices:

- Electricity: 1.50 – 2.00 LSL/kWh (i.e.: 0.073 – 0.097 EUR/kWh);
- Natural gas: not present in the Country;
- Diesel: 10 – 12 LSL/l (0.49 – 0.58 EUR/l);
- Coal: 1,200 – 1,600 LSL/t (i.e.: 58-77 EUR/t).

Energy mix: about 45% (380 GWh/y) of electricity imported from South Africa and 55% (510 GWh/y) is self-produced through hydropower plants for a total installed power of 74.7 MW. Thermal energy needs are covered by coal and biomass only (internally produced – although reserves are strongly decreasing – or imported from South Africa). Diesel and other liquid fuels (fully imported) are used for vehicles and backup power generation purposes.

Market for energy technologies: completely dependent on South Africa except for a limited number of local importers of commercial technologies (e.g.: air conditioning, lighting).

Infrastructural issues: main roads are generally well kept and safe and connect the main cities with South Africa. The country has no access to coasts and therefore no ports. The airport has only daily connections to South Africa. The electricity grid is generally reliable in urban areas and less reliable in rural areas. The overall rate of access to electricity is 30% (16% in rural areas and 66% in urban ones).

Socio-political issues: the political situation is generally stable, with occasional political demonstrations. Lesotho is a parliamentary constitutional monarchy with multiple parties and limited power to the King which represents a symbol of the national identity.

Potential for solar technologies:

The country presents a good potential for the implementation of energy from solar source, being characterized by an average global horizontal irradiation around 2,000 kWh/ m²/y. For this reason, solar energy has been inserted among priority technologies to be exploited in the upcoming years by the local Ministry of Energy and Meteorology.

Utility-scale photovoltaic is suitable for integration in the national grid to reduce dependency from electricity import from South Africa, as demonstrated by the two 20 MW plants planned to be built in Maseru and Mafetang and additional 1-5 MW plants foreseen in Leribe and Mafetang. The technical potential for utility-scale photovoltaic plants evaluated by the Department of Energy of the Ministry of Energy and Meteorology of the Kingdom of Lesotho in 2017 is of 118 MW, with 65 MW of projects identified as feasible in the medium-short term.

On the other hand, distributed generation based on small-scale photovoltaic (not connected to the grid) and solar thermal can improve living conditions and reduce energy supply costs for households and larger size buildings (public and private offices, hospitals, hotels, small manufacturing sites, etc.). In this context, it is worth highlighting that the SOLTRAIN initiative installed 10 solar thermal water heaters between 2009 and 2015 and 20 additional installations are foreseen in the upcoming years; moreover, the Italian Ministry for Environment is supporting the improvement of living conditions in four Health Centers in rural areas of Lesotho through the implementation of a set of energy efficiency actions and the significant exploitation of renewable sources including solar photovoltaic and solar thermal. Additional uses of solar energy foreseen by the Government include solar water pumping, with potential up to 37.5 MW, and solar street lighting coupled with LED lamps, already started in Maseru with more than 700 lighting poles.

The potential for solar fuels is promising, especially for the replacement of fossil fuels currently used for backup power generation and in the transport sector. In this context, it is highlighted that a World Bank supported project has developed a couple of micro-grids in rural areas of the country, one of which is completely based on diesel and would be suitable for a conversion solar fuels if available, in order to increase sustainability and reduce operating costs.

Nigeria

Country: Nigeria

Region: Western Africa

Area: 923,768 km²

Population: 214,028,000 (July 2020 est.)

Capital: Abuja

Notes: rich in fossil fuels like natural gas and oil, most populated African country, characterized by high corruption and insecurity due to civil unrest and ethnic/religious conflicts.

Climate: equatorial in south, tropical in center, arid in north; solar radiation fairly available, with global horizontal irradiation typically in the range 1,600 – 2,200 kWh/ m²/y.

Economy: Nigeria is strongly dependent on the oil sector as a source of revenue. The banking sector was fairly active until the 2008-2009 global crisis but now is less developed. Other important sectors are agriculture and telecommunications. The economic development of the country is hindered by a significantly high corruption, inefficiencies in the public sector and insecurity related to civil unrest, ethnic and religious conflicts, with part of the territory that is not under the full control of the Government. The strategies for the upcoming years aim at fighting corruption and developing stronger public-private partnerships for infrastructural development (roads, electricity) and agriculture.

Natural Resources: natural gas and oil, tin, iron ore, coal, limestone, niobium, lead, zinc.

Energy prices:

- Electricity: 27 – 45 NGN/kWh (i.e.: 0.06 – 0.10 EUR/kWh);
- Natural gas: not used in the Country;
- Diesel: 220 – 400 NGN/l (0.50 – 0.87 EUR/l);
- Coal: not used in the Country.

Energy mix: biomass is the dominant source of energy in Nigeria, due to domestic cooking and heating uses; oil production is one of the main sources of income for the Nigerian economy but is almost fully exported, with liquid fuels derived from oil that are used only for vehicles and backup power generation purposes. As concerns electricity, about 80% (8 TWh/y) is self-produced with oil- and gas-fired power plants and 19% (2 TWh/y) produced from hydropower.

Market for energy technologies: local importers of almost all types of energy technologies are available and they mainly refer to Europe or China for the import of devices.

Infrastructural issues: main roads in Lagos and in main cities are generally well kept, although huge traffic jams occur. Rural areas are almost not served by reliable roads and where present these are typically not safe and well maintained. The country has 5 main ports (the Lagos Port Complex and Tin Can Island Port, Calabar Port, Delta Port, Rivers Port in Port Harcourt, Onne Port) handling both containers and bulk goods, especially to

support the oil and gas industry and to export production. There are 8 international airports and 20 other airports served by national airlines. The electricity grid is generally reliable in urban areas and less reliable in rural areas. The overall rate of access to electricity is 59% (41% in rural areas and 86% in urban ones).

Socio-political issues: the political situation is generally unstable, with civil unrest often taking place and parts of the country that are under full control of the Government, like in the North where Boko Haram is operating, replacing the Nigerian Government with an Islamic state under strict Sharia. Nigeria is a federal constitutional republic.

Potential for solar technologies:

The country offers good opportunities for the implementation of energy from solar source, being characterized by an average global horizontal irradiation higher than 1,600 kWh/m²/y.

Specifically, utility-scale photovoltaic would be suitable for integration in the national grid to increase the environmental and economic sustainability of the electricity generation, but this potential is not exploited yet. In the last years, the Nigerian Electricity Regulator Commission has issued licenses to 8 solar projects for a total of 868 MW and power purchase agreements were signed with 14 potential independent power producers for a total of 1 GW, but so far none has reached financial close.

On the other hand, distributed generation based on small-scale photovoltaic (not connected to the grid) and solar thermal can improve living conditions and reduce energy supply costs for households and larger size buildings (public and private offices, hospitals, hotels, small manufacturing sites, etc.). In this context, it is worth highlighting that the Nigeria Energy Support Programme of GIZ and the EU have supported the constitution of a solar-powered mini-grid in Umon Island and Bagana, Cross River State, through which a 50 kW photovoltaic plant supplies power (replacing a previously existing diesel generator) to a hundred households in a rural area not served by the national grid. Moreover, other projects exist in the field of solar water pumping to support agricultural development and solar cooking systems have been provided to rural areas to be used as replacement of solid fuels-based cooking.

The potential for solar fuels is promising, especially for the replacement of fossil fuels currently used for backup power generation and in the transport sector, but it shall be highlighted that in a country like Nigeria, characterized by one of the world's highest oil and gas reserves, the competition of conventional fossil fuels would be very high and could strongly hinder the switch to solar fuels.

Sudan

Country: Sudan

Region: Eastern Africa

Area: 1,861,300 km²

Population: 45,561,000 (July 2020 est.)

Capital: Khartoum

Notes: population is concentrated along the Nile banks and in main urban areas, while most of the territory is desertic; social unrest was high in the last decade, mortality rate is high and median age is low.

Climate: hot and dry (arid desert); rainy season varies from region to region, usually in the period from April to November; very good availability of solar radiation, with global horizontal irradiation typically in the range 2,100 – 2,400 kWh/m²/y

Economy: Sudan was subject to US sanctions and embargo until October 2017, this constituted a significant obstacle to the economic development of the country. Sudan had a consistent oil production but three quarters of it was lost with the secession of South Sudan in 2012. Now most of the population is employed in the agricultural sector and living close or below the poverty line. The government is attempting to develop non-oil related industries including gold mining and specific agricultural production like Arabic gum, of which Sudan is the largest producer in the world.

Natural Resources: oil; small reserves of iron ore, copper, chromium ore, zinc, tungsten, mica, silver, gold.

Energy prices:

- Electricity: 2.50 – 3.60 SDP/kWh (i.e.: 0.038 – 0.055 EUR/kWh);
- Natural gas: not present in the Country;
- Diesel: 40 – 50 SDP/l (0.60 – 0.80 EUR/l);
- Coal: not present in the Country.

Energy mix: 100% (14 TWh/y) of electricity is self-produced, mainly through hydropower plants (51%) or oil-fueled power plants (44%). Natural gas is not used in the Country although reserves are available. Although oil production has decreased after the secession of South Sudan, it is still important in the national economy and energy sector. Diesel and other liquid fuels are used for vehicles and backup power generation purposes.

Market for energy technologies: the local market is currently focusing almost exclusively on solar-powered water pumping systems, with components imported from Europe or China; other applications of renewables are underdeveloped; local importers of commercial technologies (e.g.: air conditioning, lighting) are also available.

Infrastructural issues: main roads around Khartoum are generally quite well kept and connect the Capital with the main cities. Other roads are significantly underdeveloped and less safe and rural areas are often difficult to reach. The country has its main port in Port Sudan, along the Red Sea, which handles containers and bulk goods and is the main hub for imports/exports in the country. International airports are located in Khartoum and Port Sudan, with another 7-8 airports served by national commercial airlines. The electricity grid is generally reliable in urban areas and less reliable in rural areas. The overall rate of access to electricity is 45% (31% in rural areas and 71% in urban ones).

Socio-political issues: the political situation is relatively unstable. The 2019 revolution ended the military regime that ruled the country from its independence and conflicts are ongoing in several regions, like Darfur, South Kordofan and Blue Nile. Moreover the country recently experienced the secession of South Sudan in 2012; Sudan is now in a transitional period, ruled by a Sovereignty Council formed by the military council and the civil opposition.

Potential for solar technologies:

The country offers good opportunities for the implementation of energy from solar source, being characterized by an average global horizontal irradiation above 2,100 kWh/m²/y. For this reason, solar energy is one of the sources that is highly supported by international cooperation projects in the area although support is limited in this transitional period where support for the Government is low and competencies in the energy field are distributed across many actors including the Ministry of Energy and Mining (formerly Ministry of Water Resources, Irrigation, and Electricity), the Sudan Electricity Holding Company, the Dams Implementation Unit.

Utility-scale photovoltaic is suitable for integration in the national grid to reduce the use of fossil fuels for power generation purposes, but this potential is practically not exploited so far, since only two 5 MW photovoltaic plant are operational in Sudan, one in Al-Fashir and

one in Al-Daien. Several projects have been announced, including 250 MW of photovoltaic plants, but all of them have encountered issues in securing funding and have been canceled or downsized.

On the other hand, distributed generation based on small-scale photovoltaic (not connected to the grid) – and to a much lesser extent solar thermal – can improve living conditions and reduce energy supply costs for agricultural activities, households and other buildings (public/private offices, hospitals, etc.). In this context, it is worth highlighting that the UNDP is supporting rural electrification, foreseeing significant penetration of small-scale solar power systems. The Italian Ministry for Environment is supporting several solar pumping projects in the River Nile and North Kordofan States, where currently highly-expensive diesel-fueled systems are used, and the UNHCR is promoting solar cooking systems, especially for refugees.

The potential for solar fuels is promising, especially for the replacement of fossil fuels currently used for backup power generation and in the transport sector, especially in rural areas where the price of liquid fuels becomes very high due to transport costs.

2.4. Conclusion

The chapter provided a technological roadmap for solar fuel technologies for 2030 and 2050, an economic roadmap for solar fuels through 2100 and a market outlook for solar fuels.

The technological roadmap for 2030 and 2050 aimed at assessing the main technological challenges and bottlenecks that must be overcome to reach the production of solar fuels at commercial scale. It showed that while some technologies seem to be more advanced and may reach commercial deployment in the mid-term (e.g. Proton Exchange Membrane electrolyser), several challenges are to be overcome for other solar fuels technologies to reach the full-scale deployment.

Regarding the electrochemical technologies, the analysis has shown that PEMEC has the potential to reach full market availability within 5 years. Upscaling to GW production will require strong reduction or substitution of noble metal catalysts like PGM. For SOEC, the technology's TRL stands between 6 and 7. This means that prototypes have been tested in the field. Some of the key bottlenecks towards SOEC's market implementation include the stability of the solid oxide membrane and the high operation temperature. Its market availability will also depend on the integration of low-cost batteries to keep the system in operation for low renewable power generated at night, with clouds or low wind. With a TRL between 3 and 4, the PEC technology is developed at small-scale prototype level or with sub-systems are developed in laboratory. One of the key bottlenecks in the technology's development is corrosion. Within the next 10 years, we expect the technology to go through the prototyping stage successfully, with a later market introduction around 2040.

On the chemical pathway, the TRL of the photocatalytic particulate or colloidal systems technology ranges between 2 and 3. This means the technical analysis of the concept is investigated and partially the technological concept is experimented and validated at laboratory scale. While the technology currently faces bottlenecks related to the development of a gas separation membrane, ionic charge carrier mediators and materials that provide process stability, high catalyst efficiency and high photosensitivity, we expect market introduction of the technology around 2050.

Regarding Solar thermochemical hydrogen production systems, as part of the thermochemical pathway, the overall TRL of the system ranges between 5-7. The main technological issues are related to the materials suitable for high-temperature, the durability and hydrogen yield, and the reduction of temperatures and production costs. In terms of development, we foresee improvements in the technology to reach a TRL of 7 by 2030 and full-scale demonstration around 2035, with commercial deployment in years up to 2050.

For the Biochemical pathway, biohybrid systems production is currently deployed at very low TRL (TRL 2-3). Several improvements in the technology are needed, especially

concerning reactor design and configuration, durability of materials employed in the photoelectrochemical section, metabolic efficiencies and integration of the different components within the overall system. Regarding microalgae, while the technology has already reached a commercial-scale production of added-value compounds such as nutraceuticals, cosmetics, pigments, food ingredients, an effective market deployment of microalgae-based solar fuels still faces several challenges, especially from an economic perspective due to the high production costs. In this context, great technical improvements are needed for a larger-scale deployment of the technology.

Following this analysis, an economic roadmap for solar fuels was developed in the report, as a continuation to the technology roadmap which analysed the key challenges, bottlenecks and opportunities that could pace solar fuel technologies' development over time. In this context, the economic roadmap aimed at analysing the economic and cost-competitiveness of the different pathways for solar fuel production. The objective was to study the cost performance of the technologies over time, and to assess at which point in time they could become cost competitive with their fossil counterparts. The economic roadmap analysis was carried out through a time series LCOE analysis through 2100, looking at the competitiveness of the different technologies in producing different fuels, namely hydrogen, methanol, ethanol and methane. The results of the analysis for Europe are presented in this report, under two investment scenarios: stable and scale; the former one being characterised by normal investment levels and the latter by an investment push in the studied technologies.

Looking at the hydrogen technologies, the analysis demonstrated that while AEC currently benefits from a cost-advantage amongst the green hydrogen technologies, PEMEC stands out as the most promising technology due to its cost competitiveness over time, under the two scenarios. PEMEC is expected to surpass its fossil benchmark, SMR, as early as 2039 under a scale scenario. Regarding methanol production, CO₂ hydrogenation could reach cost parity with its fossil benchmark, motor gasoline, in 2053 under a stable scenario. With rapidly rising gasoline prices, CO₂ hydrogenation could become market competitive as of 2042 with an investment push. Against this, microalgae for ethanol production remains less affordable than motor gasoline through 2100, reflecting the low maturity and relative inefficiency of the technology. Power-to-methane also comes out as a promising technology expected to reach cost parity with natural gas in 2060 under a scale scenario.

Our analysis therefore identified PEMEC, CO₂ hydrogenation and power-to-methane as key solar fuel technologies which are expected to reach market competitiveness with their fossil benchmarks by 2040 to 2060. The economic roadmap is also complemented by our project report 2.2, presenting a market outlook for solar fuels and solar fuel technologies through 2100. The report foresees the future potential demand for solar fuels and required investments in the PEMEC, CO₂ hydrogenation and power-to-methane technologies necessary to meet this forecasted demand.

Finally, a market outlook for solar fuels was developed to assess the potential contribution of solar fuels to worldwide decarbonised energy systems in 2050 and 2100. The analysis comprised a forecast of final energy consumption, broken down by region (Africa, Asia, Australia and New Zealand, Europe, North America, and South America), by sector (industry, transport, buildings, and other) and by fuel type (biomass, coal, e-fuels, electricity, gas, heat, hydrogen, and oil). Both hydrogen and E-fuels, i.e. synthetic fuels manufactured from green hydrogen and CO₂, were considered to be solar fuels for the purpose of the analysis.

The analysis considered three scenarios for the development of worldwide energy systems: a Reference scenario, assuming a baseline level of effort toward decarbonisation corresponding to current efforts; a 2°C scenario, where efforts are made to limit global temperature rises to 2100, relative to pre-industrial levels, by no more than 2°C, and a 1.5°C scenario.

In the 2°C scenario, solar fuels would be expected to contribute to 3.8 percent of our energy needs worldwide in 2050, and 5.8 percent in 2100. Looking at individual sectors, for the 2°C scenario, we foresee solar fuels contributing to just 0.8 percent of energy needs

in industry in 2050, and 1.5 percent in 2100. In transport, our analysis expects solar fuels to contribute to 11 percent of energy demand in 2050, rising to 15.2 percent in 2100. Finally, in buildings, solar fuels can be expected to contribute to 3.1 percent of final consumption in 2050, and 4.7 percent in 2100.

Evidence gathered through stakeholder workshops held as part of this study, and through literature review, reveals a number of factors that could impact the uptake of solar fuels worldwide, including:

- Costs of solar fuels, which are primarily driven by the price of solar electricity at first vs. costs of comparable fossil fuels,
- Costs of adapting end-use systems to solar fuels, such as changing from coal to hydrogen in steel manufacturing,
- Infrastructure costs,
- Demand for carbon-neutral industrial products, vehicles and transportation services, and heating and cooling technologies in buildings, and
- Supportive regulations and policies such as those implementing carbon pricing mechanisms.

Industry, in particular, could potentially become early adopters of solar fuel technologies in certain applications. As industries are increasingly considering carbon capture and storage schemes, CO₂ may become more readily available, and could serve as an input to solar fuel production. These solar fuels could be produced and used on-site to power the same CO₂-emitting industrial processes, thereby closing the carbon loop. Such schemes, with the right incentives, could prove attractive to industries, driving them to invest in early-stage technologies.

The analysis provides a detailed outlook for Africa in particular, for which a slightly lower contribution from solar fuels is expected. Some of the reasons for this include a high cost of capital in Africa as well as high costs for utilizing solar fuels in end-use applications. This is especially true for hydrogen—even though it is expected to reach market maturity sooner than other solar fuels, the cost to businesses, developers, and vehicle owners and operators to adapt their industrial processes, buildings and vehicles to run on hydrogen remain very high. Nevertheless, the lack of legacy infrastructure in many parts of Africa, coupled with its high solar irradiance factor, make it an ideal target for investment in solar fuels. The development of local solar fuel supply chains could spark greater local demand, and contribute to increasing the contribution of solar fuels to Africa's energy needs at a greater pace than originally expected.

3. Creation of an International Solar Fuel Forum

This chapter will present the building blocks that were used to develop the International Solar Fuels Forum, a digital space for exchange and discussion between experts and stakeholders of solar fuels developments. It will highlight the key components that were used to build the Forum together with the activities that were undertaken to engage with the community.

3.1. Objectives and scope of the International Solar Fuel Forum

In order to stimulate expert awareness and information exchange of scientists, industry, authorities and civil society on solar fuels, the research and findings of the study, the International Solar Fuel Forum aims to develop a strong worldwide communication network. This online network, using existing and freely accessible IT tools would offer the possibility for real-time feedback and input from leading experts in the field of solar fuels, through the online discussions in virtual workshops and in the Forum space. This network created would be an engaging tool for distant and online information exchange, strictly adhering to confidentiality and data protection requirements.

The network has the objective of creating new discussions through virtual workshops, while drawing on pre-existing clusters of scientific research networks. An emphasis on multinational engagement, particularly from Mission Innovation countries, was a crucial element for the success of the solar fuel stakeholder engagement.

The International Solar Fuel Forum created through this project was carefully crafted with all these elements in mind to support the study and build a network around the shared topic of solar fuel technologies.

3.2. The Solar Fuel stakeholder engagement and communication strategy

The Solar Fuel stakeholder engagement is made up of several different activities to develop the communication network. These are divided into the elements needed to build the communication network, the contextual factors that affect the network and the engagement activities with the network itself.

In Figure 105 below, these different elements are represented as building blocks needed to construct the Solar Fuel stakeholder engagement and communication strategy. This includes a strong foundation of Privacy and data protection measures, a well-developed communication action plan and a recognisable visual identity. The tools that were used are then added to the foundations, which include the technical solution of the Webex suite and the project's EY landing page.

Once these initial blocks have been constructed, the contextual factors are taken into account, notably the impact of the global outbreak of the COVID-19 virus and the international nature of the stakeholders who registered for the project.

The top section of the construction is about engaging with the communication network. This was done through the email network, the International Solar Fuel Forum on Webex Teams and the Solar Fuel survey. Supported by these three are the virtual workshops, which make up the main stakeholder engagement point for real-time global discussion on solar fuel technologies.

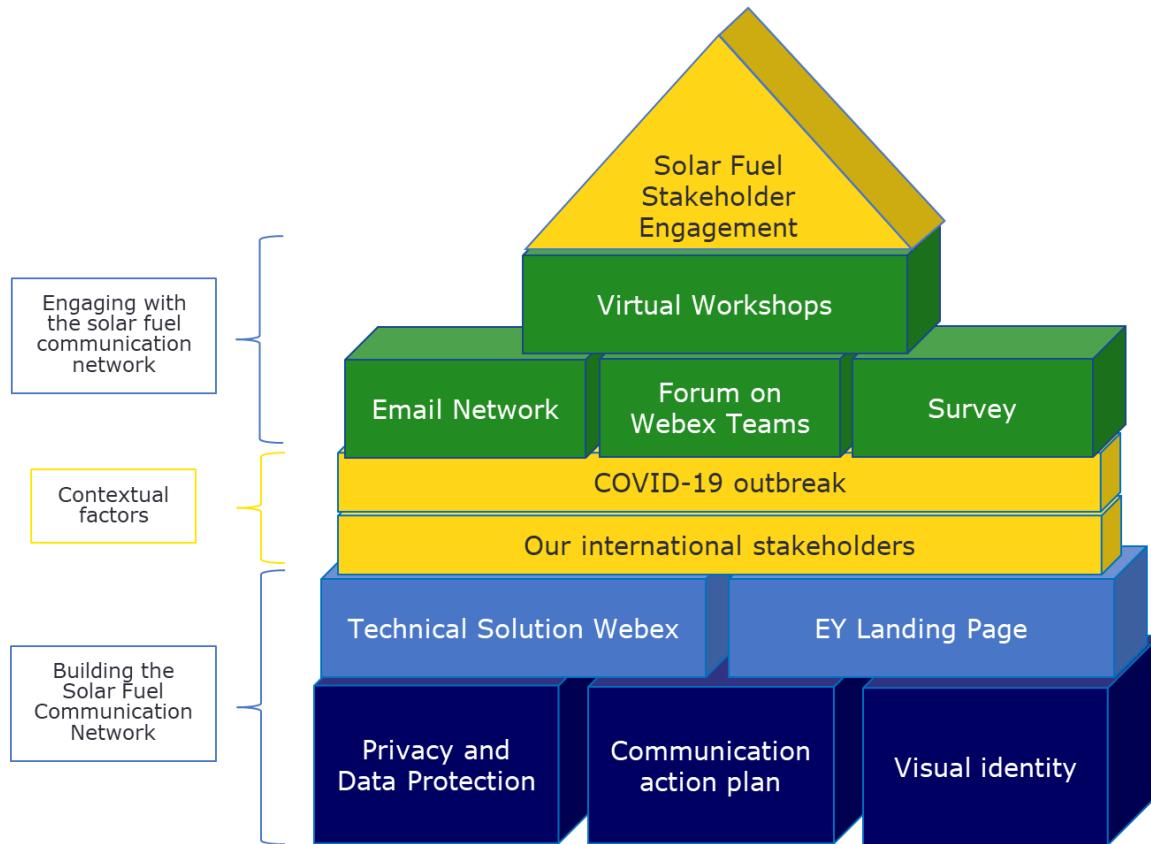


Figure 105 - Building blocks needed to create the International Solar Fuel Forum

In the following chapters, we will present the aims and means used to deliver on the objectives of the Solar Fuel communication network set out in the Terms of Reference. We will describe and analyse the network as well as present an overview of the various communication means used to form the network and summarise the activities undertaken.

The next chapter will present the key blocks used to set up the International Solar Fuel Forum. This includes examining the communication action plan devised by the team, the visual identity and the privacy and data protection measures put in place. The project webpage, mailbox and the technical solution of Webex Meetings and Webex Teams will be further detailed.

Will then analyse the engagement within the solar fuel communication network, especially within the new communication environment caused by the global outbreak of the COVID-19 virus. The communication action plan use and the stakeholders registered will be examined alongside the detailed overview of the use of the online Forum and the virtual workshops.

Finally, we will present the way forward for the International Solar Fuel Forum. In this, we will explain possible future actions with the network.

3.3. Building the Solar Fuel Communication Network

To build a global communication network for information exchange and discussion on solar fuels within the project, several elements were required. Taking into account the specifications of this network in the Terms of Reference, the project team agreed with DG RTD on the best way to proceed to have the correct technical infrastructure and attract a maximum amount of stakeholders.

This chapter will focus on presenting the foundational blocks and technical blocks of the Solar Fuel stakeholder engagement, focusing on how these were designed to fit the requirements of the project and any obstacles encountered.



Figure 106 - Building blocks for creating the Solar Fuel communication network

3.3.1. Stakeholder Engagement and communication strategy

The stakeholder engagement and communication strategy created for the project lays out the practical path to building the network of the International Solar Fuel Forum. It shows the efforts undertaken to identify our stakeholders and get them to join our network. The purpose of the stakeholder mapping and the development of the communication action plan was to find out who could be part of the network and see what best ways to reach them to engage and inform them about the project. A mapping of the participant communication path through the strategy allowed us to see where communication is needed, where drop-off points may be and where new connections with participants may be made.

This section will give an overview of the strategy devised, while later Chapter 3.4.2 will outline the outcome of this strategy's implementation.

3.3.1.1. Stakeholder mapping

As per the Terms of Reference for the project, the International Solar Fuel Forum aims to involve experts and stakeholders in the area of solar fuels across the world. In this, scientists, experts, industry, authorities and civil society stakeholders were the central target of the Forum.

Through the stakeholder mapping conducted by the team, four groups of target stakeholders were identified:

Stakeholders mapped from consortium partners who have the scientific and industry contacts. The individuals and organisations designated by the consortium partners as relevant to the project are the basis for the stakeholder outreach.

Mission Innovation stakeholders, particularly those involved with Challenge 5 on solar fuels, represented a key target stakeholder group. Reaching MI stakeholders relied on gaining access to the MI network, which was done through the European Commission who are co-leading the Mission Innovation Challenge 5.

DG RTD stakeholders and wider network who were potentially interested in joining the network. This group consists of the network of DG RTD, relying on DG RTD to send invitations to their contacts.

Other sub-contacts from the three lists above who received the communications via someone who had registered for the project. The sharing of the information helped in further developing our stakeholder list throughout the project.

3.3.1.2. Overview of the communication action plan

With these stakeholders in mind, the communication action plan was designed to track the communication journey of the stakeholder and address where communication is needed so that a maximum amount of mapped stakeholders join the project's database.

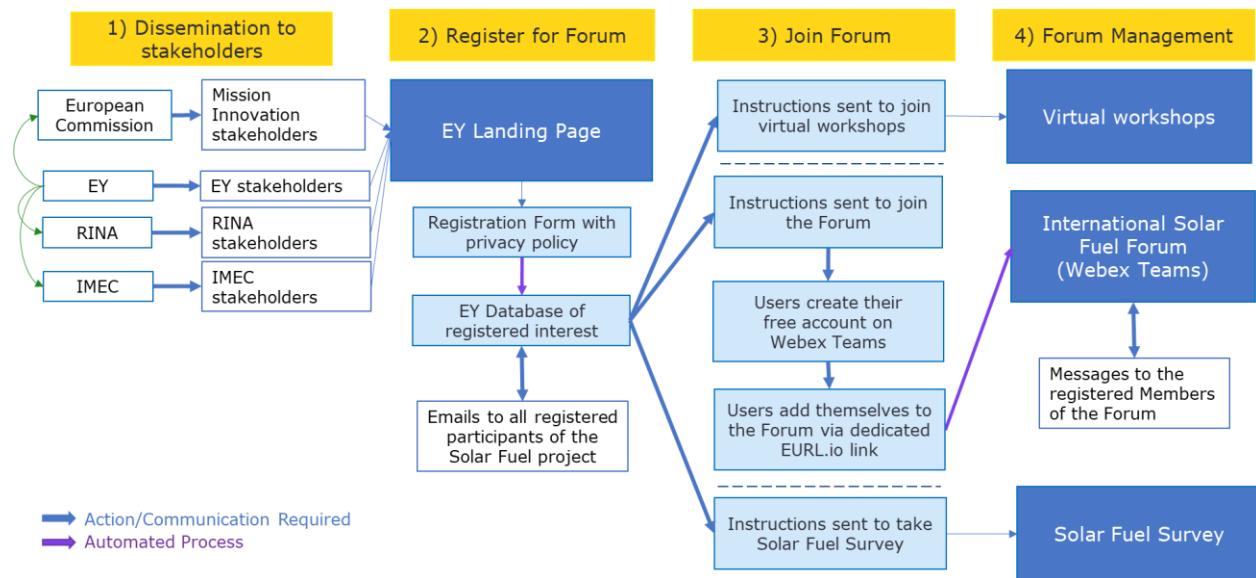


Figure 107 - Overview of communication action plan¹¹⁷

The action plan is divided into four main phases. The first phase is **dissemination to stakeholders**, which was the first contact with the identified stakeholders about the project. The aim of this phase was to inform stakeholders about the Solar Fuel study and the creation of the International Solar Fuel Forum, and ask them to register their contact details with us to receive future communication.

To contact stakeholders in full respect of data privacy measures, the dissemination was divided into four groups. Each group received the email created by the team in the project branding with respect of project visibility, for them to distribute to their own network of stakeholders. As the targeted stakeholders were registered with partner organisations on their email lists, the contact details of the stakeholder could not be transferred to the central project team and contacted without the prior consent of the stakeholders.

The second phase of the action plan was the **registration for the Forum**. The main activities of this phase were to develop the project's EY landing page, registration form and privacy policy to be able to collect the contact information of the stakeholders who register their interest for the project.

The third phase was focused on the transition from the database of registered interest to **joining the activities of the International Solar Fuel Forum**. This was divided into three main communications: inviting stakeholders to join the virtual workshops, inviting them to add themselves to the Forum on Webex Teams and inviting them to take the solar fuel survey. This phase relied on simple instructions presented in the emails to stakeholders and reminders to ensure that the potentially interested stakeholders would pursue the activities and did not miss out on the discussions.

Phase four consisted of **forum management** by the project team, which included sharing workshop material, communicating to the registered participants via Webex Teams platform and following up on the survey. Ahead of the workshop, the team populated the Forum with relevant information to encourage participation in the workshops. The preparation, execution and follow-up of the virtual workshops of the International Solar Fuel Forum was also an activity of this phase, which took place via email and via the Forum. Stakeholders part of the email list received all the information about the workshops by

¹¹⁷ Note: the action plan has been revised since the Interim report on the project. In particular, the way users join the Forum was modified. Instead of the EY team adding the emails of participants into the Forum directly and in bulk, and then asking participants to create their profile to have access, the stakeholders now receive instructions on how to create their account and add themselves to the Forum. Additionally, the virtual workshops and the solar fuel survey have been added to this diagram of the strategy.

email to avoid any stakeholders missing out on the workshop invitations if they were not on the Forum platform.

3.3.1.3. Project email address

Emails were the main communication mean for the stakeholder engagement and communication strategy. They allowed new stakeholders to be informed, whilst building the database of registered participants and disseminating project information to the stakeholders.

To effectively use the means of email as a project, it was necessary to create a dedicated project email address. This was done by the project team with EY email facilities. The email address ‘info.solarfuel@be.ey.com’ is a shared mailbox managed by the EY project team and represented the main contact point for the project team from the perspective of the participants. The email address was key to be able to send out emails to participants with a central address to reply to in case of queries.

3.3.2. Visual identity

3.3.2.1. Branding and logos

A successful stakeholder engagement relies on a visual identity that is coherent, recognisable and pleasing to the audience. The details of the colour palette, images and logos help to reinforce the messages of the initiative and build a stronger image and recall of the project in the target audience. The project team first designed a colour palette and a variety of logos drawing on the main imagery and sentiments of the message of the project. These were further refined in discussion with the European Commission, with the final selection of the logos made by DG RTD on 30 January 2020.

The colour palette of the project is comprised of vibrant colours to reflect the nature of renewable energy, which is perceived as healthy, clean and positive. These colours were combined with European Commission colours to reflect the EU-funding of the project, particularly the EU official blue and yellow would be used as primary and complementary colours. The additional green in the palette plays the role of the tertiary colour, to be used for smaller details to add a fresh and natural touch to the brand.

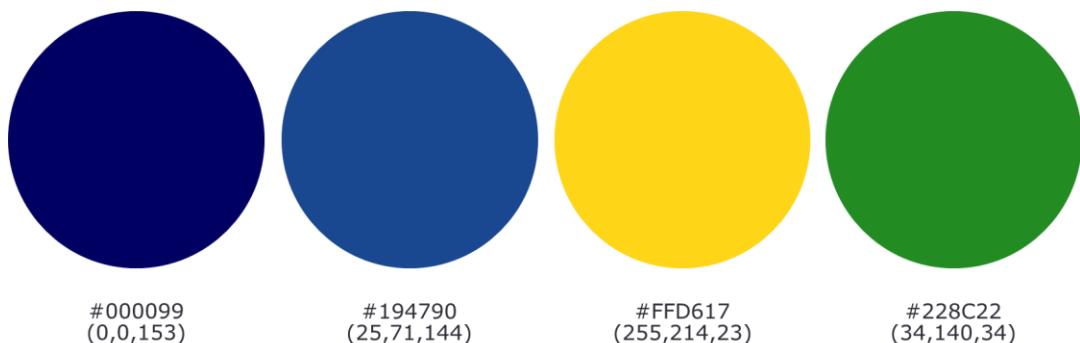


Figure 108 - Colour Palette

For the logos, it was important to have a clear, identifiable and simple logo that could be easily linked to the project. The imagery of the sun is naturally associated with solar fuels, which combined with the imagery of a droplet adds a sentiment of renewability. The droplet signifies the fuel that is produced as part of the solar fuel technologies, but could also be perceived as a water droplet which is part of the image of renewability and transition towards a cleaner energy ecosystem.

In practical terms, 26 logos¹¹⁸ were designed during the inception phase, with three logos chosen by DG RTD for the project: two stand-alone and one with an integrated title. Among

¹¹⁸ Examples of the 26 initial designs can be found in Annex VI: Examples of other logo designs.

the stand-alone logos, one was designed with a blue background, which was the default logo used, and one with a transparent background.



Figure 109 - Logo - Stand-alone default (left) and secondary (right)

The default stand-alone logo was mainly used to allow for a quick identification of the project on other platforms – for example, it was used as the ‘profile picture’ of the International Solar Fuel Forum account on the Webex applications. The full logo with title integration was used as the main ‘signature’ logo, which featured at the top of all email communication from the Solar Fuel project team.



Figure 110 - Logo - Title Integration

The visual identity was also applied to define images to complement the branding of the project webpage and the email template. The consistency was ensured throughout the project, paying special attention to the font, colours and imagery used.

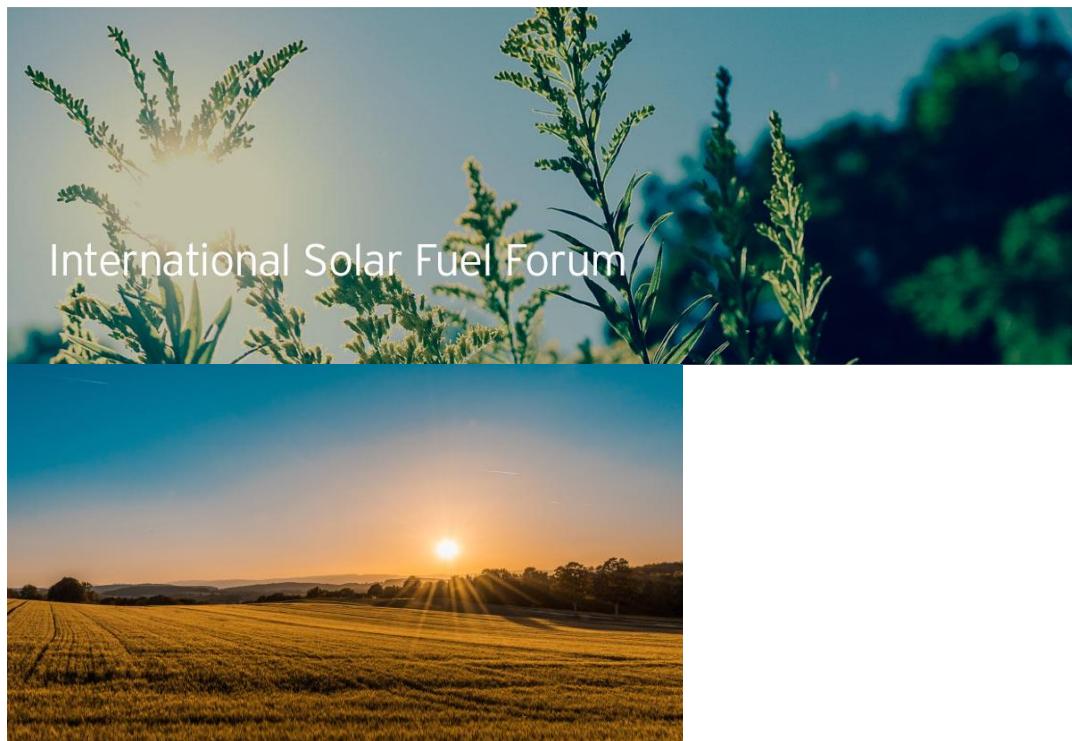


Figure 111: Examples of complementary branding images

3.3.2.2. Mail template

Part of the branding package developed was a dedicated email template. This ensured consistent visibility through all mail communications to the participants. An email banner was created to be placed at the top of the emails with the logo to frame the emails. The rest of the template presented a clean and clear message. This was ensured by setting formatting guidelines for the text.

Table 30 - Text formatting specifications for the email template

Headings Font: Helvetica, 14pt, Blue (#000099)	Normal Text Font: Helvetica, 12pt, Black
Call to Action button Font: Helvetica, 14pt, white text Background: rounded-edge blue rectangle (#000099)	Footer Font: Helvetica, 9pt, Black

Mailchimp was used as a tool to edit the template and fill in the content. This was then transposed into a html-rich text Outlook mail to be sent out from the dedicated solar fuel project email address to stakeholders without entering the contacts into Mailchimp.



Figure 112 - Extract from an email – designed banner

An important part of the template was the footer of the email which presents the option to unsubscribe by contacting the team. This also presented the link to the International Solar Fuel Forum privacy policy devised specially for the project. More detailed information on this is presented below in section 3.3.3.

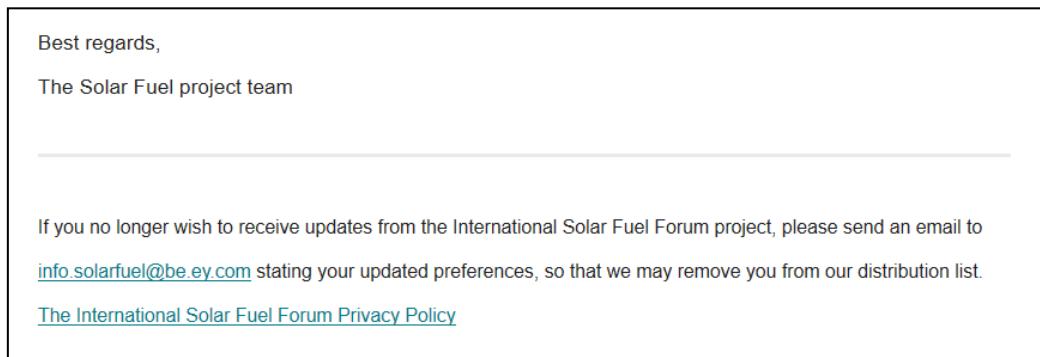


Figure 113 - Extract from an email - privacy footer

3.3.3. Project webpage

The need for a webpage was identified early on in the project, with the aim to serve as a static centralised information point about the project initiative and contain a registration form to collect the contact details of the interested stakeholders, in line with the privacy and data protection considerations.

3.3.3.1. Building the webpage

The International Solar Fuel Forum webpage is hosted on the EY Belgium website at the following URL: https://www.ey.com/en_be/consulting/international-solar-fuel-forum. In practical terms, it is composed of a static webpage with expandable boxes with information on the project and the study, with a 'call to action' button at the end of the page. This button links to a registration form page which is hosted in EY's web environment and linked to EY Belgium's marketing platform which allows the data to be collected and exported by a trained EY user.

The registration form¹¹⁹ allows visitors to enter their personal contact details for the purpose of the project. This includes First Name, Last Name, Email, Organisation and Job Title, collected by EY on behalf of DG RTD to set up a database of interested stakeholders for the project.

3.3.3.2. Privacy and data protection measures

To have a webpage and collect the personal data through the registration form, the project team ensured that the necessary privacy and data protection measures were in place.

The International Solar Fuel Forum Privacy Policy¹²⁰ was developed in consultation with an EY data privacy legal expert. This policy was made accessible via a clearly signalled link on the registration form page. The acknowledgement of having read the privacy policy and accepted its terms is a mandatory pre-condition for visitors to submit their details through the form. This was ensured through a checkbox embedded in the form.

The privacy policy ensured that the visitors were aware of the project, the role of data controller held by the European Commission's DG RTD and that of the data processors which are the consortium partners. It also details what data will be collected, for what purpose and duration as well as the relevant directives, rights and responsibilities of the parties involved.

The website also had the necessary cookies policy in place from EY, due to the site being held on an EY website. Visitors are informed about the different cookies in place, their usage and the options they had to accept or reject certain cookies upon arrival on the webpage.

Once the contact details of the participants were collected through the registration form, guaranteeing the confidentiality and treatment of the data according to the privacy policy was a priority for the project team. In practice, one team member had access to the registration form to export the data and track registrations. The registration details were shared among consortium partners under the privacy policy when necessary (for the conference invitation), however only the EY team was actively tracking the status of registration data.

3.3.4. Technical solution: Webex

The Forum itself required a technical solution to host the online discussions according to the requirements laid out in the Terms of Reference. These were to use existing and freely

¹¹⁹ Available at: <https://emeia.ey-vx.com/1733/137528/landing-pages/register.asp>

¹²⁰ Available at: <https://emeia.ey-vx.com/1733/137528/landing-pages/privacy.asp>

accessible IT, which had the confidentiality and data protection measures in place to be able to host virtual workshops to engage international experts.

In the early research and discussions with the team, multiple possible solutions were proposed which were narrowed down to Microsoft Teams or Cisco Webex. After consideration of the specific capability requirements and the European Commission's own familiarity and use of Webex, it was agreed that Webex would be suited to the needs of the task.

The project team bought a one-year license for Webex as the technical solution for the Forum (February 2020 – February 2021). This included both Webex Meetings and Webex Teams. Webex Meetings is an internationally-recognised cloud-based virtual conferencing tool. Webex Teams is a newer addition to the Webex suite which enables collaboration through chat 'spaces,' file sharing, calling and other collaboration tools.

Webex is a global tool as users can join from most locations around the world. The platform is accessible via the Webex websites online via a URL link, or via the desktop applications which can be downloaded for free. The platform has data security measures in place¹²¹, and data gathered from the platform are stored on servers in Europe.

3.3.4.1. Hosting the workshops on Webex Meetings

Webex Meetings was the main tool to enable the International Solar Fuel Forum workshops. It is widely used for conference audio and visual calls through its intuitive and easily accessible platform.

Table 31 - Webex Meetings - features

 Webex Meetings	Key Features: Audio, video and screen sharing; 'Raise hand' to indicate if participants have a question; Chat for questions/remarks or technical questions during the call; Built-in polling: single, multiple or 'short' answer questions, with timer available and poll results sharing.
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The license acquired to host meetings allows for up to 200 people in one call. The admin has access to their own Webex online hub to schedule meetings and track meeting data and statistics. In the meeting, the host has control over the participants in the meeting with the ability to mute/unmute and expel participants, among others features.

3.3.4.2. Building the Forum on Webex Teams

The second part of the technical solution is the online collaboration platform itself, which is hosted through Webex Teams to create the online Forum. Webex Teams is a conference-driven online platform which allows users to collaborate in online teams to chat, call and share documents with other users in the Team. The participants will be able to consult the workshop agenda and documents circulated via the Forum, and chat to fellow Forum members on technological developments.

Table 32 - Webex Teams - features

¹²¹ More information on the Webex security and privacy measures is available via their White Paper Series, available at: <https://help.webex.com/en-us/nv2hm53/Cisco-Webex-Security-and-Privacy>

 Webex Teams	<p>Key Features:</p> <p>Chat in dedicated Space¹²² of International Solar Fuel Forum, moderated by @EYSolarFuel (paid license);</p> <p>File sharing in the Forum;</p> <p>Calls in Teams – fewer features than Webex Meetings, available to participants for calls in small groups.</p>
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Access to Webex Teams is free for users, upon the creation of a free account on the Webex Teams website. Some users may already have access to the platform via their organisation's license, which they can also use to join the Forum. By using a 'bot' called EURL.io available within Webex Teams, the project team created a joining page¹²³ for the Forum on Webex Teams where participants can enter their email to add themselves to the Forum space.

The Forum is a space moderated by the EY project team. Multiple administrators could manage a Team; this means that EY and the European Commission can both be administrators of the International Solar Fuel Forum, if the European Commission has a Webex Teams licensed account. Among other elements, the administrator controls who has access to the Team by being able to add or delete users in the Team. The licenced moderator also brings the capability to hold calls to the entire space. This means that when the license-holder leaves the space, the space loses this capability unless the moderator role is taken over by another license-holder.

In preparing the Forum, the team created a welcome banner and a code of conduct to be posted in the Forum. The code of conduct, found in Annex VII: Forum Code of Conduct and Welcome Banner contains guidelines on the purpose of the Forum, what is not permitted in the moderated space (such as harmful or abusive language, commercial content or editing of the structure of the space) and the consequences thereof. This document also includes tips on how to use Webex Teams so that users could make the most out of the tool.

3.4. Engaging with the Solar Fuel network

Having now examined the main tools needed to build the solar fuel network, this chapter will analyse the engagement with the network and explain how this took place. The contextual development of the global outbreak of COVID-19 virus will be further detailed and the impact it had on the project in terms of the changing communication environment. The results of the communication action plan will be examined, and the considerations made to account for the international stakeholders who registered for the project.

The engagement with the solar fuel network revolved around four main activity blocks: the email network updates, the online Forum on Webex Teams, the Solar Fuel survey and the virtual workshops. The use of these blocks to contribute to stakeholder engagement and stakeholder satisfaction will be explained in further detail in the chapter.

¹²² Webex Teams operates in 'Spaces' which are the equivalent to channels. The International Solar Fuel Forum is one main space. Users have the possibility to create separate spaces which could be a chat with one other person or create their own groups outside of the ISFF space.

¹²³ Users can visit <https://eurl.io/#9yjK0NALo> and enter their email address to be automatically added to the ISFF on Webex Teams.

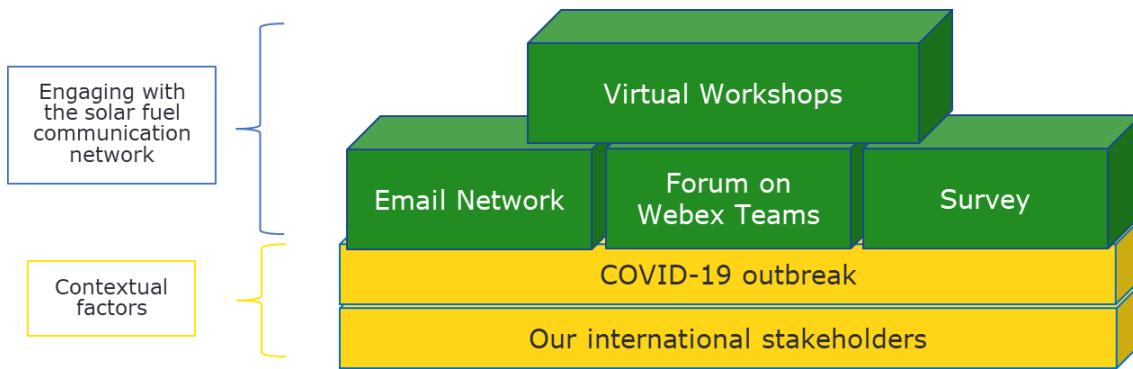


Figure 114 - Building blocks for engaging with the Solar Fuel communication network and contextual factors

3.4.1. Outbreak of COVID-19 and impact on the communication environment

The global outbreak of the COVID-19 virus in early 2020¹²⁴ has caused a fundamental shift in our society. With the virus spreading so easily, countries have had to take national confinement and lockdown measures to ease the pressure on hospitals while limiting the spread among the population. This has led to many EU societies struggling with limited economic activity due to quarantine measures, while ordinary activities have been forced to relocate to the digital sphere including the widespread use of remote working.

A new communication context has emerged from the past months under the COVID-19 pandemic. A large number of activities and actions, including communication activities such as events, press meetings and conferences moved to the digital space to quickly adapt to the 'new normal' and not to lose the attention of the audience. This is not an exception for EU actors, with many major EU events such as the EU Business Summit 2020 already being moved to the digital space.

The result is a more crowded and volatile digital communication space which has become the central mean for working and socialising due to social distancing and lockdown measures. In the context of the solar fuel project, the online nature of the workshops was suited to these new measures. However, this also meant that the virtual workshops were one of many virtual events, competing for the time and attention of participants online.

The project team assessed this new environment and took measures to mitigate against information being lost in the large amount of notifications generated. This included well-timed and scheduled emails, adequate reminders and communicating this new environment and possible implications to DG RTD. The uncertainty and shift in ways of working caused some delay compared to the original timings of the workshops, however once the delay was adjusted, the workshops were able to run according to the new plan agreed with DG RTD.

3.4.2. Communication action plan in use

Before assessing who the stakeholders of the project are, this section will explain how the communication action plan, described in section 3.3.1, was used in practice. A detailed overview of the emails designed and sent during the project can be found in Annex IX: Timeline of emails to stakeholders.

The dissemination to stakeholders began in February 2020 after the launch of the project webpage and registration form on 14 February 2020. An email invitation was prepared by the project team to be distributed by IMEC and RINA to their list of stakeholders, and by the European Commission to their own stakeholders to respect the data privacy of each of the stakeholders respective lists. For the Mission Innovation stakeholders, the European

¹²⁴ Timeline of European Commission response to events at: https://ec.europa.eu/info/live-work-travel-eu/health/coronavirus-response/timeline-eu-action_en

Commission contacted their network to organise a call to present the project. The call was held in late February, which resulted in the first participant registration for the project on 28 February 2020.

Reminder emails were sent out by the partners and then a welcome email was also prepared to keep stakeholders informed about upcoming activities. By 1 May after these initial emails, a total of 36 stakeholders had registered their interest in the project¹²⁵.

Once the Forum and survey were ready and open, the stakeholders were informed by email. Following this, the team noticed a growth in registrations as the emails were being shared outside our initial stakeholder list. An email was also prepared for IMEC and RINA to send to their stakeholders in May, as the final email informing them about the project and asking them to register. This was to ensure that these external stakeholders had the opportunity to be informed, without them having the feeling of receiving emails from IMEC or RINA on other projects that they were not interested in. Before the time of the first workshop on 3 June, the list of stakeholders had grown to 48 people.

Throughout the project, the team continuously engaged with Mission Innovation to encourage their stakeholders to participate. Several stakeholders from Mission Innovation attended the workshops and provided further inputs through email correspondence. Nonetheless, due to conflicting timelines among others, further alignment between the outputs of this study, and corresponding Mission Innovation deliverables, was limited.

In June, emails were sent to stakeholders regularly, containing the invitations to the workshops and paired with the reminders to take the solar fuel survey and join the Forum. The registration list was growing as the link to register was also advertised by the project team in the workshops themselves to encourage the stakeholders who had joined the workshop but were not registered with us to sign up. By the end of June, 62 stakeholders were registered for the project.

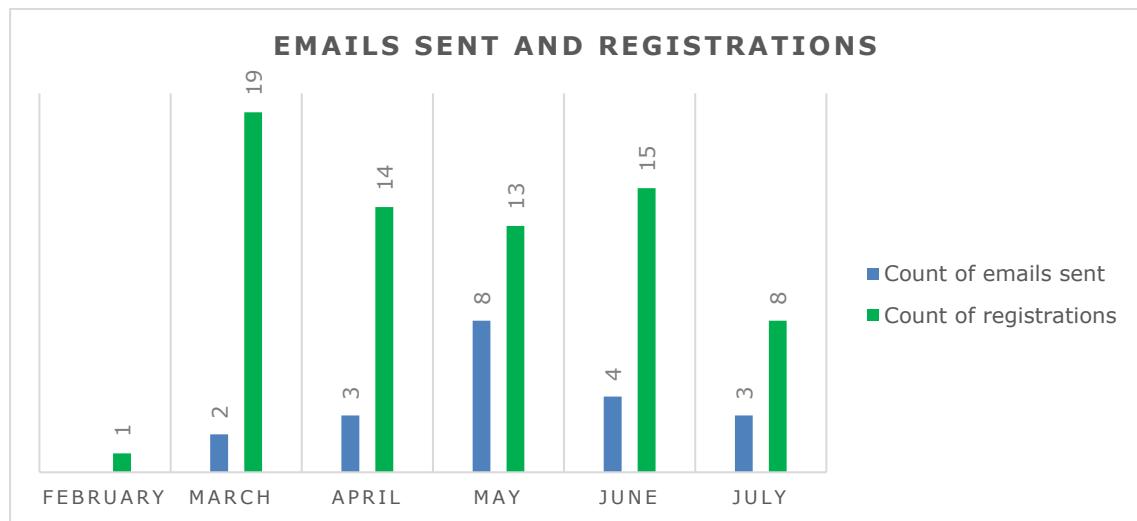


Figure 115 - Timeline of emails sent out and stakeholder registrations

The solar fuel engagement strategy was built around the concept of the privacy gateway: to ensure that all the data from the stakeholders was collected under the application of a privacy policy. The primary stakeholder list counts all registered through the registration form on the webpage through the International Solar Fuel Privacy Policy. However, the project team noticed that other stakeholders were getting involved in the activities of the project without having registered via this webpage. These are stakeholders who received

¹²⁵ These figures in this section do not include the Solar Fuel project team members (15 people) or the DG RTD representatives (2 people).

the information about the project from someone who was on the list, thereby being recruited by an unidentified multiplier.

These stakeholders who had not registered via the project webpage had instead provided their contact details through joining the Forum, registering or joining the workshops, or by taking the solar fuel survey. The data collected through these three other gateways was bound by its own privacy policies – the Webex privacy policy and terms of use, and the EY survey tool privacy policy, respectively. The project team decided to keep the data obtained through these three platforms, clearly marked as collected under separate policies.

At the end of the workshops on 8 July, a privacy email was sent to all the stakeholders who had not yet registered through the main webpage of the project. This was to ensure that those who wished to continue to be informed about the project beyond the activity they first signed up for could do so by registering through the webpage. By the end of July, the stakeholder list had grown to 70 registered stakeholders.

3.4.3. Importance of the email network

The mailing network created for the project was an essential activity which contributed to stakeholder engagement. All updates on the project went through email to the stakeholders. This medium also allowed the network to grow, as emails could be easily forwarded on by stakeholders to their own networks.

The project team used the dedicated email address created for the project to send out the mail emails to project participants. For the solar fuel survey, as this was created using a dedicated EY survey tool these were sent out by the email of the survey tool itself. This was to enable the system to send unique survey links to the participants, to detect if that person had taken the survey or if they needed to be sent an email reminder to complete it. The branding and email template of the Solar Fuel project was used by the survey tool where possible to keep a consistent image with the rest of the emails from the project team.

In the communication environment of COVID-19, special attention was paid to email reminders. The team would send the invites and information by email and then proceed to verify who had acted on the information, remove these people from the distribution list, and then send a reminder email to all those who had not yet reacted to the information. In this way, participants had another chance to react in case they had not seen the first email.

The project mailbox was also given as the main contact point for stakeholders to contact the project team and speakers. This proved particularly useful when participants wanted to share additional material with the speakers after the workshop, as they were able to email info.solarfuel@be.ey.com directly to reach the project team.

3.4.4. Our international stakeholders

After examining the methodology and environment for the stakeholder engagement, this section will now provide an overview of who our stakeholders are. By the end of the project, a total of 141 stakeholders were involved – this includes 70 registered stakeholders, 15 solar fuel project team members, 2 European Commission representatives and 54 stakeholders exclusively obtained from the workshop registration/attendance, survey or Forum. For the purpose of the overview, all the 141 stakeholders will be analysed, with a further breakdown per workshop attendance given in section 3.4.7.

The main characteristic of the stakeholder network is its international nature. The stakeholders come from organisations in 25 different countries (with three stakeholders from pan-European or international organisations)¹²⁶. Of these, 15 are countries involved

¹²⁶ This data was extracted from researching the location of their organisation, or optionally provided from them directly when registering for the workshops.

in Mission Innovation, represented by 76 stakeholders, whilst 10 are non-Mission Innovation countries represented by 62 stakeholders.

Table 33 - Distribution of stakeholders per country of organisation

Mission Innovation countries	Number of stakeholders	Non-Mission Innovation countries	Number of stakeholders
Australia	19	Belgium	32
Austria	1	China	1
Brazil	1	Cyprus	1
Denmark	1	Estonia	1
Finland	3	Greece	2
France	11	Hungary	1
Germany	8	Portugal	1
India	6	Slovenia	2
Italy	5	Spain	19
Japan	2	Switzerland	2
Netherlands	7	Data not available	3
Norway	4		
Republic of Korea	4		
Sweden	2		
United Kingdom	2		
Total	76	Total	62
		Total	141

The stakeholders cover diverse sectors, notably from academia and research centres (universities, national scientific institutes, technological centres), from industry (multi-national energy, electrical, chemical and petro-chemical companies; industry associations such as SolarPower Europe) and from cross-sector scientific initiatives (such as SUNERGY). The stakeholders were experts in their field, divided across researchers, professors, business managers, policy advisors and project managers. The competitive yet diverse and cross-sectoral nature of solar fuel is evident in the diversity of the profiles of the stakeholders.

The international nature of the stakeholders provided the project team the opportunity to re-assess the appropriate timings for the workshop. 19 out of the 25 countries were in Europe, with Australia, India, Brazil, Japan, the Republic of Korea, China adding the international dimension. It was decided to vary the times of the workshop to better accommodate the different time-zones of the stakeholders, as will be explained later in section 3.4.7.

3.4.5. Solar Fuel survey

The Solar Fuel introductory survey was an activity designed by the project team to gather feedback on the study from the expert stakeholders. This was made up of a series of multiple choice and open-field questions where stakeholders could provide their opinion on the study methodology, the technological pathways and the input data.

The survey helped the team to shape the content for the workshops, responding to the contents of the survey. Particularly for the first workshop, the survey results were presented by the team and discussed with stakeholders.

To help the stakeholders in completing the survey, a 'study guide' was also prepared by the project team. This document described the four technological pathways, the aims of the study and the terminology used. The guide was available to consult on the first pages of the survey and available via the online forum for participants.

The completion rate of the survey remained lower than expected, with 12 stakeholders responding to all the questions and submitting. However, as the survey was to a level of scientific detail, these 12 replies already provided rich data for the team to analyse. This same level of scientific detail in the questions may have also been a factor influencing the lower rate of survey completion. Some differences over terminology used in the study and the survey were also raised at the first workshop despite the clarification in the study guide, which may have hindered the completion of the survey for a small number of stakeholders.

3.4.6. The International Solar Fuel Forum on Webex Teams

The International Solar Fuel Forum on Webex Teams was designed as the online meeting place of experts during the project, especially between the workshops. The set-up and features described in section 3.3.4 were implemented to enable virtual discussions via the chat space on the online platform.

The invitation to join the Forum were first sent in early May, attached with 3-step instructions created by the team on how users could easily create their free Webex Teams account and join the Forum. As a moderated space, the participants could write messages, tag other participants and share documents in the space. In July, the Forum had a total of 21 people, including 15 external stakeholders, 5 team members and one European Commission representative¹²⁷.

Despite being encouraged numerous times to use the space to ask questions or share comments or observations, the utilisation of the online Forum by participants remained limited. Its main use was as an information flow on the project. The project team posted the invitations to the workshops and the links, accompanied by the workshop agenda. The material from after the workshops, including the PowerPoint slides and minutes of the question and answer session (Q&A) was also posted in the Forum for participants to consult.

A total of 31 posts have been made on the Forum, 29 of which were from the project team's @EYSolarFuel account relating to the project updates¹²⁸. The two other updates were one reaction by a stakeholder to a post by the project team, and one by another project team member's account addressing one stakeholder.

The first post by @EYSolarFuel was on 12 May 2020 consisting of the welcome banner. The other 28 posts were spread across 13 different individual days, with sometimes multiple posts on the same day around the time of the workshops to maximise participation in the workshops. The tone of the messages was kept light and engaging, with the use of relevant emojis where appropriate.

The lack of interaction from stakeholders on the Forum may also have been impacted by the outbreak of COVID-19 which affected engagement levels. In the crowded and relentless digital environment that our stakeholders now had to navigate from home, people may have been less likely to sign up and interact with a new platform when they are already receiving information from various online sources. The team recognised this risk and therefore more emphasis was placed on emails being the main source of information, with the Forum being the secondary source for information and more geared towards a space for stakeholders to interact with the project teams and other stakeholders.

A further note on the limited discussions in the Forum is possibly related to the competitive nature of solar fuels. Particularly in the current state of investment, where parties are interested to scope out what is currently happening without revealing their own

¹²⁷ This figure does not include the host @EYSolarFuel account (shared project team account) and the EURL.IO bot account, which brings the total number of the Forum to 23.

¹²⁸ The number of posts in the Forum is accurate as of 9 September 2020 and subject to change as the Forum is being used to promote the invitation, registration and follow-up from the conference to be held on 30 September – 1 October 2020.

development plans at the early stages of this solar fuel. This may have influenced the reserved nature of the stakeholders in the online forum.

3.4.7. The International Solar Fuel Forum virtual workshops

The virtual workshops of the International Solar Fuel Forum were the key activities of the Solar Fuel engagement, providing a real-time global discussion on various solar fuel technologies and pathways. The aim of the workshops was to discuss and document endeavours on solar fuels, to engage international experts and contribute to the ongoing discussion on the topic.

Five workshops were originally planned, however in the context of the COVID-19 outbreak, the decision was taken with DG RTD to reduce the number of workshops to three in total, with one introductory workshops and two pathways per workshop. All stakeholders would be invited to each workshop so that if an expert in one field also wanted to hear about the developments in another field, they could easily join the workshop.

The three workshops were hosted by the International Solar Fuel Forum on Webex Meetings across the month of June 2020. The topics and timings were carefully calculated to reflect a balanced audience and thematic representation. An overview of the workshops and topics can be found in Table 34.

Table 34 - Overview of workshops held

	Workshop	Topic	Date and time
1	Introductory Workshop	Introduction to study and presentation of survey results	Wednesday 3 June 2020, 10:00-12:00 CET
2	Electrochemical / Thermochemical Workshop	Electrochemical and Thermochemical solar fuel pathways	Wednesday 17 June 2020, 10:00-12:00 CET
3	Chemical / Biochemical Workshop	Chemical and Biochemical solar fuel pathways	Monday 29 June 2020, 15:00-17:00 CET

The international nature of the topic was reflected in the diverse audience of the workshops. An important element was to have at least participants from 10 different countries at each workshop, which was a reality for two out of the three workshops hosted¹²⁹. A further important requirement was that the 10 different countries would include at least five Mission Innovation countries¹³⁰. This was achieved for all three workshops, with 8 Mission Innovation countries present for the first, 9 for the second and 5 for the third workshop¹³¹.

3.4.7.1. Preparation for the workshops

Before diving into the details of each workshop, this section will explain the communication strategy and preparation needed for all the workshops. Once the time and date of the workshops had been agreed with DG RTD, the team prepared the workshop content and structure.

¹²⁹ The first and second workshop had over 10 different countries; workshop three had 7 different countries (including the Solar Fuel project team and DG RTD representatives, when attended workshop).

¹³⁰ List of Mission Innovation countries retrieved from <http://mission-innovation.net/>

¹³¹ Figures based on location of organisation or optionally provided by the participants when registering for the workshops. Includes project team and DG RTD representatives, when they attended workshop. Excludes the one project team shared account that hosts the workshop).

Ahead of each workshop, an agenda was prepared and designed and sent out to the participants by email, followed by a reminder. For the second and third workshop, the team combined the follow-up material from the previous workshop with the invitation to the next, to further motivate the stakeholders to join the next workshop. For each workshop, participants were sent a link to register their attendance by entering their name and email address into the dedicated Webex online form. After this, they were automatically sent the meeting joining details by Webex, accompanied by a calendar invite with the details.

The agenda and joining details for each meeting was also posted in the International Solar Fuel Forum on Webex Teams as a second point of information for stakeholders. The minutes of the Q&A and the presentation slides were also posted in the Forum after the workshops. The team reminded the stakeholders that they could ask any additional questions to the speakers or the project team in the Forum, to encourage stakeholder engagement in between the workshops.

The agenda was designed to balance the presentation of the study from the project team with the discussions from the stakeholders. As such, equal time was given to the presentation (50-60 minutes) and the Q&A session (50-60 minutes). To make the workshops interactive, the team also used live polling via the Webex polling capabilities. This involved short 3-5 minute short polls sent to participants in real-time via Webex to answer multiple choice questions. This not only furthered the discussion after the polls, but allowed the project team to gage the participants' reactions to the material that was being discussed.

The coordination before the workshop within the project team was a vital component of the successful seamless flow of the workshops. In particular, the assessment of the roles, needs and run-through required helped the team to identify any potential obstacles using the virtual tool from different locations ahead of the workshops.

In particular, four roles were elaborated to use with Webex, as illustrated in Table 35. During the workshops, the Facilitator and Host role were occupied by one team member, while the presenter role was assigned to the different speakers as the workshop developed. Thanks to the internal detailed workshop plans and the run-throughs with the project team, the transitions and hand-overs between presenters was smoothly executed during the workshops.

Table 35 - Roles and capabilities for the virtual workshops

Workshop Roles:

- '**Participants**': mute/unmute themselves, chat with Host and in general chat (not 'Presenter')
- '**Presenter**': assigned by the Host, can share screen;
- '**HostTechnical Assistance**.
- '**Facilitator**': speaking host who leads the meeting, transitions between speakers and presents polling results.

Note: the roles marked in quotation are roles recognised in Webex Meetings, which are assigned certain abilities within the meeting environment.

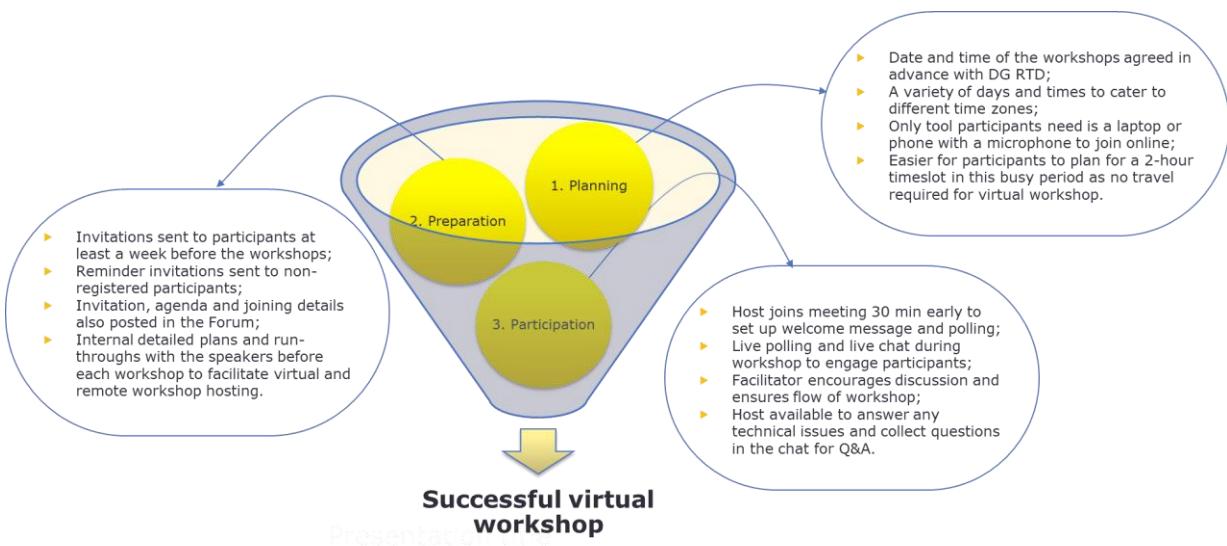


Figure 116 - Planning for a successful virtual workshop

Other elements necessary to prepare ahead of the workshop were the Meeting Code of Conduct and the recording disclaimer, which were displayed in the first few slides of the meeting for participants to acknowledge. The workshops were recorded within Webex to allow the project team to complete the minutes of the Q&A. It was made clear in the recording disclaimer slide the purpose and use of this recording, with the link to the EY privacy policy under which this recording would be treated. Examples of these slides can be found in Annex X: Meeting Code of Conduct and Recording Disclaimer slides.

3.4.7.2. Overview of participation per workshop

To better assess the success in terms of attendance of each workshop, the number of registrations and participants will be presented. We will provide an overview of the countries of the organisations in attendance. Note that the figures in this chapter do not include the project team's 'International Solar Fuel Forum' account which hosts each meeting. However, it does include the members of the project team and the DG RTD representatives if and when they joined the meetings.

When organising virtual events, there is the risk that participants connect to the session for a period of time and disconnect if they no longer find the content relevant or interesting. At physical events, it is much more difficult to leave an event during a session, however in the digital space where the participants are not present as a group but as individual connected devices, it is easier to drop out of the call. Therefore, a further point included in the following analysis is the time spent per participant at the workshop. This allows us to see if participants were interested enough to stay for most of the workshop, or perhaps interest was lost earlier on.

First workshop

The first workshop was designed as the introduction to the project and the study, with the first discussions on the survey results. 33 people registered for the workshop and 36 people joined¹³². Most of the people who registered joined the meeting, with 4 new people joining who had not registered. These four people demonstrate a multiplier effect, as they had obtained the joining details from someone who had already registered for the meeting.

¹³² These figure does not include the project team 'Host' account.

The 36 attendees joined from 13 different countries, mostly from Belgium (12 attendees) followed by Spain (7 attendees). A total of 8 Mission Innovation countries were represented through 16 of the participants.

The average time¹³³ spent on the workshop was high for this session at 107 minutes per participant, out of the 132 minutes total duration of the workshop. Furthermore, 72% of participants stayed connected to the workshop for over 90 minutes.

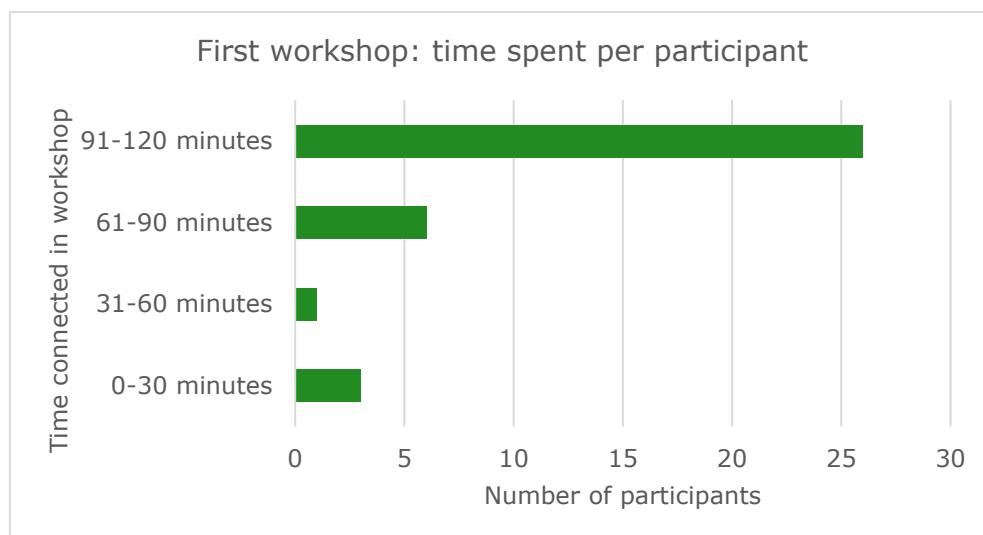


Figure 117 - Time spent in first workshop by participants

Source: post-meeting report from Webex

The workshop was run smoothly, with orderly stakeholder discussion during the Q&A session. Some overtime was recorded as the discussion progressed, with stakeholders happy to stay connected for the additional twelve minutes.

Second workshop

The second workshop was dedicated to the Electrochemical and Thermochemical solar fuel pathways identified in the study. This workshop drew in the highest number of people, with 54 registrations and 57 people in attendance. Only 4 people joined who had not previously registered, indicating a high proportion of interest in the workshop¹³⁴.

The 57 attendees joined from 14 different countries, Belgium again featuring as top country with 16 attendees, followed by Australia (12 attendees) and Spain (7 attendees). Out of 14 total countries, 9 were Mission Innovation countries, represented by 29 participants.

The average time was also very high for this workshop at 86 minutes out of the 114 minutes duration of the workshop, with 31 people staying between 91-120 minutes¹³⁵.

¹³³ The average time does not include the project team 'Host' account, which connects to the meeting before the meeting start.

¹³⁴ These figure does not include the project team 'Host' account.

¹³⁵ The average time does not include the project team 'Host' account, which connects to the meeting before the meeting start.

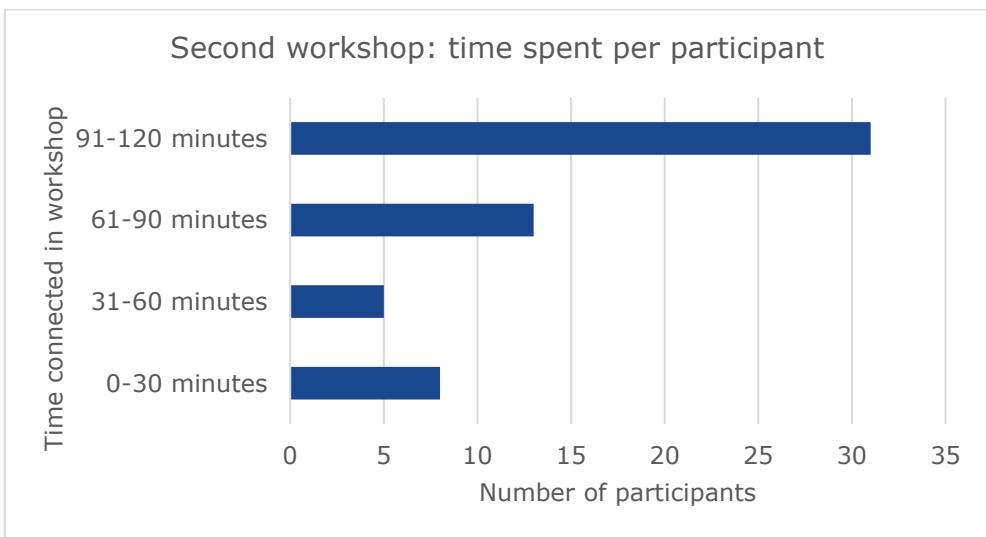


Figure 118 - Time spent in second workshop by participants

Source: post-meeting report from Webex

The workshop participants showed great interest in the subject matter of the discussions. The workshop agenda and timings ran smoothly, with some small technical issues on the user-end regarding a failure of the sound drive. Investigations into these issues after the workshop suggests that it could be when users mute their call in the application as well as outside of the Webex environment on their computer or on the phone whilst not being aware of it. Overall, these technical issues which affected three participants did not hinder the discussion, as the people in question were instead invited to share their thoughts in the chat which was picked up by the Facilitator and replied to during the workshop by the speakers.

After the second workshop, the project team presenters also received additional stakeholder interest by email, where a participant wanted to share a study that they had raised during the workshop.

Third workshop

The third and final workshop focused on the Chemical and Biochemical solar fuel pathways. The registrations and attendance for this workshop were among the lowest, with 40 registrations and 22 people in attendance¹³⁶.

Among the 22 attendees, there was a good representation across seven countries with 9 participants from Belgium, and equal numbers of 3 people from Australia, India and Spain. Ten people from five different Mission Innovation countries were present at the virtual workshop.

The discussion in the Q&A of this workshop was somewhat more limited than the other two, with the facilitators and speakers trying to ask the audience questions with little reply. As such, the workshop ended after an hour and a half. Despite this, the average time¹³⁷ spent at the workshop remained high at 72 minutes out of the total 86 minutes of the workshop, demonstrating a willingness to listen-in even if the participants themselves are not openly discussing.

¹³⁶ These figure does not include the project team 'Host' account.

¹³⁷ The average time does not include the project team 'Host' account, which connects to the meeting before the meeting start.

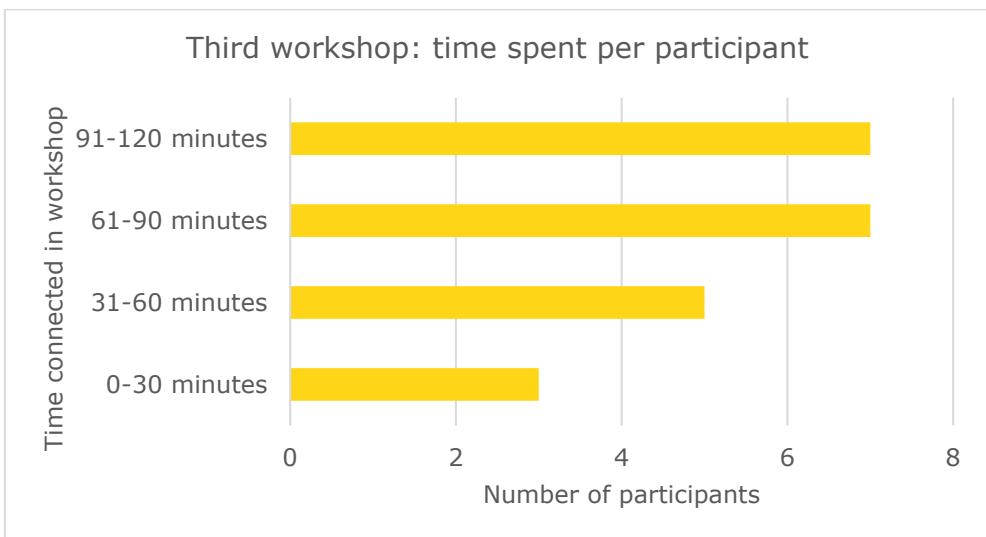


Figure 119 - Time spent in third workshop by participants

Source: post-meeting report from Webex

3.4.8. Stakeholder management

At the close of the workshop, the final follow-up emails and content from the workshop was sent to the extended list of 141 stakeholders. This list of stakeholders then had to be cleaned of all contacts who were not registered for the project via the webpage so that those who had registered for the whole project could be contacted about the upcoming conference.

To do so, the team composed a privacy email stating why their data was currently held depending on their specific purposes and what they can do to stay informed about the project, should they choose to do so. It was important for the participants to be given the choice to actively subscribe and register their details or have the option to not reply and be removed from our contacts.

In practice, one email and one reminder¹³⁸ were sent to encourage the contacts who were not centrally registered for the project via the webpage registration form to do so. A total of 8 additional stakeholders registered their contact details with us after the privacy email. After this, the save the dates could be sent to the registered contacts in compliance with the privacy policy of the project.

3.5. Way forward for the Solar Fuel network

The solar fuel network exists as a database of contacts registered for the purpose of the project and the online Forum in Webex Teams. If the European Commission wished to take over and continue the project past the expiration of this contract, there are a few options in place:

Activate the email database: DG RTD is the data controller for the solar fuel project, which means they are the ultimate owners of the data collected. This database of contacts can be transferred to the European Commission to continue communication on the solar fuel project. This would mean the project team sending to DG RTD the database of 70 contacts registered for the project.

- It must be noted that the privacy policy in place allows these stakeholders to be contacted solely for the project in question. However, DG RTD could ask these

¹³⁸ See Annex IX: Timeline of emails to stakeholders to preview the emails.

stakeholders to sign up to another newsletter or subscription list if this is applicable, before retiring the ISFF list.

- The privacy policy would need to be adjusted and the stakeholders notified, should DG RTD continue with the list of stakeholder within the project after the expiry of the current contract with the consortium led by EY.

Take over role as moderator of Forum on Webex Teams: the Forum on Webex Teams was created by the project team and now exists as Space moderated by the project team. The call capabilities are granted to each member of the Forum through the license-holder @EYSolarFuel team account. Once the project team leave the space, these capabilities will be taken away unless another license-holder is appointed as moderator before this. If DG RTD desired, they could become the moderator of the space if they acquire a Webex Teams license. The messages of the previous moderator and previous discussions will remain in the Forum, however the moderation rights will be transferred to the new DG RTD account who can then post as their own profile in the Space.

- If the Space is not pursued further, the team will 'archive' the space within Webex Teams so that it is no longer active.

4. Outreach and Dissemination

This chapter will present the activities undertaken and material developed for the dissemination of the study key results on the definition of solar fuel value chains, the roadmap and outlook for solar fuels and the creation of the international solar fuel forum.

4.1. Final conference on solar fuels research & invest

As part of the EU-funded project “Solar Fuels Research & Invest: Defining and developing the global solar fuel value chain: techno-economic analysis and pathways for sustainable implementation”, CEPS, along with its partners EY, IMEC and RINA, organized a conference to disseminate results of the project and foster collaboration between stakeholders in the solar fuels research and investment community. Following developments and restrictions related to Covid-19, the conference was organized fully online.

To ensure full engagement of participants, the event was divided into four shorter sessions organized over two days, with each session lasting no more than 3 hours.

- The first day (30th September 2020) featured a public conference to present the technical and economical findings of the project, as well as giving a broader overview of solar fuel value chains and their role in the EU green energy transition.
- The second day (1st October 2020) featured two invitation-only sessions, one for the Electrochemical and Chemical pathways and one for the Thermochemical and Biochemical pathways. The invitation-only sessions targeted a smaller audience of experts to ensure dynamic interaction among all participants to explore opportunities for future collaboration.

Final versions of the agendas for both days are available in the annexes.

4.1.1. Day 1 – 30 of September 2020 – Public session

The public conference was organized using the ZOOM Webinar functionality. This option allowed the host and the panellists to share their screen, video and audio, while attendees had view-only rights. Interaction between panellists and attendees was organised through the chat as well as the dedicated Q&A feature and poll question tool available on ZOOM, managed by the moderators. This specific set-up was chosen to reflect the nature of the public conference, which aimed at presenting the results of the study to a larger audience.

‘Save the date’ and invitations were sent via CEPS mailing lists targeted to experts in energy, climate change and circular economy as well as to selected stakeholders identified by the Consortium partners. Table 36 below contains the record of email interactions with invitees to the public conference.

Table 36 - Communication with invitees to the public conference

Date	Email subject
27/07/2020	Save the date - Solar Fuels Research & Invest
17/08/2020	Save the date - Solar Fuels Research & Invest
10/09/2020	Invitation - Solar Fuels Research & Invest
21/09/2020	Invitation - Solar Fuels Research & Invest
29/09/2020	Connection details - Solar Fuels Research & Invest
30/09/2020	Reminder - Solar Fuels Research & Invest
30/09/2020	Reminder Afternoon Session - Solar Fuels Research & Invest Conference
02/10/2020	Solar Fuels Research & Invest - Thank you message

Registrations to the public conference and the invitation-only sessions were handled through the CEPS online registration system. Information on the dates, topics of discussion, panellists, agendas and registration were published on the event webpage,

hosted on the CEPS website: <https://www.ceps.eu/ceps-events/solar-fuels-research-invest/>

The event was also advertised through CEPS social media accounts: Twitter @CEPS_thinktank (47.200 followers) and LinkedIn CEPS Centre for European Policy Studies (26.012 followers). Dynamic posts were published with the purpose of attracting additional stakeholders and raise interest in the event (see Figures 120 to 126). The social media strategy started in mid-August and included the publication of a sponsored LinkedIn post to reach out to stakeholders with specific experience on the topic (see Table 34 for the full list of published posts). Tags and hashtags related to the project partners, as well as the topics of the conference included: @EYnews, @imec_int, @RINA1861, @EU_Commission, @Energy4Europe, #EUGreenDeal, #CleanEnergyEU. Posts were published following Twitter Global Engagement, which shows peaks of engagement from users by timing, in order to reach maximum impact.



Figure 120 - Tweet No. 1 - @CEPS_thinktank account



Figure 121 - Tweet No. 2 - @CEPS_thinktank account



Figure 122 - Tweet No. 3 - @CEPS_thinktank account



Figure 123 - Tweet No. 4 - @CEPS_thinktank account



Figure 124 - LinkedIn Join Us Today – CEPS (Centre for European Policy Studies)



Figure 125 - Sponsored LinkedIn – CEPS (Centre for European Policy Studies)

Table 37 - Posts on Twitter and LinkedIn

Date	Publication	Total views/reactions
1/10/20	Tweet No. 5 – Watch again YouTube	1.988 impressions
30/9/20	LinkedIn Image No. 5 - Join us today	866 impressions
30/9/20	Tweet No. 4 – Join us now - Afternoon session	2.063 impressions
30/9/20	Tweet No. 3 – Join us now – Morning	2.211 impressions
28/9/20	Tweet No. 1	2.366 impressions
24/9/20	Tweet No. 2	2.434 impressions
22/9/20	Tweet No. 2	2.337 impressions
21/9/20	Tweet No. 1	2.135 impressions
21/9/20	LinkedIn	1.517 impressions
15/9/20	Tweet No. 1	2.095 impressions
15/9/20	LinkedIn	1.765 impressions
10/9/20	Tweet No. 1	2.305 impressions
7/9/20	LinkedIn	1.487 impressions
4/9/20	Tweet No. 1	2.387 impressions
2/9/20	Tweet No. 1	3.566 impressions
25/8/20	Tweet No. 1	2.982 impressions
17/8/20	Tweet No. 1	2.567 impressions
15/8/20	LinkedIn	2.686 impressions
The sponsored LinkedIn post was published from 07/09/2020 to 30/09/2020. It received a total of 12.867 impressions, which represent how many times the content was displayed by unique viewers.		
Total impressions		52.618

As a result of the communication strategy about 200 persons registered for the event, including officials from the European Commission, policy-makers from other organisations and experts on solar fuels from industry, academia and research institutes. The final list of registered participants for the public conference can be found in Annex II and results on use of interactive tools (e.g Q&A features and poll questions) in Annex III. Table 38

presents the ZOOM attendee report, which outlines the number of participants who joined each session.

Table 38 - ZOOM Attendee report: public conference

Day 1 – 30 of September 2020 – Public session		
	Morning session	Afternoon session
Actual Duration (minutes)	194	243
Unique Viewers	66	47
Total Users	127	98
Max Concurrent Views	43	27
Unique viewers:	Shows the total number of participants who attended the event, considering a single registration.	
Total users:	Shows the total number of logins to the event. It is usually higher than 'Unique viewers', because it does not differentiate participants with a single entry or multiple registrations to the session.	
Max concurrent views:	Shows the maximum number of participants who attended the event simultaneously.	

The public conference was streamed on the [CEPS Think Tank YouTube channel](#), and the recording of the event was shared with all registered participants in the final "Thank you" message, which also included PDF copies of all the presentation shown during the event. By the 2nd of October 2020, 103 views were recorded (70 for the morning session and 33 for the afternoon) in playback.



Figure 126 - CEPS Think Tank YouTube channel conference live stream and recording

4.1.2. Day 2 – 1st of October 2020 – Invitation-only sessions

The invitation-only sessions organised on the second day allowed for direct and dynamic exchanges with experts, relying on the ZOOM Meetings functionality. This option allowed all participants to share their screen, video and audio as well as using the chat function, under supervision by the host and moderators. The target audience included high-level experts from industry, academia and research institutes. The invitees included attendees to the public conference as well as additional experts identified by the Consortium partners. Table 39 below contains the record of email interactions with invitees to the initiation-only sessions.

Table 39 - Communication with invitees to the invitation-only sessions

Date	Email subject
21/09/2020	Invitation - Special Session Solar Fuels Research & Invest Conference
25/09/2020	Invitation- Special Session Solar Fuels Research & Invest Conference

28/09/2020	Invitation reminder
28/09/2020	Send out of calendar invites
30/09/2020	Invitation reminder
02/10/2020	Thank you message

Registrations to the invitation-only sessions were handled through the CEPS online registration system. 26 participants registered for the morning session and 13 for the afternoon session. The final list of registered participants to the invitation-only sessions can be found in Annex IV. Table 40 summarises the duration and number of participants in the two sessions.

Table 40 - ZOOM Attendee report: invitation-only sessions

Day 2 – 1st of October 2020 – Invitation-only sessions		
	Morning session: Electrochemical and chemical pathways	Afternoon session: Thermochemical and biochemical pathways
Actual Duration (minutes)	159	125
Participants	41	20

4.1.3. IT support and preparatory activities

Permanent IT support was provided by the CEPS team, for both the Consortium partners and the attendees, before and during the event. In addition, a number of meetings were scheduled and hosted by CEPS as preparatory activities for the final conference to ensure the smooth execution of the event (see Table 41).

Table 41 - Preparatory meetings

Date	Objective	Participants
29/09/2020	Conference rehearsals	Consortium partners + CEPS Comms Team + CEPS IT Team
21/09/2020	Conference preparation call – Discuss the format and test the ZOOM platform	Consortium partners + CEPS IT Team
14/09/2020	Conference planning	Consortium partners + CEPS Comms Team

4.2. Video productions

As per the requirements of the ToR, we produced for the purpose of the project two professional short videos summarising solar fuel development and key results of our study. In order to ensure the quality and professionalism of the videos, the exercise was outsourced to the video production company 87seconds. The production company ensured alignment of the videos with the European Commission's guidelines on audiovisual products¹³⁹, as required in the Terms of Reference.

Regarding content, the first 20 second video aims at providing a basic presentation of solar fuels and their applications across different sectors. The video intends to introduce and raise awareness about solar fuels amongst a wide audience.

¹³⁹ <https://audiovisual.ec.europa.eu/en/>

The 2-3 minute video introduces viewers to the study, its context and key results. It complements the short video outlined above by providing further analysis. It consists in an interview video, divided in key questions that cover four main areas of analysis being: a presentation of solar fuels; the different technological pathways to produce solar fuels; the challenges and opportunities to solar fuel developments; the future role of solar fuels in meeting our energy needs. The project's five core team members were interviewed for the video.

The videos were shared with DG RTD in parallel to this report and shall be used by the Contracting Authority as key dissemination tool to share with stakeholders the results of the study, but also to inform and raise awareness about solar fuels to a wider audience.

4.3. Written dissemination material

4.3.1. Presentation of key study results

As per the requirements of the terms of reference, the key study results are outlined in a 20-slide presentation. The presentation was compiled to be disseminated to stakeholders and was shared with DG RTD in parallel to this report.

4.3.2. Policy Brief

Reaching the goals of the Paris Agreement on climate change will require substantial efforts by all countries worldwide to lower, as much as possible, the greenhouse gas emissions associated with their energy consumption. Solar photovoltaic ("PV") is a key component in many countries' plans for reaching their targets under the Paris Agreement. Indeed, the price of PV modules has declined by a factor of 10 in as many years, and is expected to continue declining. Solar PV is now cost-competitive with fossil fuel-based power generation in many jurisdictions, and is expected to be the least expensive form of power generation overall by 2030.

Electrifying end-uses of energy, in particular of passenger road transportation but including a wide range of applications in energy, buildings and transport as well, is another key component in most countries' climate plans. On top of mitigating greenhouse gas emissions, electrification often results in energy efficiency gains relative to fossil fuel-based applications, as is the case for electric vehicles.

Nevertheless, renewable electricity alone cannot address all of the challenges inherent to the decarbonisation of our energy consumption. Firstly, not all energy end-use cases are susceptible to being electrified in the short or medium term, with long-haul air transport being a prime example. Additionally, solar PV and most other renewable energy sources are characterised by a high degree of variability in their output levels. This variability calls for flexible storage capacity to address both short term needs, balancing intra-day fluctuations, as well as long-term needs to balance the seasonal variation in renewable energy production seen in most jurisdictions. On top of temporal imbalance, there is a clear geographical imbalance in the distribution of resources (chiefly wind, sun and land) required for renewable energy production. Many regions that are blessed with an abundance of these resources have relatively small populations and correspondingly low energy consumption, while highly populated regions such as Europe have more limited resource availability.

Solar fuels, i.e. synthetic energy carriers derived from solar energy, can help address the three challenges discussed above, i.e. the resistance to electrification in some applications, as well as the temporal and geographical variability in renewable energy production. Solar fuels can be produced through different technological pathways, including Electrochemical, Chemical, Thermochemical and Biochemical processes. The most viable pathway for solar fuels production currently is the electrolysis of water for the production of hydrogen, an example of the electrochemical pathway. This pathway combines the production of electricity from solar PV, with water electrolysis in a second stage. A promising, but early

stage technology called the photoelectrochemical cell combines both stages in one module, producing hydrogen directly from sunlight energy.

A techno-economic analysis was carried out for a number of solar fuel pathways as part of the "Solar Fuels Research & Invest: Defining and developing the global solar fuel value chain: techno-economic analysis and pathways for sustainable implementation" commissioned by DG RTD. The analysis reveals that energy input costs, namely the cost of solar PV, accounts for the majority of the costs for producing solar fuels. The cost of solar PV modules is expected to continue its decline, suggesting a future where solar fuels could potentially become competitive with comparable fossil fuels. The question becomes: what is the cost performance of solar fuel technologies over time, and at which point in time do they overcome the cost advantage enjoyed by their fossil counterparts, if at all.

The forward-looking analysis reveals three main pathways of interest to our energy needs in industry, transport and buildings. The first is a form of electrolysis of water using a proton exchange membrane electrolyser cell, for the production of hydrogen. The second is the production of methanol through CO₂ hydrogenation, using green hydrogen produced through e.g. solar-powered PEMEC, and CO₂ captured directly from the air, or through carbon capture and utilisation¹⁴⁰. The third is power-to-methane, which consists in the production of methane from green hydrogen and CO₂, similarly to CO₂ hydrogenation.

The analysis reveals that water electrolysis could compete with fossil-based hydrogen production before 2040, with a possible accelerated time to market depending on factors such as solar irradiance or synergies with local industry. E-fuels¹⁴¹ could follow suit in the short term, with methanol produced through CO₂ hydrogenation expected to reach cost parity with the price of motor gasoline, factoring in a carbon price of approximately €178 per tonne of CO₂, by the early 2040s. Power-to-methane, on the other hand, would reach cost parity around 2060.

- A number of factors are expected to impact the uptake of solar fuels worldwide, including:
- Costs of solar fuels, which are primarily driven by the price of solar electricity at first vs. costs of comparable fossil fuels,
- Costs of adapting end-use systems to solar fuels, such as changing from coal to hydrogen in steel manufacturing,
- Infrastructure costs,
- Demand for carbon-neutral industrial products, vehicles and transportation services, and heating and cooling technologies in buildings, and
- Supportive regulations and policies such as carbon pricing mechanisms.

Industry, in particular, could potentially become early adopters of solar fuel technologies in certain applications. As industries are increasingly considering carbon capture and storage schemes, CO₂ may become more readily available, and could serve as an input to solar fuel production. These solar fuels could be produced and used on-site to power the same CO₂-emitting industrial processes, thereby closing the carbon loop. Such schemes, with the right incentives, could prove attractive to industries, driving them to invest in early-stage technologies.

¹⁴⁰ In that case, for CO₂ hydrogenation coupled with CCU to be truly carbon neutral, the fuel resulting from the fuel's combustion would have to be captured again to close the carbon loop.

¹⁴¹ E-fuels are synthetic fuels, either gaseous or liquid, produced through the use of electricity to produce hydrogen, which is combined with carbon dioxide to produce hydrocarbon fuels.

Solar fuels could contribute approximately to 4 to 6 percent of worldwide energy needs in 2050, and 6 to 10 percent in 2100. A concerted effort by stakeholders in energy supply chains, in sectors where energy end-use cases could transition to solar fuels, and by policymakers and consumers will be required to ensure that targets for solar fuel supply matches demand targets. Policymakers, in particular, should consider the following:

- Early and significant investments in solar fuel technologies, through e.g. subsidies for capital expenditures or fiscal incentives,
- Demand-side policies mandating minimum shares of carbon-neutral fuels, such as solar fuels, in the energy mix in specific sectors in e.g. industry or transport,
- Fair, and increasingly strict carbon pricing, and

Given the challenges related to infrastructure, in particular for hydrogen, a concerted policy is needed to prioritise applications where infrastructure needs are minimal, e.g. by developing solar fuel production capacity within the same facility as existing large scale industrial plants to leverage synergies between CO₂ derived from carbon capture and solar fuel production.

4.3.3. Flyer

As per the requirements of the terms of reference, the key results of the study are presented in a Flyer format. The flyer was developed to be disseminated to stakeholders and was shared with DG RTD in parallel to this report.

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6. Annexes

6.1. Annex I: LCOE model methodology

The key economic and technical concepts that serve as fundamentals of the model are the learning rate and the leveled cost of energy. They are presented as follows:

The Learning Curve - Learning rate

The theory of the learning curve or experience curve introduced by T.P Wright was based on the idea that the time required to perform a task decreases as a worker gets more experience. In his theory, Wright described a synchronous cost decline with an increased production performance (Wright, 1936). Today, an abundant amount of variations is used in specialized applications, albeit drawing their fundamentals from T.P Wright's initial work.

In an energy application, the concept is defined as a relationship between the cumulative installed capacity^{142*} and the decreasing cost per unit of installed capacity (Rubin et al., 2004; van der Zwaan & Rabl, 2003) . In this study, the learning curve was adopted to estimate the cost reduction as the technology components gets more mature.

***Installed capacity:** The maximum output of electricity that a generator can produce under ideal conditions. Capacity levels are normally determined as a result of performance tests and allow utilities to project the maximum electricity load that a generator can support. Capacity is generally measured in megawatts or kilowatts.

Calculation of the learning rate

In theory, an 80% learning curve shows that the cumulative average cost (and time) will decrease by 20% each time the number of unit's doubles. The Learning Rate is equal to 20% (*Progress Ratio*=1- learning rate). The relationship between the quantity x_t produced at time t, the cost $C(x_t)$ compared with the output quantity, the corresponding cost $C(x_0)$, and the learning parameter b, can be expressed as follows:

$$C(x_t) = C(x_0) * \left(\frac{x_t}{x_0}\right)^{-b}$$

$$\text{LR} = 1 - 2^{-b}$$

Using this equation, the cost savings over time are estimated as a specific technology matures, i.e. the worldwide capacity installed has increased.

The learning rate will be used as a parameter for the definition of different scenarios referring to growth scale.

The Levelized Cost of Energy (LCOE)

There are many methods to estimate the economic feasibility of an energy production project, but the Levelized Cost of Energy ("LCOE") is mostly used when a comparison of different electricity generation technologies is needed or when the grid parity for emerging technologies is considered (Branker et al., 2011). The LCOE is a similar concept of the determination of the payback period for energy systems. However, instead of measuring how much is needed to recoup the initial investment, the LCOE determines how much

¹⁴² U.S. Energy Information Administration (EIA)

money must be made per unit of electricity (kWh) to recoup the lifetime costs of the system.

The estimation of LCOE allows different energy investment projects to be compared with one another, namely, it allows the comparison of different technologies (wind, solar, natural gas) of different projects sizes, capital cost, risk return or capacities. To compare these projects on an equal basis, production cost (e.g. for 1kg of Hydrogen) is calculated based on a yearly basis assuming a fixed number of operating hours per year. Capital cost (CAPEX) is estimated based on a standard discounting method. The LCOE can also be viewed as the price at which electricity is sold in order for the plant not to operate with a loss (International Energy Agency, 2005). "Levelized" shows that this measure is expressed as a consistent energy output vis-à-vis different projects, or as cost per unit of energy. This study uses the latter, specifically € / kWh.

Calculation of LCOE

In this study, the LCOE calculation is based on previous works in the production of renewable energies (EIA, 2013; Kost et al., 2018). In general, the LCOE of renewable technologies depends on the following parameters:

- ▶ *Specific Investment Cost*: construction and installation of power plants with upper and lower limits (data retrieved from literature and current power plants). Start up and shut down calculations are neglected in our calculation.
- ▶ *Local condition*: typical irradiance and wind conditions for different locations
- ▶ *Operating Cost* during the power plant's operational lifetime
- ▶ *Financing Condition*: Earnings calculated on the financial market and maturity periods on technology specific surcharges and continent-specific financing conditions

$$LCOE = \frac{Io + \sum_{t=1}^n \frac{A_t}{(1+i)t}}{\sum_{t=1}^n \frac{M_{t,el}}{(1+i)t}}$$

LCOE : Levelized cost of energy in EUR/kWh

Io : Investment expenditure in EUR

A_t : Annual total cost in EUR per year t

M_{t,el} : Produced amount of electricity in kWh per year

i : Real interest rate in %

n: Economic lifetime in years

Converting the forgoing theoretical formula into the format that is being used by the model, is done as follows (for a given year *i*, region *j* and technology *k*):

$$LCOE_{i,j,k} = \frac{Capital\ Costs_{i,k} * CRF_{i,j} + Fixed\ O&M_{i,k} * Capital\ Costs_{i,k}}{8760 * Capacity\ Factor_{i,k}} + \\ Variable\ O&M_{i,j,k} * Output_k$$

Hours/year: 8760

Capital Costs_{i,k}: Total investment costs of building a plant (€/kWh).

$CRF_{i,j}$: Capital Recovery Factor: Ratio of the annuity of capital costs to its present value. It determines the amount of capital cost that is to be allocated in each specific year as a capital expenditure.

$$CRF_{i,j} = \frac{r_j * (1 + r_j)^{n_i}}{(1 + r_j)^{n_i} - 1}$$

With r_j being the discount rate related to a specific region. The discount rate is determined by regional risk factors, legislative environment and technology readiness. The assumptions made for the estimation of the discount rate for each region are presented in the respective section in of the report.

$Fixed\ O\&M_{i,k}$: Fixed operating and maintenance expenses (% of capital costs).

$Capacity\ Factor_{i,k}$: % of a year the plant is running at full installed capacity.

$Variable\ O\&M_{i,j,k}$: Variable operating and maintenance expenses (labour, waste disposal, electricity, H₂O, CO₂) that are reported in mass of the fuel (€/kg).

$Output_k$: Specific energy of the fuel (kg/kWh). The mass of fuel related to technology k equivalent to 1 kWh.

Ultimately, each world area's LCOE is modelled with respect to i, j, k in terms of € / kWh. As such, a comprehensive comparison can be made with regard to which technology/pathway –fuel combination is the most favourable in each respective world region.

6.2. Annex II: Regional assumptions

Table 42 – Regional assumptions (technology agnostic)

Non-Time-based Assumptions	Regions					
	Europe	Asia	North America	South America	Africa	Australia
Discount rate	9.0%	11.0%	10.0%	14.0%	16.0%	10.0%
Inflation	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CO ₂ emission price	27.80 €	10.00 €	20.00 €	15.00 €	5.00 €	18.00 €
CO ₂ emission yearly increment	7.00%	7.00%	7.00%	7.00%	7.00%	7.00%
CO ₂ resource price	136.36 €	136.36 €	136.36 €	136.36 €	136.36 €	136.36 €
CO ₂ resource price decline	-4.0%	-2.0%	-4.0%	-2.0%	-1.5%	-3.0%
CO ₂ range	1.0%	1.5%	1.5%	2.5%	3.0%	2.0%
EUR/USD	1.1	1.1	1.1	1.1	1.1	1.1
Electricity price conventional	0.0700 €	0.0600 €	0.0700 €	0.1100 €	0.1500 €	0.0800 €
Electricity price increment	1.5%	1.0%	1.0%	0.5%	0.0%	1.0%
Electricity price range	0.5%	0.5%	0.5%	0.5%	3.0%	1.0%
H ₂ O price	2.00 €	2.00 €	2.00 €	2.50 €	3.00 €	2.00 €
H ₂ O price change	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
H ₂ O price range	1.0%	1.0%	1.0%	2.0%	2.0%	1.0%
Corporate income tax	0.4	0.4	0.4	0.4	0.4	0.4
Property tax	0.02	0.02	0.02	0.02	0.02	0.02
EoL Salvage	10%	10%	10%	10%	10%	10%
Labour costs FTE a Year	80000.00	40000.00	80000.00	40000.00	20000.00	80000.00
O ₂ Price	2260.00	2260.00	2260.00	2260.00	2260.00	2260.00
O ₂ price change	-1.0%	-1.0%	-1.0%	-1.0%	-1.0%	-1.0%
O ₂ price range	1.0%	1.0%	1.0%	1.0%	1.5%	1.0%
CH ₄ price	0.01 €	0.01 €	0.01 €	0.01 €	0.01 €	0.01 €
CH ₄ price change	1.2%	1.2%	1.0%	1.0%	1.0%	1.0%
CH ₄ price range	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
Biomass price	180.00	120.00	90.00	250.00	250.00	300.00
Biomass price change	1.0%	0.5%	2.0%	-1.0%	-0.5%	-2.0%
Biomass price range	1%	2%	1%	1%	3%	3%
Solar irradiance factor	55%	60%	65%	80%	100%	100%

6.3. Annex III: Time-based assumptions

Table 43 – Time-based assumptions (technology specific)

2020-2029		EUR/kW			% of capital costs										MW Cumul. Installed Capacity (MW)			Yearly scale growth			No scale growth			€/ton produced		/MW		/kWh		kWh output/kWh input		Ton in/Ton produced		Ton in/Ton produced		Ton/Ton produced CO2 Pollution of Primary process		Ton/Ton produced O2 output		Ton/Ton produced H2 Efficiency	
Technology Pathway	Technology	Capital costs	Min Cap	Max Cap	Plant Lifetime	Fixed O&M cost	Operatin g hours	Operatin g Days	Capacity factor	Min capacity	Max capacity	Learning rate	Yearly scale growth	No scale growth	Waste Disposal Costs	Labour FTE required	Labour FTE/kWh	Energy input	H2O efficiency	CO2 efficiency	Ton in/Ton produced	Ton in/Ton produced	Ton/Ton produced CO2 Pollution of Primary process	Ton/Ton produced O2 output	Ton/Ton produced H2 Efficiency																
Electrochemical AEC		1410	1128	1974		4.0%	18	250	51%	20%	80%	22000	18%	10%	7%	1.00 €	0.5	9.73E-04	65.4%	11.2%									1.6%												
Electrochemical PEMEC		2108	1686	2951		4.0%	16	250	46%	20%	70%	1000	21%	30%	20%	0.20 €	0.6	1.31E-03	62.9%	11.2%									1.6%												
Electrochemical SOEC		4820	3856	6748		5.0%	12	250	34%	15%	60%	100	28%	20%	10%	0.20 €	0.7	2.04E-03	68.0%	11.2%									1.6%												
Chemical Methanation	Artificial Leaf Power-to-methane	3000	2500	4000	20	5.0%	3	365	13%	5%	20%	0.01	20%	10%	7%	0.50 €	0.3	2.40E-03	896.0%									1.6%													
Biochemical Hydrogenation	Microalgae CO2 Hydrogenation	600	150	1350	25	5.0%	18	365	75%	40%	80%	1000	10%	7%	4%	1.00 €	0.2	2.67E-04	0	36.4%									56.3%												
Comparables MP		600	500	700	20	7.0%	18	365	75%	40%	80%	70000	10%	7%	4%	3.00 €	0.3	4.00E-04	0%	72.8%									18.9%												
Comparables SMR		600	500	700	25	7.0%	18	365	75%	40%	80%	70000	10%	7%	4%	3.00 €	0.3	4.00E-04	0%	72.8%									18.9%												
Comparables Solar PV		550	246	780	30	10.0%	18	365	75%	40%	85%	270000	10%	7%	4%	2.00 €	0.5	6.67E-04	70%	5.6%									1.1%												
Comparables Wind Power		1100	800	1450	20	2.5%	8	365	33%	20%	40%	228000	23%	17%	12%			0	0.00E+00																						
2030-2039																																									
Electrochemical AEC						5.0%	18	250	51%	25%	80%		17%	7%	5%	1.00 €	0.5	9.73E-04	68.0%	11.2%									1.6%												
Electrochemical PEMEC						5.0%	18	250	51%	25%	75%		20%	20%	10%	0.20 €	0.5	9.73E-04	67.0%	11.2%									1.6%												
Electrochemical SOEC						6.0%	16	250	46%	25%	70%		23%	30%	20%	0.20 €	0.6	1.31E-03	75.0%	11.2%									1.6%												
Chemical Methanation	Artificial Leaf Power-to-methane				20	5.0%	3.5	365	15%	5%	15%		18%	18%	13%	0.20 €	0.3	2.06E-03	896.0%									1.6%													
Biochemical Hydrogenation	Microalgae CO2 Hydrogenation				25	5.0%	18	365	75%	40%	80%		10%	6%	4%	2.00 €	0.2	2.67E-04	0	0.0%	36.4%	0.0%							50.7%												
Comparables MP					22	8.5%	8	365	33%	20%	40%		25%	20%	12%	0.30 €	0.218	6.54E-04	32%	0.0%	270.0%								0.0%												
Comparables SMR					23	7.0%	18	365	75%	40%	80%		10%	5%	3%	3.00 €	0.3	4.00E-04	0%	0.0%	72.8%	0.0%							18.9%												
Comparables Solar PV					26	7.0%	18	365	75%	40%	80%		10%	5%	3%	3.00 €	0.3	4.00E-04	0%	0.0%	72.8%	0.0%							18.9%												
Comparables Wind Power					27	10.0%	20	365	83%	40%	85%		10%	3%	2%	3.00 €	0.5	6.00E-04	70%	5.6%									1.1%												
					22	3.0%	9	365	38%	25%	43%		23%	12%	6%	- €	0	0.00E+00																							

2040-2049																			
Electrochemical AEC	6.0%	18	250	51%	25%	80%	14%	4%	2%	1.00 €	0.4	7.79E-04	70.0%	11.2%	1.6%	1.6%			
	6.0%	22	250	63%	30%	80%	17%	10%	5%	- €	0.5	7.96E-04	70.0%	11.2%	1.6%	1.6%			
	7.0%	18	250	51%	30%	80%	18%	25%	15%	- €	0.5	9.73E-04	77.0%	11.2%	1.6%	1.6%			
	20	6.0%	4	365	17%	5%	30%	15%	20%	15%	- €	0.3	1.80E-03	896.0%	1.6%	1.6%			
	25	5.0%	19	365	79%	40%	80%	10%	4%	2%	2.00 €	0.2	2.53E-04	0	0.0%	36.4%	0.0%	45.6%	
	24	10.0%	10	365	42%	25%	50%	22%	15%	10%	- €	0.218	5.23E-04	38%	0.0%	160.0%		0.0%	
	27	7.0%	18	365	75%	40%	80%	10%	4%	2%	3.00 €	0.3	4.00E-04	0%	0.0%	72.8%	0.0%	18.9%	
	27	7.0%	18	365	75%	40%	80%	10%	4%	2%	3.00 €	0.3	4.00E-04	0%	0.0%	72.8%	0.0%	18.9%	
	25	10.0%	20	365	83%	40%	85%	10%	1%	0%	4.00 €	0.5	6.00E-04	70%	5.6%		1.1%		
	25	3.5%	10	365	42%	25%	45%	15%	5%	2%	- €	0	0.00E+00						
2050-...																			
Electrochemical AEC	6.0%	18	250	51%	25%	80%	14%	0%	0%	1.00 €	0.4	7.79E-04	70.0%	11.2%	1.6%	1.6%			
	7.0%	22	250	63%	30%	80%	17%	2%	2%	- €	0.5	7.96E-04	72.0%	11.2%	1.6%	1.6%			
	8.0%	18	250	51%	30%	80%	18%	2%	2%	- €	0.5	9.73E-04	80.0%	11.2%	1.6%	1.6%			
	20	7.0%	5	365	21%	5%	45%	18%	3%	8%	- €	0.3	1.44E-03	896.0%	1.6%	1.6%			
	25	5.0%	20	365	83%	40%	80%	10%	0%	0%	2.00 €	0.2	2.40E-04	0	0.0%	36.4%	0.0%	41.0%	
	25	11.0%	14	365	58%	30%	70%	12%	3%	3%	0.20 €	0.218	3.74E-04	44%	0.0%	90.0%		0.0%	
	27	7.0%	18	365	75%	40%	80%	10%	1%	1%	4.00 €	0.3	4.00E-04	0%	0.0%	72.8%	0.0%	18.9%	
	27	7.0%	18	365	75%	40%	80%	10%	1%	1%	4.00 €	0.3	4.00E-04	0%	0.0%	72.8%	0.0%	18.9%	
	25	10.0%	20	365	83%	40%	85%	10%	-2%	-2%	5.00 €	0.5	6.00E-04	70%	5.6%		1.1%		
	25	3.5%	10	365	42%	28%	45%	10%	2%	2%	- €	0	0.00E+00						

6.4. Annex IV: Selection of patents from the patent analysis for the solar thermochemical reactor, biohybrid system, and microalgae

UNIV NORTH CHINA ELECTRIC POWER A thermo-chemical hydrogen production reaction performance evaluation system and method based on solar light simulator		✓ Alive
Title DWPI: Thermochemical hydrogen production reaction performance evaluation system based on solar concentrating simulator includes raw material feeding section, evaporator/pre-heater, micro multichannel reactor and chromatograph		
Publication number (Kind Code): CN110407171A		
Publication Date: November 5 th , 2019		
Current IPC: C01B000332; C01B000338; G01N003002 ; G01N003086		
Abstract A thermochemical hydrogen production reaction performance evaluation system based on solar concentrating simulator comprises raw material feeding section, evaporator/pre-heater, micro multichannel reactor (24), condenser (6), chromatograph (9), flow pipeline system and solar light simulator. The raw material feeding section comprises liquid input section and gas input section. The evaporator/pre-heater is set with spraying device. The micro multichannel reactor, evaporator/pre-heater and condenser are connected through high temperature resistant pipeline. The chromatograph is equipped with computer control center. The flow pipeline system comprises check valve (2), flow meter (3) and connecting pipeline. The solar light simulator comprises high power xenon lamp light source and high reflectivity elliptical reflector. An INDEPENDENT CLAIM is included for thermochemical hydrogen production reaction performance evaluation method based on solar concentrating simulator. A thermochemical hydrogen production reaction performance evaluation system based on solar concentrating simulator. The drawing shows a schematic diagram of thermochemical hydrogen production reaction performance evaluation system based on solar concentrating simulator. (2) Check valve; (3) Flow meter; (6) Condenser; (9) Chromatograph; (24) Micro multichannel reactor.		
Novelty A thermochemical hydrogen production reaction performance evaluation system based on solar concentrating simulator comprises raw material feeding section, evaporator/pre-heater, micro multichannel reactor (24), condenser (6), chromatograph (9), flow pipeline system and solar light simulator. The raw material feeding section comprises liquid input section and gas input section. The evaporator/pre-heater is set with spraying device. The micro multichannel reactor, evaporator/pre-heater and condenser are connected through high temperature resistant pipeline. The chromatograph is equipped with computer control center. The flow pipeline system comprises check valve (2), flow meter (3) and connecting pipeline. The solar light simulator comprises high power xenon lamp light source and high reflectivity elliptical reflector.		

INHA UNIVERSITY
Apparatus for producing hydrogen using solar thermochemistry

✓ Alive

Title DWPI:

Apparatus useful for producing solar thermochemical hydrogen, comprises an inert gas supply line for supplying inert gas, a thermal oxidation line for thermal oxidation reaction, and a water splitting line for water decomposition reaction

Publication number (Kind Code):

KR1594665B1

Publication Date:

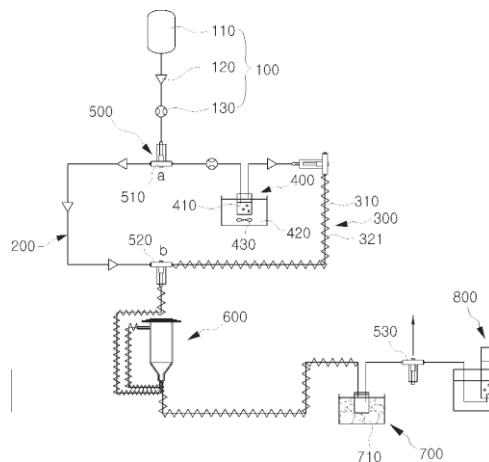
February 29th, 2016

Current IPC:

B01J000700;

B01J001918;

C01B000310



Abstract

Apparatus comprises an inert gas supply line (100) for supplying an inert gas, a thermal oxidation line (200) for thermal oxidation reaction, a water splitting line (300) for water decomposition reaction, branched from a first branch point of the thermal oxidation line, and joint from a second branch point of the thermal oxidation line, a steam supply unit (400) for supplying steam, a switching valve (500) for alternatively switching the water decomposition line and the thermal oxidation line, and a reactor for generating hydrogen using solar radiation energy and flowing steam and inert gas. Apparatus comprises an inert gas supply line (100) for supplying an inert gas, a thermal oxidation line (200) for thermal oxidation reaction, branched from the inert gas supply line, a water splitting line (300) for water decomposition reaction, branched from a first branch point of the thermal oxidation line, and joint from a second branch point of the thermal oxidation line, a steam supply unit (400) for supplying steam, connected to the water splitting line, a switching valve (500) for alternatively switching the water decomposition line and the thermal oxidation line, located on the first branch point with the second branch point, and a reactor for generating hydrogen using solar radiation energy and flowing steam and inert gas through the supply line, connected to the second branch point. The reactor is segmented as a front first internal space and a rear second internal space having metal oxide supported porous materials in an interior side. The supply line is provided with a first supply line for supplying the inert gas with steam in the second inner space, connected with the second internal space of the reactor, connected to other end of the first branch point, and a second supply line for supplying the inert gas and the steam in the first internal space, and heat exchanger in the second inner space, connected to first internal space of the reactor, and the second internal space. The apparatus is useful for producing solar thermochemical hydrogen (claimed). The apparatus improves reliability of reactor, degradation of reactive porous medium, reduces hydrogen production and improves reactivity, and has long service life. Preferred Components: The inert gas is nitrogen. Preferred Components: The reactor has a main body provided with a first connector connected with the first supply line, located backwardly to the second inner space, forwardly to the first inner space by the carrying member, opened from front side, a second connector connected to the second supply line, and a discharge port, a window made of transparent material for entering sunlight in the first inner space, bonded to front of the main body, and plate shaped concentrator for condensing the sunlight into the window, provided on one side of the window. The apparatus further comprises a water trap for collecting and converting steam discharged from the reactor in water, provided on a discharge line and connected to the discharge port, and a hydrogen generation unit for collecting or storing hydrogen gas discharged from the water trap, an heat insulating member located on outside of the reactor. The diagram shows a schematic representation of the apparatus for producing solar thermochemical hydrogen. (100) Inert gas supply line; (200) Thermal oxidation line; (300) Water decomposition line; (400) Steam supply unit; (500) Switching valve

Novelty

Apparatus comprises an inert gas supply line (100) for supplying an inert gas, a thermal oxidation line (200) for thermal oxidation reaction, a water splitting line (300) for water decomposition reaction, branched from a first branch point of the thermal oxidation line, and joint from a second branch point of the thermal oxidation line, a steam supply unit (400) for supplying steam, a switching valve (500) for alternatively switching the water decomposition line and the thermal oxidation line, and a reactor for generating hydrogen using solar radiation energy and flowing steam and inert gas.

Advantages

The apparatus improves reliability of reactor, degradation of reactive porous medium, reduces hydrogen production and improves reactivity, and has long service life.

INHA UNIVERSITY
Reactor for producing hydrogen using solar thermochemistry

✓ Alive

Title DWPI:

Reactor useful to produce solar energy thermochemical hydrogen, comprises a main body formed with an inner space for accommodating energy during solar radiation, and a carrying member placed inside the inner space for generating hydrogen

Publication number (Kind Code):

KR1567190B1

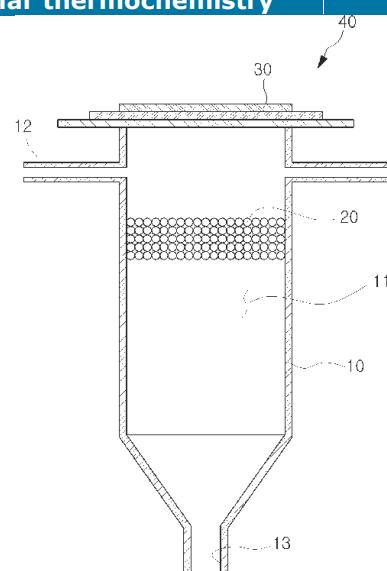
Publication Date:

November 16th, 2015

Current IPC:

B01J001924;

C01B000310



Abstract

Reactor comprises a main body (100) formed with an inner space (110) for accommodating energy during solar radiation, an inlet port (121) for introducing working fluid into one side of the inner space, and an outlet port (130) for discharging the working fluid heated by the energy during solar radiation from the other side of the inner space; and a carrying member (200) arranged inside the inner space for generating hydrogen using the solar radiation energy and is surface coated with metal oxide. Reactor comprises a main body (100) formed with an inner space (110) for accommodating energy during solar radiation, an inlet port (121) for introducing working fluid into one side of the inner space, and an outlet port (130) for discharging the working fluid heated by the energy during solar radiation from the other side of the inner space; and a carrying member (200) arranged inside the inner space for generating hydrogen using the solar radiation energy and is surface coated with metal oxide. The carrying member comprises a first carrying member placed at the central portion for concentrating the solar energy, and a second carrying member arranged along the periphery of the first carrying member and is made of a material having thermal conductivity higher than the first carrying member. The reactor is useful for producing solar energy thermochemical hydrogen (claimed). The reactor uniformly induces vigorous reactions and, ensures uniform heat delivery, and increases hydrogen production amount. Preferred Components: The main body comprises a cylindrical first main body having inner circumferential surface coupled to the carrying member and is arranged along the outer circumferential surface of the inlet port, a window made of transparent material to enable entering of the sunlight and is coupled to the front surface of the main body, and a second main body coupled to the rear end of the main body and the outlet port and is formed with a funnel-shaped opening at the upper surface. The first the carrying member is disc-shaped and is made of ceramic-based material. The second carrying member is made of metallic material and is combined with the first carrying member and is placed on a penetrating portion formed corresponding to the shape of the first carrying member. The reactor further comprises a heat insulating member placed outside the reactor. The drawing shows a schematic representation of the reactor. (100) Main body; (110) Inner space; (121) Inlet port; (130) Outlet port; (200) Carrying member

Novelty

Reactor comprises a main body (100) formed with an inner space (110) for accommodating energy during solar radiation, an inlet port (121) for introducing working fluid into one side of the inner space, and an outlet port (130) for discharging the working fluid heated by the energy during solar radiation from the other side of the inner space; and a carrying member (200) arranged inside the inner space for generating hydrogen using the solar radiation energy and is surface coated with metal oxide.

Advantages

The reactor uniformly induces vigorous reactions and, ensures uniform heat delivery, and increases hydrogen production amount.

Title DWPI:

Catalyst for thermochemical generation of hydrogen from water and/or thermochemical generation of carbon monoxide from carbon dioxide comprises solid solution of cerium dioxide and uranium dioxide

Publication number (Kind Code):

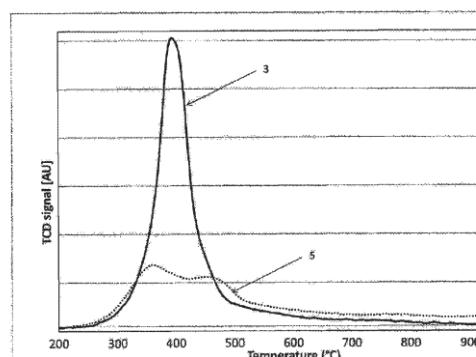
US9675961B2

Publication Date:

June 13th, 2016

Current IPC:

B01J002312;	B01J002106;	B01J002310;
B01J003500;	B01J003502;	B01J003510;
B01J003703;	B01J003708;	B01J003710;
B01J003712;	B01J003716;	C01B000304;
C01B000306; C01B003240		



Abstract

Catalyst for thermochemical generation of hydrogen from water and/or thermochemical generation of carbon monoxide from carbon dioxide comprises a solid solution of cerium dioxide and uranium dioxide. INDEPENDENT CLAIMS are included for: solid solution comprising cerium dioxide, uranium dioxide and zirconium dioxide, where the amount of zirconium dioxide is at most 40 mol.% based on the total amount of cerium dioxide, uranium dioxide and zirconium dioxide; method for producing the solid solution involving dissolving a cerium salt, a uranium salt and optionally a zirconium salt in water followed by precipitation at a pH of at least 8 by addition of a base; a method for producing the catalyst involving the method for producing the solid solution followed by drying the obtained precipitate and calcining the precipitate at elevated temperature; a method for generation of hydrogen from water and/or generation of carbon monoxide from carbon dioxide involving: (a) providing the catalyst; (b) reducing at least part of the catalyst at a first elevated temperature; and (c) oxidizing the at least partially reduced catalyst of step (b) by contacting the at least partially reduced catalyst with water and/or carbon dioxide at a second elevated temperature which may be the same or different from the first elevated temperature; and a reactor for generating hydrogen and/or carbon monoxide comprising a reaction zone comprising the catalyst, means for heating the reaction zone, means for introducing gasses into the reaction zone and means for extracting gasses from the reaction zone. The catalyst is useful for thermochemical generation of hydrogen from water and/or thermochemical generation of carbon monoxide from carbon dioxide. The solid solution of cerium dioxide and uranium dioxide is useful as catalyst for the thermochemical generation of hydrogen from water and/or the thermochemical generation of carbon monoxide from carbon dioxide (all claimed). Catalyst is provided for thermochemical generation of hydrogen based on metal oxide reduction and oxidation cycles where the amount of energy that is required for the reduction of the catalyst is relatively low. When in use, the catalyst results in relatively high yield of hydrogen formation. Preferred Composition: A molar ratio of cerium and uranium is from 50 to 0.05, preferably from 10 to 0.1, more preferably from 10 to 1. The solid solution further contains zirconium dioxide in an amount of at most 40.0 mol% based on the total amount of cerium dioxide, uranium dioxide and zirconium dioxide. A total amount of cerium dioxide, uranium dioxide and optionally zirconium dioxide in the solid solution is at least 95.0wt%, preferably at least 99.0 wt%, more preferably at least 99.9 wt% based on the weight of the solid solution. Preferred Component: The solid solution has a fluorite crystal structure. Preferred Conditions: The second elevated temperature is lower than the first elevated temperature. The first elevated temperature is from 600° C to 1200° C, preferably from 1000° C to 1200° C. The second elevated temperature is from 600° C to 1000° C, preferably from 600° C to 900° C. The first and/or second elevated temperature is obtained by heating using solar energy.

Novelty

Catalyst for thermochemical generation of hydrogen from water and/or thermochemical generation of carbon monoxide from carbon dioxide comprises a solid solution of cerium dioxide and uranium dioxide.

Advantages

Catalyst is provided for thermochemical generation of hydrogen based on metal oxide reduction and oxidation cycles where the amount of energy that is required for the reduction of the catalyst is relatively low. When in use, the catalyst results in relatively high yield of hydrogen formation.

MILLENNIUM CELL INC.
Thermochemical hydrogen produced from a vanadium decomposition cycle

✓ Alive

Title DWPI:

Producing hydrogen comprises decomposing metal halide compound to reduce metal in metal halide compound from initial valence state to lower valence state, separating oxygen and acid and reacting acid and reduced metal halide

Publication number (Kind Code):

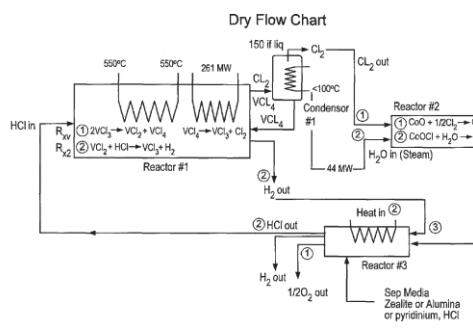
US8287838B2

Publication Date:

October 16th, 2012

Current IPC:

C01G002302; B01J000702; B01J000804;
 B01J000810; B01J001912; B01J001918;
 B01J001920; C01B000300; C01B000306;
 C01B000308; C01B000352; C01B000701;
 C01B000703; | C01B000704; C01B001302



Abstract

Producing hydrogen comprises: decomposing a metal halide compound (MX) using heat and in the presence of a catalyst to reduce the metal (M) in MX from an initial valence state to a lower valence state, where a gas is formed, then the gas is reacted with water in the presence of an acid-absorbing material to form oxygen and an acidic compound, the acid compound is formed by an acid and the acid absorbing material; separating the oxygen; separating the acid from the acid absorbing material; and reacting the acid and the reduced metal halide to produce hydrogen and MX. Producing hydrogen comprises: decomposing a metal halide compound (MX) using heat in the presence of a catalyst to reduce the metal (M) in MX from an initial valence state to a lower valence state; where a gas is formed, then the gas is reacted with water in the presence of an acid-absorbing material to form oxygen and an acidic compound, the acid compound is formed by an acid and the acid absorbing material; separating the oxygen; separating the acid from the acid absorbing material; and reacting the acid and the reduced metal halide to produce hydrogen and MX, where MX is vanadium trichloride, and the catalyst is capable of lowering the decomposition temperature of vanadium trichloride. The method is useful for producing hydrogen (claimed), which is useful as a fuel or a feedstock to make methane. The process: is economical, and eco friendly; and saves energy. Preferred Process: The process is a dry process. In the process: at least one of the reactions is a wet reaction; operated as a batch process, or continuous process; solar power is used as a source of heat for at least one of the reactions; and a first portion of the second salt forming the double salt: is sodium, potassium, vanadium, chromium, niobium, titanium, molybdenum, manganese, iron; or is different than M; and a second portion of the second salt forming the double salt: is chlorine, bromide or iodine; and is the same as X. The heat used in: all reactions is at a temperature equal to or lower than the temperature of the heat used in reducing MX to a lower valence state; all reactions is at 600° C or below; and reducing MX to a lower valence state is at 400° C or below. The process further comprises feeding the produced hydrogen into: an integrated gas combination cycle; a gas turbine to generate electricity; a process for generating natural gas from coal; and a process for refining crude oil. Preferred Components: The catalyst is: lead (IV) chloride, antimony pentachloride, chromium (IV) chloride, manganese (IV) chloride, cobalt (III) chloride, potassium nickel tetrachloride (KNiCl₄), nickel (III) chloride, bismuth pentachloride, iron (III) chloride(preferred), or copper (II) Chloride; used in reacting the gas with water and acid-absorbing material; and a cobalt catalyst or a copper catalyst. The acid absorbing material is: capable of regenerating by heat; a polymer having an active amine group, amines, or compounds that form a hydrogen halide salt; and monoethanolamine, diethanolamine, triethanolamine, melamine, zeolites, charcoals, silicas, alumina, magnesia or compounds that have any functionality that can reversibly absorb acid gas. The source of heat for at least one of the reactions is exhaust from a gas turbine, flue gases, waste heat from any chemical reactions, where heat is available, foundry cooling processes, burning of off-gases from a refinery, and oil and natural gas well, intentional burning of lower British thermal unit (BTU) gases which produce a lower flame temperature than pure fuels, and the burning of any fuels for the purpose of generating hydrogen and oxygen. The X is chlorine, bromine and iodine. The MX is in the form of a double salt comprising a second salt. M is vanadium, chromium, niobium, titanium, molybdenum, manganese or iron.

Novelty

Producing hydrogen comprises: decomposing a metal halide compound (MX) using heat and in the presence of a catalyst to reduce the metal (M) in MX from an initial valence state to a lower valence state, where a gas is formed, then the gas is reacted with water in the presence of an

acid-absorbing material to form oxygen and an acidic compound, the acid compound is formed by an acid and the acid absorbing material; separating the oxygen; separating the acid from the acid absorbing material; and reacting the acid and the reduced metal halide to produce hydrogen and MX

Advantages

The process: is economical, and eco friendly; and saves energy.

JAPAN ATOMIC ENERGY AGENCY The thermochemistry hydrogen production method		✓ Alive
Title DWPI: Thermochemistry hydrogen production involves forming sulfuric acid phase and hydrogen iodides phase, separating formed sulfuric acid phase and hydrogen iodides phase, and purifying impurity using reactive stripping gas		
Publication number (Kind Code): JP2011219331A		
Publication Date: November 4 th , 2011		
Current IPC: C01B000302		
Abstract A thermochemistry hydrogen production method involves forming sulfuric acid phase and hydrogen iodides phase from by Bunsen reaction from water as raw material, separating formed sulfuric acid phase and hydrogen iodides phase, purifying impurity contained in sulfuric acid phase and hydrogen iodides phase using reactive stripping gas, and manufacturing hydrogen by hydrogen iodide decomposition reaction from purified hydrogen iodides. The reactive stripping gas is mixed gas which consists of oxygen and inert gas. A thermochemistry hydrogen production method. The method is excellent in hydrogen production efficiency. Preferred Components: The inert gas is inert gas containing nitrogen, helium, and/or argon. The drawing shows a schematic diagram of purification process of sulfuric acid phase and hydrogen iodides phase in iodine-sulfur-water material manufacture cycle. (203) Stripping column; (204) Temperature control device; (205) Product tank; (206) Stripping gas holder; (207) Flowmeter		
Novelty A thermochemistry hydrogen production method involves forming sulfuric acid phase and hydrogen iodides phase from by Bunsen reaction from water as raw material, separating formed sulfuric acid phase and hydrogen iodides phase, purifying impurity contained in sulfuric acid phase and hydrogen iodides phase using reactive stripping gas, and manufacturing hydrogen by hydrogen iodide decomposition reaction from purified hydrogen iodides. The reactive stripping gas is mixed gas which consists of oxygen and inert gas.		
Advantages The method is excellent in hydrogen production efficiency.		

Title DWPI:

Artificial photosynthesis system for producing carbon-based chemical compound, has microorganism that includes metabolic pathway which reduces carbon dioxide and generates carbon-based compound using electrons or hydrogen

Publication number (Kind Code):

US10160980B2

Publication Date:

2018-12-25

Current IPC:

C12M000100 | C12P000502 | C12P000754 |
C25B000100 | C25B000110 | C25B000908 |
C25B001102 | C25B001104

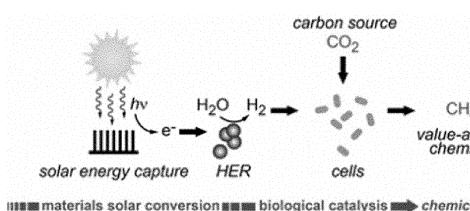


FIG. 1A

Abstract

The system (100) has a membrane that separates a photoanode chamber (105) and a photocathode chamber (110). A photoanode assembly (127) oxidizes water to generate oxygen, protons, and electrons, and permeates to the protons and allows the protons to travel to the photocathode chamber. An electrical connection provides electrons to a photocathode assembly (137). A microorganism (145) arranged in the photocathode chamber has a metabolic pathway which reduces carbon dioxide and generates a carbon-based compound using the electrons or hydrogen formed by two protons. An electrical connection (140) is adapted to electrically connect the photoanode assembly comprising multiple nanostructures located on one substrate (125), and the photocathode assembly comprising multiple nanostructures located on other substrate (135). One nanostructure comprises titanium oxide, and other nanostructures comprise silicon and indium phosphide. The microorganism comprises *Sporomysa ovata* and *Methansarcina barkeri*, and the carbon-based compound comprises acetate and methane. The microorganism is selected from a group consisting of bacteria and archaea. The microorganism comprises an archaea belonging to the genus *Methansarcina* and a bacteria belonging to the genus *Sporomysa*. The microorganism is located on other nanostructures of the photocathode assembly. The photoanode assembly, the photocathode assembly, the membrane, and the microorganism are arranged in water when the system is in operation. The water has about 0.5 grams/liter to 30 grams/liter of a salt dissolved in the water. The photocathode chamber includes an inlet (150) operable to allow the carbon dioxide to flow through the water and be dissolved in the water and an outlet (155) operable to allow a portion of the carbon dioxide not dissolved in the water to flow out of the photocathode chamber. One nanostructure comprises multiple nanowires (120) which are arranged on one substrate with an end of each of the nanowires in contact with one substrate such that a length of each of the nanowires forms an angle with the substrate of about 45-90°. A UV light filter (160) is positioned to block UV light from irradiating the photocathode assembly. The membrane is impermeable to oxygen and oxygen radicals. The photocathode assembly is coated with an oxide layer and a metal layer. The photoanode assembly comprises an n-type semiconductor, and a p-type semiconductor. The n-type semiconductor has a larger band gap than the p-type semiconductor. An INDEPENDENT CLAIM is included for a method for producing a carbon-based chemical compound which involves arranging a microorganism in the photocathode chamber. The photoanode assembly and the photocathode assembly are irradiated with a light. The protons are traveled through the membrane to the photocathode chamber. The carbon-based compound is formed with the microorganism using the electrons or hydrogen formed by two protons. The photoanode assembly comprises an n-type semiconductor and a p-type semiconductor. Artificial photosynthesis system for producing carbon-based chemical compound. The materials component performs water splitting to generate hydrogen and the biological component uses the reducing equivalents for carbon dioxide fixation. The biological catalysts operate at near thermodynamic potential. The overpotential is associated with hydrogen evolution from water, and a more facile reaction to catalyze through sustainable electrochemical and photochemical unit compared with carbon dioxide reduction. The integration between materials science and biology separates the demanding dual requirements for light-capture efficiency and catalytic activity, respectively, and a route is provided to bridge efficient solar conversion in robust solid-state devices with the broad synthetic capabilities of living cells.

Novelty

The system (100) has a membrane that separates a photoanode chamber (105) and a photocathode chamber (110). A photoanode assembly (127) oxidizes water to generate oxygen, protons, and electrons, and permeates to the protons and allows the protons to travel to the photocathode chamber. An electrical connection provides electrons to a photocathode assembly (137). A microorganism (145) arranged in the photocathode chamber has a metabolic pathway

which reduces carbon dioxide and generates a carbon-based compound using the electrons or hydrogen formed by two protons.

Advantages

The materials component performs water splitting to generate hydrogen and the biological component uses the reducing equivalents for carbon dioxide fixation. The biological catalysts operate at near thermodynamic potential. The overpotential is associated with hydrogen evolution from water, and a more facile reaction to catalyze through sustainable electrochemical and photochemical unit compared with carbon dioxide reduction. The integration between materials science and biology separates the demanding dual requirements for light-capture efficiency and catalytic activity, respectively, and a route is provided to bridge efficient solar conversion in robust solid-state devices with the broad synthetic capabilities of living cells.

HARVARD UNIVERSITY Carbon fixation systems and methods		✓ Alive
Title DWPI:	Fixing carbon using bacteria to produce product, comprises splitting water using cathode and anode in solution having chemolithoautotrophic bacteria to form hydrogen and oxygen, providing carbon dioxide, and limiting bioavailable nitrogen	
Publication number (Kind Code):	US20200255870A1	
Publication Date:	2020-08-13	
Current IPC:	C12P000702 C25B000104 C25B000304 C25B001104 C25B001508	
Abstract	<p>Fixing carbon using bacteria to produce a product, comprises: splitting water using a cathode including a cobalt-phosphorus alloy and an anode including cobalt phosphate in a solution containing a chemolithoautotrophic bacteria to form hydrogen and oxygen in the solution; providing carbon dioxide in the solution; and limiting bioavailable nitrogen in the solution to below a threshold nitrogen concentration to cause the chemolithoautotrophic bacteria to produce a product. INDEPENDENT CLAIMS are also included for: a system comprising a reactor chamber with a solution contained, where the solution includes hydrogen, carbon dioxide, bioavailable nitrogen, and a chemolithoautotrophic bacteria, and a pair of electrodes that split water contained within the solution to form the hydrogen, where the pair of electrodes comprise a cathode including a cobalt-phosphorus alloy and an anode including cobalt phosphate and a concentration of the bioavailable nitrogen in the solution is below a threshold nitrogen concentration to cause the chemolithoautotrophic bacteria to produce a product; and a chemolithoautotrophic bacterium, where the bacterium is resistant to reactive oxygen species. The method is useful for fixing carbon using bacteria to produce a product. The method utilizes the electrode pair that removes extracted metal ions from the cathode by depositing them onto the anode which maintains extraneous cobalt ions at low concentrations within solution and delivers low applied electrical potential to split water to generate hydrogen. Preferred Method: The method further comprises: continuously bubbling carbon dioxide through the solution; maintaining an isolated gas volume above a surface of the solution within a head space of a reactor chamber; replenishing the isolated gas volume to an original composition for at least one time interval. Splitting of the water is controlled to generate hydrogen at a rate equal to a rate of hydrogen consumption by the bacteria. Preferred Components: The chemolithoautotrophic bacteria is: a Ralstonia eutropha bacteria; and resistant to reactive oxygen species. The chemolithoautotrophic bacteria have been engineered to produce: an alcohol; or at least one of a fatty acid, an alkane, a polyhydroxyalkanoate or an amino acid. Preferred Components: The solution includes a phosphate. Preferred Components: The</p>	

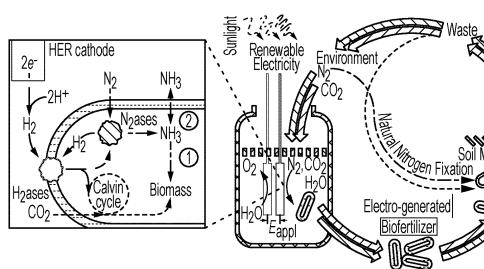
system further comprises: an inlet to the reactor chamber, where the inlet is in fluid communication with a source of carbon dioxide that is continuously bubbled through the solution; and an isolated gas volume above a surface of the solution within a head space of a reactor chamber. Preferred Components: The product is: an alcohol; or at least one of a fatty acid, an alkane, a polyhydroxyalkanoate or an amino acid. The isolated gas volume comprises primarily carbon dioxide.

Novelty

Fixing carbon using bacteria to produce a product, comprises: splitting water using a cathode including a cobalt-phosphorus alloy and an anode including cobalt phosphate in a solution containing a chemolithoautotrophic bacteria to form hydrogen and oxygen in the solution; providing carbon dioxide in the solution; and limiting bioavailable nitrogen in the solution to below a threshold nitrogen concentration to cause the chemolithoautotrophic bacteria to produce a product.

Advantages

The method utilizes the electrode pair that removes extracted metal ions from the cathode by depositing them onto the anode which maintains extraneous cobalt ions at low concentrations within solution and delivers low applied electrical potential to split water to generate hydrogen.

HARVARD UNIVERSITY Biofertilizer and methods of making and using same		✓ Alive
Title DWPI:	Producing a biofertilizer in a bioreactor, involves generating hydrogen in a bioreactor comprising microorganisms which express a hydrogenase and a nitrogenase, and growing the microorganisms in the bioreactor in culture media	
Publication number (Kind Code):	US20200102254A1	
Publication Date:	2020-04-02	
Current IPC:	C05F001720 C05F001108 C25B000100 C25B000104 C25B001104	
Abstract	<p>Biofertilizer is produced in a bioreactor, by: (a) generating hydrogen (H_2) in a bioreactor comprising microorganisms which express a hydrogenase and a nitrogenase, where the bioreactor further comprises a source of nitrogen (N_2) and carbon dioxide (CO_2); and (b) growing the microorganisms in the bioreactor in culture media in the presence of the H_2 to produce a biofertilizer. INDEPENDENT CLAIMS are included for: (1) a biofertilizer prepared by the method above; or a biofertilizer comprising an amount of <i>Xanthobacter autotrophicus</i> for enhancing a soil microbiome and for increasing crop yields and optionally following microorganisms below; (2) enriching a soil microbiome which involves contacting a soil microbiome with the biofertilizer prepared by the method above; (3) increasing the yield of a crop grown in soil, which involves treating the soil with the biofertilizer prepared by the method above; (4) a system for generating a biofertilizer, comprising a bioreactor, culture medium, a source of H_2 generated by water-splitting, and a culture of microorganisms which express a hydrogenase and a nitrogenase and are capable of metabolically coupling H_2 - oxidation with nitrogen-fixation to produce NH_3; (5) a plant seed comprising a coating of an amount of <i>X. autotrophicus</i> and optionally of the following microorganisms below; or a plant seed comprising a coating of an amount of the biofertilizer; (6) improving crop yield which involves preincubating a plant seed with an amount of <i>X. autotrophicus</i> or the biofertilizer before sowing the plant seed; and (7) an engineered soil for growing plants or crops comprising naturally-occurring soil mixed with a biofertilizer comprising <i>X. autotrophicus</i> and optionally microorganisms below; or an engineered soil for growing plants or crops comprising naturally-occurring soil mixed with the biofertilizer. Fertilizer. No biological data given. None given. The methods are useful for producing biofertilizer in bioreactor; for enriching a soil microbiome; for increasing the yield of crop grown in soil; and for improving crop yield (all claimed). The method results in enhanced plant characteristic as compared to crop growth without the treatment (claimed). The bioreactor system can conduct distributed nitrogen fixation with renewable electricity to produce an engineered biofertilizer enriched in ammonia and carbon, and to the use of the biofertilizer to enrich soils and/or soil microbiomes, and to enhance crop yields and other characteristics. Preferred Method: In producing biofertilizer in bioreactor, the microorganisms couple hydrogenase-dependent H_2 -oxidation with nitrogenase-dependent N_2 fixation to form ammonia (NH_3). The microorganisms assimilate the NH_3 into biomass intracellularly by glutamine synthetase. The method further involves inhibiting glutamine synthetase, thus inhibiting the</p>	

assimilation of NH₃ into biomass. The NH₃ accumulates extracellularly in the bioreactor culture media. The microorganisms couple hydrogenase-dependent H₂ -oxidation with CO₂ reduction through a carbon fixation pathway. Generating H₂ in the bioreactor is by water-splitting, where the water-splitting is powered by electricity or renewable electricity or solar-based electricity. The method further involves obtaining the biomass for use as a biofertilizer. Enriching soil microbiome involves mixing the biofertilizer with soil; and contacting the soil microbiome with polyhydroxybutyric acid (PHB)-producing bacteria; or contacting the soil microbiome with a microorganism which expresses both a nitrogenase and accumulates PHB. Increasing the yield of crop grown in soil involves mixing the soil with the biofertilizer; and contacting the soil with PHB-producing bacteria. The source of H₂ generated by water-splitting is generated by renewable electricity, where the renewable electricity is provided by solar power. The H₂ is generated by a water-splitting device comprising a least one pair of hydrogen-splitting electrodes and a source of solar-generated electricity. Preferred Components: The biofertilizer comprises a microbial biomass and culture media. It is enriched with ammonia and/or a carbon energy source. The microbial biomass is a liquid microbial suspension. It is a solid microbial biomass. The hydrogenase and a nitrogenase are expressed from the same or different microorganism cells. The N₂ and CO₂ are obtained from the environment. The catalyst is capable of minimizing the production of reactive oxygen species (ROS) during water-splitting. The glutamine synthetase is inhibited by an inhibitor, where the inhibitor is methionine sulfoximine or phosphinothricin. The biofertilizer is a liquid suspension. NH₃ is produced intracellularly and assimilates into biomass. The system further comprises an inhibitor of glutamine synthetase. The NH₃ accumulates extracellular in the culture media. The biofertilizer further comprises PHB-producing microorganism. The engineered soil further comprises R. eutropha or another PHB-producing microorganism. Preferred Microorganism: The microorganisms accumulate a carbon energy source, where the carbon energy source is PHB. The microorganisms are of a single type, or two or more types. The biofertilizer comprises X. autotrophicus . The microorganisms comprise bacteria. Preferably, the microorganisms comprise archaea. The microorganisms comprise fungi. The biofertilizer comprises microorganisms comprising Acidiphilum species, Acidiphilum multivorum , Alcaligenes species, Alcaligenes paradoxus , Arthrobacter species, Azohydromonas species, Azohydromonas australica , Azohydromonas species, Azohydromonas lata , Azospirillum species, Azospirillum amazonense , Azospirillum lipoferum , Azospirillum lipoferum , Azospirillum thiophilum , Azospirillum thiophilum , Beggiatoa species, Beggiatoa alba , Beijerinckia species, Beijerinckia mobilis , Bradyrhizobium species, Bradyrhizobium elnakii , Bradyrhizobium japonicum , Bradyrhizobium japonicum (strain USDA 122), Burkholderia species, Burkholderia vietnamensis , Cupriavidus species, Cupriavidus necator , Derxia species, Derxia gummosa , Herbaspirillum species, Herbaspirillum autotrophicum , Hydrogenophaga species, Hydrogenophaga pseudoflava , Mesorhizobium species, Mesorhizobium alhagi , Methylibium species, Methylibium petroleophilum , Methylocapsa species, Methylocapsa aurea , Methyloferula species, Methyloferula stellate , Methyloversatilis species, Methyloversatilis universalis , Microcyclus species, Microcyclus aquaticus , Microcyclus species, Microcyclus ebruneus , Nitrosococcus species, Nitrosococcus oceanii , Nitrosomonas communis , Nitrospirillum amazonense , Nocardia species, Nocardia autotrophica , Nocardia opaca , Oligotropha species, Oligotropha carboxidovorans , Pannonibacter species, Pannonibacter phragmitetus , Paracoccus species, Paracoccus denitrificans , Paracoccus pantrophus , Paracoccus yeei , Pelagibaca species, Pelagibaca bermudensis , Pseudomonas species, Pseudomonas facilis , Pseudoceanicola species, Pseudoceanicola atlanticus , Ralstonia species, Ralstonia eutropha , Renobacter species, Renobacter vacuolatum , Rhizobium species, Rhizobium gallicum , Rhizobium japonicum , Rhodobacter species, Rhodobacter capsulatus , Rhodobacter sphaeroides , Rhodomicrobium species, Rhodomicrobium vannielii , Rubrivivax species, Rubrivivax gelatinosus , Salipiger species, Salipiger mucosus , Sinorhizobium species, Sinorhizobium americanum , Sinorhizobium fredii , Sinorhizobium meliloti , Skermanella species, Skermanella stibiiresistens , Stappia species, Stappia aggregate , Thauera species, Thauera humireducens , Variovorax species, Variovorax paradoxus , Xanthobacter species, and Xanthobacter autotrophicus , and its combinations. The PHB-producing bacterium is Ralstonia eutropha . The microorganism is X. autotrophicus . The microorganisms undergo growth in the bioreactor to form a biomass. Preferred Device: The bioreactor is a single or a multi-chamber bioreactor. The bioreactor comprises a unit to obtain the N₂ and CO₂ from the environment. It comprises an anode and a cathode capable of catalyzing water-splitting. The bioreactor further comprises a source of N₂ and CO₂ . Preferred Crop: The crop is wheat, corn, soybean, rice, potatoes, sweet potatoes, cassava, sorghum, yams, or plantains. Preferred Seed: The plant seed is a radish plant seed. It is a wheat, corn, soybean, rice, potato, sweet potato, cassava, sorghum, yams, radish, or plantain plant seed. Preferred Device: The anode is an oxygen evolving electrode (OER). The cathode is a hydrogen evolving electrode (HER). The anode and/or the cathode are coated with a catalyst. The cathode comprises a cobalt-phosphorus (Co-P) alloy catalyst. The anode comprises a cobalt-phosphate (Co-Pi) catalyst. The bioreactor comprises electrodes comprising Co-Pi and Co-P water-splitting catalysts. Preferred Parameter: The electricity comprises a voltage of 0.1-100.0 V.

Novelty

Biofertilizer is produced in a bioreactor, by: (a) generating hydrogen (H₂) in a bioreactor comprising microorganisms which express a hydrogenase and a nitrogenase, where the bioreactor further comprises a source of nitrogen (N₂) and carbon dioxide (CO₂); and (b)

growing the microorganisms in the bioreactor in culture media in the presence of the H₂ to produce a biofertilizer.

Advantages

The method results in enhanced plant characteristic as compared to crop growth without the treatment (claimed). The bioreactor system can conduct distributed nitrogen fixation with renewable electricity to produce an engineered biofertilizer enriched in ammonia and carbon, and to the use of the biofertilizer to enrich soils and/or soil microbiomes, and to enhance crop yields and other characteristics.

HARVARD UNIVERSITY Ammonia synthesis methods and systems		✓ Alive
Title DWPI:	Artificial photosynthesis system for producing carbon-based chemical compound, has microorganism that includes metabolic pathway which reduces carbon dioxide and generates carbon-based compound using electrons or hydrogen	
Publication number (Kind Code):	EP3481770A4	
Publication Date:	2020-01-22	
Current IPC:	C01C000104 C01C000108 C12N000120 C12P000300 C12P001300 C25B000104 C25B001104 C12R000101	
Abstract	Method for producing ammonia involves dissolving hydrogen, carbon dioxide and nitrogen in a solution, and placing a glutamine synthetase inhibitor and autotrophic diazotroph bacteria in the solution. An INDEPENDENT CLAIM is included for a system for producing ammonia, comprising a reactor chamber with a solution, where the solution comprises dissolved hydrogen, carbon dioxide, nitrogen, glutamine synthetase inhibitor and autotrophic diazotroph bacteria. The method is useful for producing ammonia (claimed). The method increases the yield of ammonia. The water splitting-biosynthetic process operates at ambient conditions and can be distributed for an on-demand supply of nitrogen fertilizer. The method yields a much higher efficiency and provides a sustainable route for fertilizer production without the use of fossil fuels. Preferred Method: The step of dissolving hydrogen in the solution involves splitting water in the solution to form hydrogen and oxygen, where splitting water in the solution involves splitting water using a cathode including cobalt-phosphorus alloy and an anode comprising cobalt phosphate. The step of dissolving carbon dioxide and nitrogen in the solution involves bubbling carbon dioxide and nitrogen through the solution. Preferred Components: The solution comprises a phosphate. Preferred System: The system further comprises (a) a power source connected to a first electrode comprising a cobalt phosphorus alloy and a second electrode comprising cobalt phosphate, where the first and the second electrodes are at least partially immersed in the solution within the reactor chamber, (b) a phosphate in the solution, and (c) a gas inlet which bubbles gas through the solution within the reactor chamber. The gas source comprises at least one of nitrogen, hydrogen and carbon dioxide fluidly connected to the gas inlet.	
Novelty	Method for producing ammonia involves dissolving hydrogen, carbon dioxide and nitrogen in a solution, and placing a glutamine synthetase inhibitor and autotrophic diazotroph bacteria in the solution.	
Advantages	The method increases the yield of ammonia. The water splitting-biosynthetic process operates at ambient conditions and can be distributed for an on-demand supply of nitrogen fertilizer. The method yields a much higher efficiency and provides a sustainable route for fertilizer production without the use of fossil fuels.	

Title DWPI:

Algae cultivation system for cultivating and dewatering algae, comprises growth media reactor, photobioreactor and container, where sensor is set within container and electronically actuated gas control valve is set with container panels

Publication number (Kind Code):

US10633628B1

Publication Date:

2020-04-28

Current IPC:

C12N000112 | C12M000100 | C12M000136

Abstract

Algae cultivation system comprises growth media reactor having growth media and photobioreactor (10) partially immersed in growth media. The photobioreactor comprises container (12) and multiple panels (14) that define interior space in which algae is cultivated. The one panels is transparent. The bottom panel (16) comprises porous membrane filter (28) having 0.01-0.2 micrometer pores that enables water, carbon dioxide and nutrients contained within growth media to pass into interior space (26) and prevents contaminants contained within growth media from passing into interior space. The sensor is provided within container configured to sense parameter of algae indicative of when algae is ready for harvesting. The electronically actuated gas control valve (30) is set with container panels configured to be selectively opened and closed. The valve enables photosynthetic gas produced by algae growth within container to escape when gas control valve is open. Algae cultivation system for cultivating and dewatering algae. The algae cultivation system reduces downstream processing steps and costs, accelerates dewatering rate, increases dewatering extent, enables precise control on dewatering event in terms of timing of event, and provides backup to photosynthetic dewatering. Preferred Components: The photobioreactor comprises multiple transparent panels made of clear polymeric material.

Novelty

Algae cultivation system comprises growth media reactor having growth media and photobioreactor (10) partially immersed in growth media. The photobioreactor comprises container (12) and multiple panels (14) that define interior space in which algae is cultivated. The one panels is transparent. The bottom panel (16) comprises porous membrane filter (28) having 0.01-0.2 micrometer pores that enables water, carbon dioxide and nutrients contained within growth media to pass into interior space (26) and prevents contaminants contained within growth media from passing into interior space. The sensor is provided within container configured to sense parameter of algae indicative of when algae is ready for harvesting. The electronically actuated gas control valve (30) is set with container panels configured to be selectively opened and closed. The valve enables photosynthetic gas produced by algae growth within container to escape when gas control valve is open.

Advantages

The algae cultivation system reduces downstream processing steps and costs, accelerates dewatering rate, increases dewatering extent, enables precise control on dewatering event in terms of timing of event, and provides backup to photosynthetic dewatering.

Title DWPI:

Introduction of carbon dioxide in a photobioreactor, comprises determining a carbon dioxide deficiency in a media of bioreactor, and delivering carbon dioxide into the photobioreactor according to a duty cycle based on the determination

Publication number (Kind Code):

US9453193B2

Publication Date:

2016-09-27

Current IPC:

C12N000112 | C12M000100 | C12M0001107 | C12M000134 | C12M000136

Abstract

The method comprises determining a carbon dioxide deficiency in a media of a photobioreactor, and delivering carbon dioxide (305) into the photobioreactor according to a duty cycle based on the determination. The photobioreactor has the media and a head space adjacent to the media. The duty cycle comprises ON times and OFF times. A supply carbon dioxide is delivered to the photobioreactor and gas already in the head space is exhausted during the ON times of the duty cycle. The carbon dioxide residing in the head space diffuses into the media during the OFF times of the cycle. INDEPENDENT CLAIMS are included for:a method for growing microorganisms in a film based photobioreactor;a control system for introducing one or more gases to a photobioreactor; anda photobioreactor. The method is useful for introduction of carbon dioxide, air or inert gas in a photobioreactor for growing microorganisms such as algae (all claimed), which is useful as a feedstock for biofuel such as biodiesel, bioethanol, and/or biogasoline synthesis, where the microorganisms include *Nannochloropsis oculata* , *Nannochloropsis salina* , *Tetraselmis chuii* , *Chlorella protothecoides* , *Chlorella pyrenoidosa* , *Chlorella vulgaris* , *Haematococcus pluvialis* , and *Neochloris oleoabundans* . The method ensures economical introduction of the carbon dioxide with increased robustness thus rapidly and efficiently growing the microorganisms with high growth rate, reduced power consumption and high culture density.

Novelty

The method comprises determining a carbon dioxide deficiency in a media of a photobioreactor, and delivering carbon dioxide (305) into the photobioreactor according to a duty cycle based on the determination. The photobioreactor has the media and a head space adjacent to the media. The duty cycle comprises ON times and OFF times. A supply carbon dioxide is delivered to the photobioreactor and gas already in the head space is exhausted during the ON times of the duty cycle. The carbon dioxide residing in the head space diffuses into the media during the OFF times of the cycle.

Advantages

The method ensures economical introduction of the carbon dioxide with increased robustness thus rapidly and efficiently growing the microorganisms with high growth rate, reduced power consumption and high culture density.

Title DWPI:

Cultivating and processing microalgae, by supplying carbon dioxide into enclosed photobioreactor containing microalgae, cultivating, processing, separating biomass, extracting, separating gaseous mixture, recycling and storing oxygen

Publication number (Kind Code):

US9187724B1

Publication Date:

2015-11-17

Current IPC:

C12N000112 | C12M000100 | C12P000100 | C12P000300

Abstract

Method for cultivating and processing microalgae, involves directing a continuous supply of carbon dioxide into an enclosed photobioreactor containing microalgae, exposing the enclosed photobioreactor to insulation, cultivating, processing to create an algae biomass and a gaseous mixture, separating the algae biomass, extracting the biomass as essentially pure algae oil and oil-free algae biomass, separating the gaseous mixture into unreacted carbon dioxide, recycling the separated unreacted carbon dioxide to the photobioreactor, and storing the oxygen. Method for cultivating and processing microalgae, involves directing a continuous supply of carbon dioxide into an enclosed photobioreactor containing microalgae, exposing the enclosed

photobioreactor to insolation for the cultivation of the microalgae by controlled photosynthesis chemical reactions, cultivating the microalgae and processing the microalgae to create an algae biomass and a gaseous mixture, separating the algae biomass from the gaseous mixture, extracting the algae biomass as essentially pure algae oil and oil-free algae biomass, separating the gaseous mixture into unreacted carbon dioxide for recycling and oxygen for export, recycling the separated unreacted carbon dioxide to the photobioreactor, and storing the oxygen in synchronization with export. An INDEPENDENT CLAIM is included for system for cultivating and processing microalgae, which comprises unit for directing a continuous supply of carbon dioxide into an enclosed photobioreactor containing microalgae, unit for exposing the enclosed photobioreactor to insolation for the cultivation of the microalgae by controlled photosynthesis chemical reactions, unit for cultivating the microalgae and processing the microalgae to create an algae biomass and a gaseous mixture, unit for separating the algae biomass from the gaseous mixture, unit for separating the algae biomass into essentially pure algae oil and oil free algae biomass, unit for separating the gaseous mixture into unreacted carbon dioxide and oxygen, unit for recycling the separated unreacted carbon dioxide to the photobioreactor, and unit for storing the oxygen. The method or system is useful for cultivating and processing microalgae for producing oxygen and algal oil (all claimed) which is used as biodiesel. The method process oxygen with high purity and is performed with reduced quantity of water. Preferred Method: The method involves delivering the separated unreacted carbon dioxide to the photobioreactor at rates suited to the pattern of insolation during the 24-hour day, storing excess unreacted carbon dioxide from the photobioreactor as a liquid, and releasing through evaporation stored unreacted carbon dioxide to the photobioreactor when the photobioreactor demand exceeds the delivery of unreacted carbon dioxide. The method involves directing the unreacted carbon dioxide stored as a liquid through an evaporator and then as a vapor to the photobioreactor. The method involves directing process water and nutrients into the photobioreactor. The method involves flowing reactants including carbon dioxide, water and nutrients at predetermined rates through the photobioreactor tubes containing microalgae, and maintaining a minimized level of photosynthesis within the photobioreactor tube during periods when insolation is lacking. The method further involves configuring the photobioreactor tubes by several interconnected circular tubes, arranged in parallel flow paths, each path having a length for flow established to produce algae at a desired production level. The method further involves providing several reflecting parabolic insolation accumulators each having a reflecting parabolic surface, arranging the reflecting parabolic insolation accumulators, where the center of each of the circular interconnected tubes is located coincident with the focal point of its reflecting parabolic surface and insolation received by the area of the reflecting surface is concentrated on the circular interconnected tubes to a maximum degree. The method involves orienting the circular interconnected tubes in a north-south direction, and rotating the parabolic reflectors about their vertical axis in synchronization with the movement of the sun in the sky from dawn until sunset. The method involves concentrating the wavelengths of the internal illumination within the circular interconnected tubes in the low ends and high ends of the visible spectrum which are optimum for enhancing algae cultivation. The method involves cooling the reactants in heat exchangers located between adjacent circular interconnected tubes, within which algae cultivation occurs, to maintain the optimum temperature range for algae cultivation. The method involves providing mixing devices located between circular interconnected tubes to direct portions of the reactants toward the inside surface of the interconnected tubes, which portions have not received insolation because of inability of the photons of the insolation to penetrate to the interior of the interconnected tubes. The method involves separating gaseous mixture into unreacted carbon dioxide and oxygen by compressing the gaseous mixture of unreacted carbon dioxide and oxygen, cooling the compressed gaseous mixture to a temperature where the carbon dioxide condenses into a liquid carbon dioxide and can be separated from the oxygen, reducing the pressure of the liquid carbon dioxide to the level required for storage, separating the carbon dioxide thus produced as vapor, and recycling the carbon dioxide vapor for recompression and condensation, and compressing the oxygen separated from the liquid carbon dioxide to pressure levels causing the liquefaction of the oxygen. The method involves compressing the gaseous mixture of unreacted carbon dioxide and oxygen, cooling the compressed gaseous mixture to a temperature where the carbon dioxide condenses into a liquid carbon dioxide and can be separated from the oxygen and storing the carbon dioxide liquid in one or more suitable underground geological formations. The method involves dividing the oxygen separated from the liquid carbon dioxide into a first portion subjected to reduction in pressure to the level required for marketing and into a second portion subjected to liquefaction and storage. The method involves delivering the oxygen separated from the liquid carbon dioxide to the market under pressure at the variable rates of production. The method involves compressing oxygen vapor from the gaseous mixture to pressure levels causing the liquefaction of the oxygen, by cooling the oxygen vapor, refrigerating the cooled oxygen vapor by evaporating liquid carbon dioxide, and reducing the oxygen vapor pressure by passing the cooled oxygen vapor through an expansion valve whereby the liquefaction of oxygen occurs. The method involves compressing the oxygen vapor from the gaseous mixture to pressure levels causing the liquefaction of the oxygen, by cooling the oxygen vapor, refrigerating the cooled oxygen vapor by evaporating liquid carbon dioxide or with external sources employing a commercial refrigerant and reducing the pressure of the oxygen vapor by passing the cooled oxygen vapor through an expansion turbine with the production of by-product electricity or an expansion valve where the liquefaction of oxygen occurs. The

liquefaction of carbon dioxide vapor from the gaseous mixture involves compressing the carbon dioxide vapor and cooling the compressed carbon dioxide to generate liquefied carbon dioxide. The method involves reducing the pressure of the liquefied carbon dioxide to the level required for storage in a flash drum as carbon dioxide vapor, and recycling the associated carbon dioxide vapor for recompression. The method involves reducing the pressure of the liquefied carbon dioxide by passing the liquefied carbon dioxide through passage in an expansion turbine, and generating electricity by passing the liquefied carbon dioxide through passage in an expansion turbine. The requirements for electricity are provided by providing a photovoltaic field adjacent to the photobioreactor, and producing alternating current electricity with inversion equipment to match the frequency and voltage of the electricity otherwise supplied. The method involves supplying base load electricity by processing the oil-free algae biomass by anaerobic digestion and employing off gases produced by the anaerobic digestion as fuel for the generation of electricity in a conventional generation installation. The method involves separating carbon dioxide from methane in the off gases from anaerobic digestion, using the methane as fuel for electricity generation, and replacing a portion of incoming unreacted carbon dioxide to the photobioreactor with the carbon dioxide in the off gases from anaerobic digestion. The method involves exporting the off gases to an adjacent fossil-energy installation, separating the carbon dioxide and methane in the off gases in the adjacent fossil-energy installation, combining the carbon dioxide with the incoming unreacted carbon dioxide produced in the adjacent fossil-energy installation to the photobioreactor, supplementing fuel in the adjacent fossil-energy installation with the methane extracted from the off gases, and including the incremental electricity generated in the fossil-energy installation that is exported for use in cultivating and processing microalgae. The method involves supplying the process water by storing heated water and cooled water within a hot water storage container and a cold water storage container, respectively, cooling the heated water with absorption refrigeration having an appropriate medium as the refrigerant, and cooling the heated water with a combined induced-draft wet and a dry cooling tower. The method involves supplying heated water from the hot water storage container for the elevated temperature input required by absorption refrigeration, supplying cold water from the cold water storage container for the low temperature input required for cooling streams leaving compressors, and supplying heated water from the hot water storage container for the evaporation of liquefied oxygen and liquefied carbon dioxide. The method involves combining the process water with circulating water to provide a makeup water of reduced temperature for the photobioreactor. The method involves supplying the process water by storing heated water and cooled water within a hot water storage container and a cold water storage container, respectively, cooling the heated water with lithium bromide having water as a refrigerant in the absorption refrigeration component, and cooling the heated water with an induced-draft, combined dry-and-wet cooling tower.

Novelty

Method for cultivating and processing microalgae, involves directing a continuous supply of carbon dioxide into an enclosed photobioreactor containing microalgae, exposing the enclosed photobioreactor to insulation, cultivating, processing to create an algae biomass and a gaseous mixture, separating the algae biomass, extracting the biomass as essentially pure algae oil and oil-free algae biomass, separating the gaseous mixture into unreacted carbon dioxide, recycling the separated unreacted carbon dioxide to the photobioreactor, and storing the oxygen.

Advantages

The method processes oxygen with high purity and is performed with reduced quantity of water.

SNYDER KENNETH MATHEW MR. | WELLS FRANCES L. MS.
Algaculture system for biofuel production and methods of Alive
production thereof

Title DWPI:

Algaculture system for generating biofuel, comprises a pump/tank assembly having a mixer, a solar collector comprising interconnected tubes, axial vortex flow generators, a continuous harvester, a nutrient replenisher and pH adjuster

Publication number (Kind Code):

US9051539B2

Publication Date:

2015-06-09

Current IPC:

C12M000100 | C12M000300 | C12N000112 | A01G003300 | A01H000400

Abstract

The algaculture system (800) comprises a pump/tank assembly having a mixer, a solar collector comprising interconnected tubes, axial vortex flow generators situated at an intake portion of each of the interconnected tubes, a continuous harvester to separate a first type of algae from a second type of algae, a nutrient replenisher and pH adjuster in fluid communication with the pump/tank assembly to receive the second type of algae, and 180° fittings interconnecting the tubes to one another such that the solar connector has an undulating configuration, and a cooling tube. The algaculture system (800) comprises a pump/tank assembly having a mixer,

a solar collector comprising interconnected tubes, axial vortex flow generators situated at an intake portion of each of the interconnected tubes, a continuous harvester to separate a first type of algae from a second type of algae, a nutrient replenisher and pH adjuster in fluid communication with the pump/tank assembly to receive the second type of algae, and 180° fittings interconnecting the tubes to one another such that the solar connector has an undulating configuration, a cooling tube, a temperature control system, a nutrient gas system, a waste gas system, and a drain system. The assembly is configured to continuously mix a quantity of algae, nutrients, water and carbon dioxide. The solar collector is present in communication with an outlet of the pump/tank assembly at a proximal end. The continuous harvester is present in fluid communication with the solar collector at a distal end and the pump/tank assembly, and has a first outlet for directing the first type of algae for processing. The tubes are vertically and horizontally oriented relative to a flat surface. The cooling tube is positioned within the tube of the solar collector, and enters through an opening in a first fitting and exits through an opening in a second fitting. The temperature control system, the nutrient gas system and the waste gas system have a central supply line and a central return line. The temperature control system is present in fluid communication with the cooling tube. The nutrient gas system and the waste gas system are present in fluid communication with the interconnected tubes. The drain system is present in communication with the interconnected tubes, where a point of communication includes a valve positionable in an open position and a closed position. The continuous harvester comprises a tension bowl having a conical base, a rotating shaft centered within the tension bowl, a first outlet at a bottom portion of the tension bowl, and a second outlet at a top portion of the tension bowl. The rotating shaft is present in electrical communication with an external motor, and supports a squeegee arm. The first outlet provides an outlet for the second type of algae. The second outlet provides an outlet for the first type of algae. The squeegee arm rotates of 5-200 RPM. The mixer comprises Archimedes screw. The first type of algae is mature and cultivatable algae. The second type of algae is immature, non-cultivable algae. An INDEPENDENT CLAIM is included for a manufacturing process for producing biofuel. The algaculture system is useful for generating biofuel. The algaculture system is capable of economically, efficiently and easily generating biofuel in a viable manner with low impact of petrochemical energy and less energy consumption and without the negative environment.

Novelty

Cultivating photosynthetic microorganisms in sealed photobioreactor to obtain volatile hydrocarbon of photosynthesis, involves: culturing photosynthetic microorganism in sealed photobioreactor containing lower aqueous phase comprising photosynthetic microorganism, and upper gaseous phase having carbon dioxide concentration of $\geq 10\%$; introducing additional carbon dioxide into upper gaseous phase when carbon dioxide concentration drops below 10%; and collecting volatile product that is sequestered into gaseous phase and displaced by additional carbon dioxide.

Advantages

The method provides improved method that allows for renewable production, sequestration and trapping of volatile hydrocarbon compounds such as isoprene, alcohols and aldehydes produced by photosynthetic microorganisms; where the method is diffusion-driven process carried out in gaseous/aqueous two-phase photobioreactors for carbon dioxide uptake, and hydrocarbon such as isoprene plus oxygen emission by photosynthetic microorganisms (preferably microalgae or cyanobacteria). The diffusion-driven exchange of CO₂ with volatile hydrocarbon e.g. isoprene plus oxygen, can be scaled-up to mass culture conditions for commercial production and exploitation of volatile hydrocarbon, such as isoprene. The method involves diffusion of CO₂ from gaseous headspace into microalgal or cyanobacterial-containing aqueous phase, followed by CO₂ uptake, photosynthetic assimilation, and hydrocarbon production by these photosynthetic microorganisms, which are microalgae or cyanobacteria that are genetically engineered to produce volatile hydrocarbon. Volatile hydrocarbons are then emitted from aqueous phase and are sequestered into gaseous headspace. Periodic replacement (flushing) of volatile hydrocarbon e.g. isoprene, and oxygen content of gaseous headspace with CO₂, and passage through cooled condenser and hydrophobic solvent enables trapping and retention of volatile hydrocarbon, while effecting separation of volatile hydrocarbon from O₂ by-product of photosynthesis. The method thus allows for renewable generation of fuels and synthetic chemistry feedstock.

ROLLS ROYCE HOLDINGS PLC
Algae dryer and harvesting apparatus

✓ Alive

Title DWPI:

Drying and harvesting apparatus for large scale conversion of liquid slurry into dried product, has auger whose lower end is provided with lower dry product bin and upper end is provided with auger drive motor

Publication number (Kind Code):

US9567562B1

Publication Date:

2017-02-14

Current IPC:

F26B000332 | C12N000112 | F26B000308

Abstract

The apparatus has scraper and spray bar element that is attached to central rotating tube (70) by two hollow transfer struts so as to provide liquid communication between inner longitudinal bore of central rotating tube through two hollow transfer struts into inner throat (82) and out of liquid spray ports (84). A lower dry product bin positioned below drier vessel slot is defined by auger assembly. An auger is provided with lower dry product bin in lower end and auger drive motor to direct dried product to a release outlet for transfer to a directed location in upper end. Drying and harvesting apparatus for large scale conversion of liquid slurry into dried product. The damage potential to the algae cells is reduced during the drying process, and the algae which is healthier state and condition is delivered for processing.

Novelty

The apparatus has scraper and spray bar element that is attached to central rotating tube (70) by two hollow transfer struts so as to provide liquid communication between inner longitudinal bore of central rotating tube through two hollow transfer struts into inner throat (82) and out of liquid spray ports (84). A lower dry product bin positioned below drier vessel slot is defined by auger assembly. An auger is provided with lower dry product bin in lower end and auger drive motor to direct dried product to a release outlet for transfer to a directed location in upper end.

Advantages

The damage potential to the algae cells is reduced during the drying process, and the algae which is healthier state and condition is delivered for processing.

UNIV BOISE STATE**Ultraviolet radiation pre-treatment of wastewater, improving its utility for algal cultivation**

✓ Alive

Title DWPI:

Increasing algae production comprises measuring the light absorbance level of the waste water, introducing a desired dose of ultraviolet C to the waste water, and allowing the algae to grow and absorb nutrients present in the wastewater

Publication number (Kind Code):

US20150275166A1

Publication Date:

2015-10-01

Current IPC:

C12N000112 | C02F000132 | C02F000332 | C12M000100

Abstract

Increasing algae production in a wastewater treatment medium comprises measuring the light absorbance level of the waste water so that an appropriate level of ultraviolet c (UVc) pre-treatment can be determined; introducing to the waste water a UVc dose; and allowing the algae to grow and absorb nutrients present in the wastewater. Increasing algae production in a wastewater treatment medium comprises (a) measuring the light absorbance level of the waste water so that an appropriate level of UVc pre-treatment can be determined; (b) introducing to the waste water a UVc dose of 189-500 mW-s/cm²; (c) allowing the algae to grow and absorb nutrients present in the wastewater, where algae growth and production is increased in pre-treated wastewater in the appropriate absorbance range by as much as 88% over water that is not pretreated by UVc exposure; and (d) harvesting the algae or algae bio-material, and recycling the treated wastewater. INDEPENDENT CLAIMS are: a method of treating wastewater to enhance algae production by treating the wastewater with short wavelength UVc radiation prior to introduction of algae, so that algae growth is increased compared to non-pretreated wastewater; and a wastewater treatment pond or raceway having increased algae biomass production and altered chromophoric dissolved organic matter components due to the addition of UVc radiation at a dose of 378.5-500 mW-s/cm² and in it algae growth is increased by as much as 88% over not pre-treated water. The methods are used for increasing algae production

in a wastewater treatment; and treating wastewater to enhance algae production (all claimed). Provided is a process of remediating wastewaters, preferably agricultural wastewaters resulting from animal production or contained animal feeding operation sites. The water is treated to promote assimilation of nutrients into algal biomass, which can be harvested and sold, and the resultant wastewater is then purified. The short wavelength UV radiation (less than 280 nm wavelength) is used to pretreat wastewater, with the dose determined by absorbance of the water, not by bacterial load. Pretreated water exhibits changes in chromophoric dissolved organic matter that allows for improved and increased algae production by as much as 88%. Preferred Method: In the method of increasing algae production in a wastewater treatment medium, the algae is selected from *Botryococcus braunii*, *Chlorella* sp. (preferred), *Dunaliella tertiolecta*, *Gracilaria* sp., *Pleurochrysis carterae* (also called CCMP647), or *Sargassum* sp.. The UVC does is at a wavelength of less than 280 nm. The wastewater light absorbance is from 2.4 AU or lower. The wastewater is from animal, industrial, municipal, and other wastewater sources. The wastewater contains nitrogen, phosphorus, trace minerals, bacteria and other carbon-based by-products, where the wastewater is from animal production or contained animal feeding operations (CAFO) sites. The wastewater is from dairy production. The wastewater includes additional pre-treatments including ozone treatment, ultrasound treatment, filtration, hollow fiber filtration, sand filtration, gravel filtration, diatomaceous earth filtration, or, activated charcoal filtration. In the method of treating wastewater to enhance algae production, the wastewater after treatment has changed optical properties that allow for increased light penetration and thus increased algae growth. The changed optical properties include a reduction in activity of molecules in 280-320 nm. The treatment with UV results in a decrease in bacterial densities. The treatment with UV results in altered chromophoric dissolved organic matter. The UVC is at a wavelength of 254. The UV treatment does not alter the amount of total dissolved phosphorous. The anaerobic digester effluent light absorbance is reduced by 19-32% at 430 nm and 675 respectively. The polyhydroxyalcanoate reactor effluent light absorbance is reduced by 7-22% at wavelengths of 430 nm and 675 nm respectively.

Novelty

Increasing algae production in a wastewater treatment medium comprises measuring the light absorbance level of the waste water so that an appropriate level of ultraviolet c (UVC) pre-treatment can be determined; introducing to the waste water a UVC dose; and allowing the algae to grow and absorb nutrients present in the wastewater.

Advantages

Provided is a process of remediating wastewaters, preferably agricultural wastewaters resulting from animal production or contained animal feeding operation sites. The water is treated to promote assimilation of nutrients into algal biomass, which can be harvested and sold, and the resultant wastewater is then purified. The short wavelength UV radiation (less than 280 nm wavelength) is used to pretreat wastewater, with the dose determined by absorbance of the water, not by bacterial load. Pretreated water exhibits changes in chromophoric dissolved organic matter that allows for improved and increased algae production by as much as 88%.

**KOREA INSTITUTE OF SCIENCE AND TECHNOLOGY | YONSEI
UNIVERSITY | UNIV MYONGJI IND & ACAD COOP FOUND | UNIV
KEIMYUNG IND ACADEMIC COOP FOUND**
**Process of producing bioenergy with low carbon dioxide emissions
and zero-waste of biomass**

✓ Alive

Title DWPI:

Producing zero-waste bioenergy with reduced carbon dioxide emissions and zero-waste biomass comprises a combination of biosaccharification and alcohol fermentation processes including a biomass pretreatment

Publication number (Kind Code):

US9902977B2

Publication Date:

2018-02-27

Current IPC:

C12P000716 | C12N000112 | C12P000502 | C12P000706 | C12P000710 | C12P000764

Abstract

Producing zero-waste bioenergy with reduced carbon dioxide emissions, a minimized-waste or waste-free bioenergy production process capable of providing an optimal biomass treatment efficiency and bioenergy productivity, comprising a combination of biosaccharification and alcohol fermentation processes including a biomass pretreatment. Producing zero-waste bioenergy with reduced carbon dioxide emissions, a minimized-waste or waste-free bioenergy production process capable of providing an optimal biomass treatment efficiency and bioenergy productivity, comprising a combination of biosaccharification and alcohol fermentation processes including a biomass pretreatment, and steps described below, comprises (a) an anaerobic digestion process for (i) generating a biogas consisting of: methane, carbon dioxide, and hydrogen sulfide using a liquid byproduct including a solid biomass waste produced during

the biosaccharification/alcohol fermentation process, and a liquid fermentation waste produced during bioalcohol purification, and (ii) recycling the generated anaerobic sludge to the biomass pretreatment process; (b) an autotrophic or mixotrophic algae cultivation process comprising supplying carbon dioxide liquid necessary for algal photosynthesis during the autotrophic or mixotrophic algae cultivation process to an algae cultivation liquid by introducing the biogas generated from the anaerobic digestion process into a lower part of the algae cultivation liquid; and purifying the biogas into a methane biogas with the absorption of hydrogen sulfide; and (c) recycling the biomass harvested during the algae cultivation process to the biosaccharification/alcohol fermentation process for producing the bioalcohol, with or without going through a biodiesel production process. The method is used for producing zero-waste bioenergy with reduced carbon dioxide emissions, a minimized-waste or waste-free bioenergy production process capable of providing an optimal biomass treatment efficiency and bioenergy productivity (claimed). Provided is a method for producing zero-waste bioenergy with reduced carbon dioxide emissions, a minimized-waste or waste-free bioenergy production process providing an optimal biomass treatment efficiency and bioenergy productivity (all claimed). The delays or prevents global warming. Also provided is a method to enhance the cost-effectiveness of biodiesel production via the development of a novel usage of glycerol waste by supplying a high glycerol content waste produced during the biodiesel production process into an algae cultivation liquid of the heterotrophic algae cultivation process, or recycling it into the biosaccharification/alcohol fermentation process to utilize it as a biomass raw material for producing bioalcohol, preferably producing a biofuel using a biodiesel waste, thus enabling an eco-friendly production of a biofuel. Preferred Method: In the method above, the algae is microalgae, and the method further comprising: upon harvesting microalgae during the algae cultivation process, producing biodiesel by adding the harvested microalgae into a biodiesel manufacturing process; recycling a liquid glycerol, a byproduct from the biodiesel manufacturing process, to the biosaccharification/alcohol fermentation process; and recycling a saccharide-containing solid waste from the biodiesel manufacturing process to the biomass pretreatment process of the biosaccharification/alcohol fermentation process. The algae is macroalgae, and the method further comprising, upon harvesting macroalgae, recycling the harvested macroalgae into the biomass pretreatment process of the biosaccharification/alcohol fermentation process. The biomass pretreatment process is performed by one or more selected from mechanical treatment, heat treatment, microwave, ultrasonication, acid treatment, alkali treatment, steam explosion, electron beam irradiation, and water steaming. The biomass is one or more selected from herbaceous and woody plants, fruit pulp, freshwater and sea algae, grains, aerobic and anaerobic sludge, saccharides, polyols and carbohydrates. The anaerobic digestion process comprises a pretreatment of a non-decomposable solid biomass waste. The anaerobic digestion process is performed using an upflow anaerobic sludge blanket (UASB) reactor. The anaerobic digestion process supplies nitrogen and phosphorus to the algae cultivation liquid by adding a liquid waste to the algae cultivation process. The biosaccharification/alcohol fermentation process is either a biosaccharification and ethanol fermentation process or a biosaccharification and butanol fermentation process; or the method comprises producing butanol by adding a process byproduct generated during the biosaccharification and ethanol fermentation process for ethanol production into the biosaccharification and butanol fermentation process or the butanol fermentation process as a raw material. The anaerobic sludge generated from the anaerobic digestion process is recycled to the biomass pretreatment process, or recycled to the pretreatment process of the anaerobic digestion process, or manufactured into a biochar via pyrolysis. The algae cultivation liquid is further combined with at least one oxidizing agent selected from Fe(III) EDTA, a ferric salt exclusive of Fe(III) EDTA, oxygen (O₂), hydrogen peroxide (H₂O₂), chlorine (Cl₂), sodium hypochlorite (NaOCl), monochloroamine (NH₂Cl), and ozone (O₃), in order to treat hydrogen sulfide. The process byproduct is a liquid ethanol fermentation waste; or a solid biomass waste; or a liquid ethanol fermentation waste and a solid biomass waste. The biological oxygen demand (BOD) concentration of the liquid fermentation waste is 104 to 105 mg/L. The microalgae contain at least 30% of lipid oil per dry weight. The liquid glycerol concentration is 5-20% (w/v) relative to the amount of the biodiesel production. The saccharide-containing waste contains 45-50% carbohydrate. The pretreatment process is performed by one or more selected from mechanical treatment, heat treatment, microwave, ultrasonication, acid treatment, alkali treatment, steam explosion, electron beam irradiation, and water steaming. The Fe(III) EDTA concentration in the algae cultivation liquid is maintained at 4 mM or less. Any one of the (a) anaerobic digestion process, (b) algae cultivation process and (c) recycling process is further followed by a heterotrophic algae cultivation process. The heterotrophic algae cultivation process supplied with the liquid glycerol, a byproduct of the biodiesel manufacturing process, into the algae cultivation liquid from the biodiesel manufacturing process. The algae cultivation liquid of the heterotrophic algae cultivation process is supplied with saccharide in the amount of the difference between the amount of saccharide produced during the biosaccharification/alcohol fermentation process and the amount of saccharide converted and consumed during the same biosaccharification/alcohol fermentation process. The liquid waste from the anaerobic digestion process is supplied to the heterotrophic algae cultivation process thus supplying nitrogen and phosphorus to the algae cultivation liquid.

Novelty

Producing zero-waste bioenergy with reduced carbon dioxide emissions, a minimized-waste or waste-free bioenergy production process capable of providing an optimal biomass treatment

efficiency and bioenergy productivity, comprising a combination of biosaccharification and alcohol fermentation processes including a biomass pretreatment.

Advantages

Provided is a method for producing zero-waste bioenergy with reduced carbon dioxide emissions, a minimized-waste or waste-free bioenergy production process providing an optimal biomass treatment efficiency and bioenergy productivity (all claimed). The delays or prevents global warming. Also provided is a method to enhance the cost-effectiveness of biodiesel production via the development of a novel usage of glycerol waste by supplying a high glycerol content waste produced during the biodiesel production process into an algae cultivation liquid of the heterotrophic algae cultivation process, or recycling it into the biosaccharification/alcohol fermentation process to utilize it as a biomass raw material for producing bioalcohol, preferably producing a biofuel using a biodiesel waste, thus enabling an eco-friendly production of a biofuel.

ALGAECYTES LTD Process for production of microalgae, cyanobacteria and metabolites thereof	<input checked="" type="checkbox"/> Alive
Title DWPI:	
Enhanced production of one or more metabolites in microalgae and/or cyanobacteria, comprises culturing a microalgal or cyanobacterial strain through a production phase, and exposing the microalgal or cyanobacterial culture to a stimulus	
Publication number (Kind Code):	
CA2825856C	
Publication Date:	
2019-08-27	
Current IPC:	
C12N000112 C05D000900 C12M000104 C12N000136 C12N001300 C12P000764 C12P001904	
Abstract Process-I for the enhanced production of one or more metabolites in microalgae and/or cyanobacteria, comprises: (i) culturing a microalgal or cyanobacterial strain through a production phase; and (ii) exposing the microalgal or cyanobacterial culture to a stimulus, where the stimulus comprises (a) a decrease in pH to a pH of no more than 6, followed by an increase in pH to a pH of no less than 7 and (b) an increase in light irradiance to at least 400 μ mole/m ² /second. INDEPENDENT CLAIMS are included for: (1) a process-II for the production or growth of microalgae and/or cyanobacteria or the production of one or more metabolites derived from it, comprising (ia) an adaptation stage of culturing microalgae or cyanobacteria (a1) on a process water feedstock and selection of those microalgae or cyanobacteria able to grow on the process water feedstock, and/or (b1) under LEDs emitting 2 peaks of red and blue light within the spectrum of light wavelengths of 400-700 nm, and (iia) a production phase of culturing the selected microalgae or cyanobacteria of (a2) on the same process water feedstock used in the adaptation stage and/or under the same light conditions used in the adaption stage; (2) a microorganism-I which is, or has the identifying characteristics of, a strain of Chlorogibba allorgei deposited with the Culture Collection of Algae and Protozoa under the accession number CCAP 817/1, or a mutant strain derived from it; (3) a microorganism-II which is, or has the identifying characteristics of, a strain of Dictyosphaerium chlorelloides deposited with the Culture Collection of Algae and Protozoa under the accession number CCAP 222/98, or a mutant strain derived from it; (4) a process-III for the enhanced production of microalgae belonging to the family Pleurochloridaceae containing commercially valuable bio proteins, lipids and metabolites of eicosapentaenoic acid, myristic acid, palmitic acid, behenic acid, laurie acid, linoleic acid, a linolenic acid and stearic acid comprising using optimized light wavelengths for the culturing and production preferably in photobioreactors of lipid-rich micro-algae strains within the phylum of Chlorophyta and the family of Pleurochloridaceae; (5) a process-IV for the production of fatty acids such as eicosapentaenoic acid, myristic acid, palmitic acid, behenic acid, laurie acid, linoleic acid, a linolenic acid and stearic acid comprising preparing the algae biomass belonging to the Pleurochloridaceae family and the cyanobacteria strain from the order Chroococcales in the genera Synechocystis and Synechococcus and isolating the commercially valuable by products from the lipid(s); (6) a process-V for obtaining production of specific fatty acids in the lipid profile comprising tuning photosynthetic efficiency in the presence of select continuous light PAR wavelengths; (7) a process-VI for obtaining specific production of fatty acids in the lipid profile comprising adjusting nutrient levels in growth media with light irradiances to provide products/ingredients for either the food or cosmetics sector or for the production of biofuels; (8) a process-VII for improving the growth profile of algal cells and/or for altering or controlling the metabolite production profile, such as the fatty acid profile, of the algal cells comprising adapting the algal cells to specific conditions through multiple rounds of sub-culture with exposure to the specific conditions prior to recovery of metabolites from the algal cells; (9) a process-VIII for double phase continuous production of exopolysaccharide by cultivation of a micro-alga in an aqueous nutrient amended culture in the presence of dissolved carbon dioxide and tuned incident light energy supplied by LEDs, where exopolysaccharide	

production is enhanced by causing the culture to shift from a growth phase favouring cell division to a static phase favouring exopolysaccharide production, comprising (ib) carrying out the growth phase in a first stage operated in a continuous mode in which fresh nutrient medium or secondary process water supply is used to grow the culture to sustain exponential cell growth, and (iib) along with the supply of fresh nutrient medium and carbon dioxide to the first stage, transferring a portion of the culture to a second stage which is separate from the first stage and in which the supply of carbon dioxide and nutrients is limited to create the conditions in the second stage to enhance exopolysaccharide production while continuing to supply tuned photosynthetically active radiation (PAR) Light at set irradiance levels from tuned LEDs, whilst optionally, fresh nutrient medium or process water is also added to the first stage to continue the growth phase, optionally simultaneously; (10) a soil conditioner comprising algal biomass produced by the method-VIII; (11) a subsurface dip irrigation system comprising the soil conditioner; and (12) a system for the production of algal exopolysaccharide, comprising a first stage reaction chamber adapted to contain a culture of algae cells and having an inlet for the introduction of a nutrient medium and carbon dioxide to the chamber and an outlet for the withdrawal of culture from it, means for sensing the cell density in the chamber and generating a control function representative, means responsive to the control function for regulating the introduction of nutrient medium and carbon dioxide to the inlet and the withdrawal of culture from the outlet, second stage reaction chambers adapted to receive culture from the first stage reaction chamber, and a means for sequentially transferring culture from the outlet of the first stage reaction chamber to the second stage reaction chambers. Fertilizer. None given. The processes are useful for: the enhanced production of microalgae belonging to the family Pleurochloridaceae containing commercially valuable bio proteins, lipids and metabolites of eicosapentaenoic acid, myristic acid, palmitic acid behenic acid, laurie acid, linoleic acid, a linolenic acid and stearic acid; the enhanced production of carbohydrates including exopolysaccharide; and the enhanced production of algal and/or cyanobacterial biomass, where the algal and/or cyanobacterial biomass is useful for the production of biofuel, and as a soil conditioner or biofertilizer (all claimed). No biological data given. Preferred Components: The microalgae/cyanobacteria are green microalgae/cyanobacteria or freshwater microalgae/cyanobacteria. The microalgal strain is a phylum of Chlorophyta. The microalgal strain is a family of Pleurochloridaceae. The microalgal strain is a species of *Trachydiscus* sp. or *Chlorogibba* sp. . The microalgal strain is a species of *Dictyosphaerium chlorelloides* . The cyanobacterial strain is an order of Chroococcales. The cyanobacterial strain is a genera of *Synechocystis* or *Synechococcus* . The microalgal strain is a strain of *Chlorogibba allorgei* deposited with the Culture Collection of Algae and Protozoa under the accession number CCAP 817/1, or a mutant strain derived from it. The microalgal strain is a strain of *Dictyosphaerium chlorelloides* deposited with the Culture Collection of Algae and Protozoa under the accession number CCAP 222/98, or a mutant strain derived from it. Preferred Process: The production phase corresponds to the exponential phase of growth. The production phase involves growth of the microalgal or cyanobacterial strain under conditions that permit exponential growth. The production phase involves growth of the microalgal or cyanobacterial strain in a photobioreactor. The production phase involves growth of microalgae and/or cyanobacteria under LEDs emitting 2 peaks of red and blue light within the PAR spectrum of 400-700 nm. The cultures are not exposed to natural sunlight. The microalgal or cyanobacterial culture is exposed to the stimulus at the peak of exponential phase growth and/or at the onset of the stationary phase of growth. In the process-I or II, after the pH decrease, the pH is increased to a pH of 7-9. In the process-I or II, following exposure of the microalgae or cyanobacteria to the stimulus, the microalgae or cyanobacteria are cultured for a further period of 48 hours prior to the harvesting of the metabolite. The pH of the process water is 7-9. The temperature is maintained at 20-29° C in the adaptation stage. The microalgae and/or cyanobacteria are exposed to light wavelengths of 400-700 nm. The microalgae and/or cyanobacteria are exposed to LEDs emitting a peak of red light of 500-665 nm, preferably 660 nm, and a peak of blue light of 440-500 nm, preferably 460 nm. The microalgae and/or cyanobacteria are exposed to light with irradiance levels of 50-200 μ mole/m²/second. The adaptation stage involves: culturing the microalgal or cyanobacterial strains for a period of at least 3 months; culturing the microalgal or cyanobacterial strains for at least 6 generations of growth; and multiple rounds of sub-culturing the microalgal or cyanobacterial strains. The microalgae or cyanobacteria are sub-cultured once per month. The production phase involves: growth of the adapted microalgal or cyanobacterial strain in a photobioreactor; and culture of the adapted microalgal and/or cyanobacterial strain under conditions that permit exponential growth. The production phase involves culture of the adapted microalgal and/or cyanobacterial strain under the same lighting conditions as used for growth during the adaptation phase. The production phase is followed by a step comprising exposure of the microalgal or cyanobacterial culture to a stimulus to induce enhanced production of metabolites. The process-III, industrial by-products such as spent process water and carbon dioxide are used as reclaimed sources of nutrients and carbon to tune/adapt the algae for enhanced growth using these inputs. The process-III comprises using optimized wavelengths of light, process water and nutrient addition. The algae are maintained under the adaptation stimuli (select PAR light wavelengths and light source, process water source and other growth media constituents) to continue the adaptation selection of algae cells. The specific conditions are sub-optimal for growth of non-adapted algae. The algal cells are adapted to LED lighting, optionally at a wavelength of 400-700 nm. The algal cells are adapted to treated process water. The first stage is performed in a culture vessel which optionally has a thickness

of 3-11 cm. The method-VIII further comprises monitoring the cell density in the first stage and adding fresh nutrient medium to the first stage and transferring culture from the first stage to the second stage in response to an increase in cell density in the first stage above a designated level to maintain the cell density at the designated level. The step (iib) is implemented by successively transferring culture from the first stage to a second stage, where exopolysaccharide production occurs in the second stage reaction tanks simultaneously with cell growth in the first stage. The exopolysaccharide is produced by cultivation of *Dictyosphaerium chlorelloides*, optionally strain ALG03, or other species in the same family. The method-VIII further comprises using the algal biomass as a root soil conditioner. Preferred Components: The stimulus comprises a decrease in pH from a pH of 7-9 to a pH of 5-6. The stimulus comprises an increase in LED-delivered irradiance of 50-200 μ mole/m²/second to 400-2000 μ mole/m²/second. The stimulus additionally comprises addition of a carbon source. The decrease in pH is initiated by the addition of carbon dioxide. The pH is lowered to a pH of 5-6 for a period of 30 minutes to 2 hours, and the period precedes the increase in light irradiance. The light is generated by LEDs emitting 2 peaks of red and blue light within the spectrum of light wavelengths of 400-700 nm. The illumination rate of incident light energy is higher in the first stage than in the second stage. The illumination rate of incident light energy on cells closest to the light source is 50-500 μ mole/m²/second during the first stage and 30-200 μ mole/m²/second during the second stage. The incident light energy during the second stage has an energy content of 400-700 nm. The biomass is delivered via a subsurface drip irrigation system.

Novelty

Process-I for the enhanced production of one or more metabolites in microalgae and/or cyanobacteria, comprises: (i) culturing a microalgal or cyanobacterial strain through a production phase; and (ii) exposing the microalgal or cyanobacterial culture to a stimulus, where the stimulus comprises (a) a decrease in pH to a pH of no more than 6, followed by an increase in pH to a pH of no less than 7 and (b) an increase in light irradiance to at least 400 μ mole/m²/second.

Advantages

UNIVERSITY OF CALIFORNIA

Agents for enhancement of production of biofuel precursors in ✓ Alive microalgae

Title DWPI:

Increasing lipid production in host organism used for producing biofuel, by introducing expression vector comprising heterologous nucleotide sequence which contains lipid regulatory transcription factor gene into organism

Publication number (Kind Code):

US10472643B2

Publication Date:

2019-11-12

Current IPC:

C12N001582 | C07K001440 | C07K0014405 | C12P000764

Abstract

Method for increasing lipid production in a host organism, involves introducing into an organism an expression vector comprising a heterologous nucleotide sequence or its fragments which comprises (a) an operably linked promoter that drives expression in the organism, and (b) a lipid regulatory transcription factor gene chosen from 17 sequences. INDEPENDENT CLAIMS are included for the following: expression vector; cell; plant; and method for enhancing lipid overexpression or lipid production activity in an organism. The method is used for increasing lipid production in a host organism, preferably prokaryotic cell or eukaryotic cell, more preferably Cyanobacteria, plants, or algae (all claimed) used for producing biofuel.

Novelty

Method for increasing lipid production in a host organism, involves introducing into an organism an expression vector comprising a heterologous nucleotide sequence or its fragments which comprises (a) an operably linked promoter that drives expression in the organism, and (b) a lipid regulatory transcription factor gene chosen from 17 sequences.

Advantages

UNIV NORTH TEXAS | BOSTON UNIVERSITY

Methods for elevating fat/oil content in plants ✓ Alive

Title DWPI:

Obtaining a plant or algae cell with elevated lipid content, comprises genetically modifying a plant or algae cell to express an exogenous lipid droplet-associated protein or polypeptide

Publication number (Kind Code):

US10253325B2

Publication Date:

2019-04-09

Current IPC:

C12N001582 | C07K0014415 | C12P000764

Abstract

Obtaining a plant or algae cell with elevated lipid content, comprises genetically modifying a plant or algae cell to express an exogenous lipid droplet-associated protein or polypeptide. The lipid droplet-associated protein or polypeptide induces adipogenesis, enhances the accumulation of cellular lipid droplets, and/or reduces lipase activity. The expression of the lipid droplet-associated protein or polypeptide increases lipid content of the genetically-modified plant or algae cell as compared to a wild-type plant or algae cell of the same type. INDEPENDENT CLAIMS are also included for: the transgenic plant or algae cell with elevated lipid content when compared to a wild-type plant or algae cell of same type, where the transgenic plant or algae cell expresses the exogenous lipid droplet-associated protein or polypeptide; and screening for a functional lipid droplet-associated protein or polypeptide for elevating lipid content and/or inducing lipid droplet accumulation in a plant or algae cell, comprising: obtaining a test plant or algae cell genetically-modified to express a candidate exogenous lipid droplet-associated protein or polypeptide; and growing the genetically-modified test cell and selecting the genetically-modified test cell having elevated lipid content and/or increased lipid droplet level, when compared to a wild-type cell of the same type. The method is useful for: obtaining a plant or algae cell with elevated lipid content, where the plant cell is in a plant part which is in a plant, the plant cell is a seed cell of a plant, or a non-seed cell which is a leaf, root, stem, shoot, bud, tuber, fruit or flower cell (all claimed); and increasing energy content in crop biomass, where the plant is useful for producing e.g. biofuel, renewable chemical feedstocks and animal feed. The method: provides plants which provide biofuels with higher efficiency and cost-effective energy production; and increases production of lipids which are beneficial for human health, e.g. omega-unsaturated fat in olives, canola, corns, peanuts or sunflower seeds. Preferred Method: The method further comprises: modifying the plant or algae cell to express a combination of the exogenous lipid droplet-associated proteins or polypeptides; and down-regulating the activity of At4g24160 in the plant or algae cell. The genetic modification of the plant or algae cell comprises transforming plant or algae cell with a vector comprising a nucleic acid sequence encoding the exogenous lipid droplet-associated protein or polypeptide, where the nucleic acid is operably linked to a promoter and/or a regulatory sequence. In the screening method: the cell is a plant cell and the method further comprises regenerating the genetically-modified cell into a plant; and the cell is a plant cell and the method further comprises obtaining progeny of the plant. Preferred Components: The lipid droplet-associated protein or polypeptide is fat specific protein-27 (preferred), perilipin (PLIN)-1, PLIN-2, seipin, fat storage transmembrane protein (FIT)-1, FIT-2, acyl-coenzyme A:diacylglycerol acyl transferase-1 (DGAT-1), phospholipid: diacylglycerol acyltransferase-1 (PDAT-1), cell death activator (Cidea), or wrinkled-1 (WRI1) protein or polypeptide. The lipid droplet-associated protein or polypeptide is of animal origin. The vector is a T-DNA binary vector. The transgenic plant cell is a non-seed cell.

Novelty

Obtaining a plant or algae cell with elevated lipid content, comprises genetically modifying a plant or algae cell to express an exogenous lipid droplet-associated protein or polypeptide. The lipid droplet-associated protein or polypeptide induces adipogenesis, enhances the accumulation of cellular lipid droplets, and/or reduces lipase activity. The expression of the lipid droplet-associated protein or polypeptide increases lipid content of the genetically-modified plant or algae cell as compared to a wild-type plant or algae cell of the same type.

Advantages

The method: provides plants which provide biofuels with higher efficiency and cost effective energy production; and increases production of lipids which are beneficial for human health, e.g. omega-unsaturated fat in olives, canola, corns, peanuts or sunflower seeds.

EXXONMOBIL CORP
Method for discovering algal strains with reduced pigment to attain higher photosynthetic efficiency

✓ Alive

Title DWPI:

Determining and engineering photosynthetic mutant algal strains comprises e.g. pre-screening wild-type or parent strains to select for photosynthetic efficiency, and causing genetic mutations in group of wild-type and parent strains

Publication number (Kind Code):

US9528138B2

Publication Date:

2016-12-27

Current IPC:

C12Q000102 | C12N000112 | C12N000136 | C12Q000104

Abstract

Determining and/or engineering photosynthetic mutant algal strains, comprises: (a) pre-screening wild-type or parent strains to select for photosynthetic efficiency; (b) causing genetic mutations in the group of wild-type and/or parent strains from pre-screening; (c) screening the genetic mutant strains for photosynthetic efficiency in mass cultures; and (d) further screening genetic mutants resulting from screening (c) by measuring biomass productivity to select strains having relatively high biomass productivity. Determining and/or engineering photosynthetic mutant algal strains comprises: (a) pre-screening wild-type or parent strains to select for photosynthetic efficiency by (a1) measuring a quantum requirement of the wild-type or parent strains at a sub-saturating light intensity, (a2) for wild-type or parent strains having a quantum requirement of ≤ 15 , further measuring photosynthetic capacity to select for strains having a relatively high P(max) per cellular mass, which includes a P(max) per cellular mass for oxygen evolution of at least 100 nmol/mg dry weight/minute, a P(max) max per cellular mass for carbon fixation of at least 80 nmol/mg dry weight/minute, and/or a μ (max) for specific growth rate of at least 0.1/hour, (a3) optionally further measuring a saturating light intensity on strains satisfying the requirements of (a1) and (a2) to screen for strains whose light intensity (I_s) is at least 125 μ E/m² /s; (a4) optionally further measuring a respiration and/or maintenance rate on strains satisfying the requirements of (a1) and (a2), and optionally also (a3), to screen for strains whose respiration/maintenance rate is less than 10% of μ (max) and/or P(max) where the pre-screening results in a group of wild-type and/or parent strains for further study, and (a5) optionally producing a high light acclimated state in the wild-type or parent, which wild-type or parent passes (a1) and (a2) and optionally (a3) and optionally (a4) to determine whether the high light acclimated wild-type or parent has at least a two thirds reduction in mass of chlorophyll a per cell mass; has P(max) per cell mass within 20% of the relatively low light (sub-saturating) adapted state of the wildtype or parent, has an I_s of at least 250 μ E/m² /s, and has a quantum requirement in a short term test under sub-saturating light of at most 125% of the wild-type or parent strain in a short term test under sub -saturating light; (b) causing genetic mutations in the group of wild-type and/or parent strains from pre-screening (a) to form genetic mutant strains; (c) screening the genetic mutant strains for photosynthetic efficiency in mass cultures by (c1) measuring a pigment content in the genetic mutant strains, (c2) for genetic mutant strains having a pigment content that is reduced by at least 50%, as compared to a pigment content of its corresponding wild-type and/or parent strain, further measuring photosynthetic capacity to select for strains having a relatively high P(max) per cellular mass, that is at least 75% of a per cellular mass of its corresponding wild-type and/or parent strain, (c3) for genetic mutant strains satisfying both (c1) and (c2), measuring saturating light intensity I_s to select for strains whose I_s is at least 250 μ E/m² /s and/or whose I_s is at least twice that of its corresponding wild-type and/or parent strain, (c4) for genetic mutant strains satisfying (c1)-(c3), measuring a quantum requirement at a sub-saturating light intensity to select for strains having a quantum requirement of ≤ 15 and/or at most 125% of the quantum requirement of its corresponding wild-type and/or parent strain, and (c5) optionally, for genetic mutant strains satisfying (c1)-(c4), further measuring a respiration and/or maintenance rate to screen for strains whose respiration/maintenance rate is less than 10% of μ (max) and/or P(max) per cellular mass; and (d) further screening the genetic mutants resulting from screening (c) by measuring biomass productivity to select strains having relatively high biomass productivity, measured as ash-free dry weight per volume of culture per unit time and/or as ash-free dry weight per area of illuminated surface of the culture per unit time, at least 25% higher than that of the corresponding wild-type and/or parent strains. An INDEPENDENT CLAIM is also included for determining and/or engineering photosynthetic mutant algal strains comprising: steps (a) and (b) as above per se; screening the genetic mutant strains for photosynthetic efficiency in mass cultures by steps (c1) and (c2) as above per se, for genetic mutant strains satisfying both (c1) and (c2), measuring saturating light intensity I_s to select for strains whose I_s is at least 125 μ E/m² /s and/or whose I_s is at least twice that of its corresponding wild-type and/or parent strain, steps (c4) and (c5) as above per se; and further screening the genetic mutants resulting from screening (c) by measuring lipid and/or starch productivity to select mutant strains having a lipid productivity and/or a starch productivity that is at least 25% higher than that of the corresponding wild-type and/or

parent strains. The method is useful for determining and/or engineering photosynthetic mutant algal strains. The method provides algal strains with reduced pigment to attain higher photosynthetic efficiency. Preferred Method: In the method: the step (a5) is accomplished in a laboratory illuminator with a culture volume of the wild type or parent being diluted such that a majority of the culture volume is above I_s when exposed to a source of incident light, thus resulting in the high light acclimated wild type or parent having a chlorophyll a content per unit cell mass at least 25% lower relative to that of the wild-type or parent cultured under sub-saturating light conditions for the same period; or the step (a5) is accomplished in an open pond with a culture volume of the wild type or parent being diluted such that a majority of the culture volume is at or above light saturation when exposed to a source of incident light, thus resulting in the high light acclimated wild type or parent having a chlorophyll a content per unit cell mass at least 25% lower than that of the wild-type or parent in a typically diluted culture in which the cells have a chlorophyll a content per unit cell mass similar to that of the parent culture adapted to sub-saturating light or less. In the method, either step (b) comprises or the method further comprises a step between steps (b) and (c) that comprises probing changes in genetic expression exhibited by the high light acclimated wild type or parent that are not present in the wild type or parent prior to production of the high light acclimated state in the wild type or parent. The method further comprises prior to step (b), validating a high light acclimated wild-type or parent strain produced in step (a5) in a laboratory illuminator by growing both the high light acclimated wild-type or parent strain and the wild-type or parent strain for less than 4 hours in optically thin suspensions in front of programmable light under a light regime programmed to simulate the movements of cells in a dense suspension, where cells/culture are/is illuminated with 900-2500 $\mu\text{E/m}^2/\text{s}$ to achieve a biomass productivity of the high light acclimated wild-type or parent strain that is at least 25% higher than that of the wild-type and/or parent strain.

Novelty

Determining and/or engineering photosynthetic mutant algal strains, comprises: (a) pre-screening wild-type or parent strains to select for photosynthetic efficiency; (b) causing genetic mutations in the group of wild-type and/or parent strains from pre-screening; (c) screening the genetic mutant strains for photosynthetic efficiency in mass cultures; and (d) further screening genetic mutants resulting from screening (c) by measuring biomass productivity to select strains having relatively high biomass productivity.

Advantages

The method provides algal strains with reduced pigment to attain higher photosynthetic efficiency.

6.5. Annex V: Geographical aggregations

Table 44 – Geographical definitions

Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
Africa	Algeria	North Africa	Africa	Rest of North Africa
	Angola	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Benin	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Botswana	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Burkina Faso	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Burundi	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa

Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
	Cabo Verde	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Cameroon	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Central African Republic	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Chad	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Comoros	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	The Republic of the Congo	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Côte d'Ivoire	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	The Democratic Republic of the Congo	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Djibouti	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Egypt	North Africa	Africa	Egypt
	Equatorial Guinea	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Eritrea	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	the Kingdom of Eswatini	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Ethiopia	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Gabon	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Gambia	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Ghana	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Guinea	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Guinea-Bissau	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Kenya	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa

Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
	Lesotho	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Liberia	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Libya	North Africa	Africa	Rest of North Africa
	Madagascar	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Malawi	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Mali	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Mauritania	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Mauritius	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Morocco	North Africa	Africa	Rest of North Africa
	Mozambique	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Namibia	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Niger	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Nigeria	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Réunion		Africa	Rest of Sub-Saharan Africa
	Rwanda	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Sao Tome and Principe	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Senegal	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	the Seychelles	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Sierra Leone	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa

Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
Africa	Somalia	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	South Africa	Sub-Saharan Africa	Africa	South Africa
	South Sudan	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Sudan	North Africa	Africa	Rest of North Africa
	Tanzania	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Togo	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Tunisia	North Africa	Africa	Rest of North Africa
	Uganda	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Zambia	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
	Zimbabwe	Sub-Saharan Africa	Africa	Rest of Sub-Saharan Africa
Asia	Afghanistan	Asia	Non-OECD Asia	Rest of South Asia
	Bahrain	Asia	Middle East	Rest of Middle East
	Bangladesh	Asia	Non-OECD Asia	Rest of South Asia
	Bhutan	Asia	Non-OECD Asia	Rest of South Asia
	Brunei Darussalam	Asia	Middle East	Rest of Middle East
	Cambodia	Asia	Non-OECD Asia	Rest of Asia Pacific
	Chinese Taipei	Asia	Non-OECD Asia	Rest of Asia Pacific
	Cook Islands	Asia	Non-OECD Asia	Rest of Asia Pacific
	Democratic People's Republic of Korea	Asia	Non-OECD Asia	Rest of Asia Pacific

Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
	East Timor	Asia	Non-OECD Asia	Rest of Asia Pacific
	Fiji	Asia	Non-OECD Asia	Rest of Asia Pacific
	French Polynesia	Asia	Non-OECD Asia	Rest of Asia Pacific
	Hong Kong	Asia	Non-OECD Asia	Rest of Asia Pacific
	India	Asia	Non-OECD Asia	India
	Indonesia	Asia	Non-OECD Asia	Indonesia
	Iran	Asia	Middle East	Iran
	Iraq	Asia	Middle East	Rest of Middle East
	Israel	Asia	Israel	Rest of Middle East
	Japan	Asia	Japan	Japan
	Jordan	Asia	Middle East	Rest of Middle East
	Kiribati	Asia	Non-OECD Asia	Rest of Asia Pacific
	Korea	Asia	Korea	Korea
	Kuwait	Asia	Non-OECD Asia	Rest of Asia Pacific
	Lao People's Democratic Republic	Asia	Non-OECD Asia	Rest of Asia Pacific
	Lebanon	Asia	Non-OECD Asia	Rest of Asia Pacific
	Macau, China	Asia	Non-OECD Asia	Rest of Asia Pacific
	Malaysia	Asia	Non-OECD Asia	Malaysia
	Maldives	Asia	Non-OECD Asia	Rest of South Asia
	Mongolia	Asia	Non-OECD Asia	Rest of Asia Pacific

Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
	Myanmar	Asia	Non-OECD Asia	Rest of Asia Pacific
	Nepal	Asia	Non-OECD Asia	Rest of South Asia
	New Caledonia	Asia	Non-OECD Asia	Rest of Asia Pacific
	Oman	Asia	Middle East	Rest of Middle East
	Pakistan	Asia	Non-OECD Asia	Rest of South Asia
	Palau	Asia	Non-OECD Asia	Rest of Asia Pacific
	Papua New Guinea	Asia	Non-OECD Asia	Rest of Asia Pacific
	People's Republic of China	Asia	Non-OECD Asia	China
	Philippines	Asia	Non-OECD Asia	Rest of Asia Pacific
	Qatar	Asia	Middle East	Rest of Middle East
	Samoa	Asia	Non-OECD Asia	Rest of Asia Pacific
	Saudi Arabia	Asia	Non-OECD Asia	Saudi Arabia
	Singapore	Asia	Non-OECD Asia	Rest of Asia Pacific
	Solomon Islands	Asia	Non-OECD Asia	Rest of Asia Pacific
	Sri Lanka	Asia	Non-OECD Asia	Rest of South Asia
	Syria	Asia	Middle East	Rest of Middle East
	Thailand	Asia	Non-OECD Asia	Thailand
	Tonga and Vanuatu	Asia	Non-OECD Asia	Rest of Asia Pacific
	Turkey	Turkey	Non-OECD Asia	Rest of Asia Pacific

Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
	United Arab Emirates	Asia	Middle East	Rest of Middle East
	Viet Nam	Asia	Non-OECD Asia	Vietnam
	Yemen	Asia	Middle East	Rest of Middle East
Australia and New Zealand	Australia	Australia	Australia	Australia
	New Zealand	New Zealand	New Zealand	New Zealand
Europe	Albania	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Armenia	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Austria	Western Europe	Austria	EU 28
	Azerbaijan	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Belarus	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Belgium	Western Europe	Belgium	EU 28
	Bosnia and Herzegovina	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Bulgaria	Eastern Europe	Non-OECD Europe and Eurasia	EU 28
	Croatia	Eastern Europe	Non-OECD Europe and Eurasia	EU 28
	Cyprus	Western Europe	Non-OECD Europe and Eurasia	EU 28
	Czech Republic	Eastern Europe	Czech Republic	EU 28
	Denmark	Western Europe	Denmark	EU 28

Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
	Estonia	Eastern Europe	Estonia	EU 28
	Finland	Western Europe	Finland	EU 28
	France	Western Europe	France	EU 28
	Georgia	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Germany	Western Europe	Germany	EU 28
	Gibraltar	Western Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Greece	Western Europe	Greece	EU 28
	Hungary	Eastern Europe	Hungary	EU 28
	Iceland	Western Europe	Iceland	Rest of Europe
	Ireland	Western Europe	Ireland	EU 28
	Italy	Western Europe	Italy	EU 28
	Kazakhstan	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Kosovo	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Kyrgyzstan	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Latvia	Eastern Europe	Latvia	EU 28
	Lithuania	Eastern Europe	Lithuania	EU 28
	Luxembourg	Western Europe	Luxembourg	EU 28

Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
	Malta	Western Europe	Non-OECD Europe and Eurasia	EU 28
	Moldova	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Montenegro	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Netherlands	Western Europe	Netherlands	EU 28
	Norway	Western Europe	Norway	Rest of Europe
	Poland	Eastern Europe	Poland	EU 28
	Portugal	Western Europe	Portugal	EU 28
	Romania	Eastern Europe	Non-OECD Europe and Eurasia	EU 28
	Russian Federation	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Serbia	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Slovak Republic	Eastern Europe	Slovak Republic	EU 28
	Slovenia	Eastern Europe	Slovenia	EU 28
	Spain	Western Europe	Spain	EU 28
	Sweden	Western Europe	Sweden	EU 28
	Switzerland	Western Europe	Switzerland	Rest of Europe
	Tajikistan	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	The Republic of North Macedonia	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe

Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
	Turkmenistan	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	Ukraine	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
	United Kingdom	Western Europe	United Kingdom	EU 28
	Uzbekistan	Eastern Europe	Non-OECD Europe and Eurasia	Rest of Europe
North America	Canada	Canada	Canada	Canada
	Mexico	Mexico	Mexico	Mexico
	United States	United States	United States	United States
South America	Anguilla, Antigua and Barbuda	Latin America	Non-OECD Americas	Rest of Latin America
	Argentina	Latin America	Non-OECD Americas	Argentina
	Aruba	Latin America	Non-OECD Americas	Rest of Latin America
	Bahamas	Latin America	Non-OECD Americas	Rest of Latin America
	Barbados	Latin America	Non-OECD Americas	Rest of Latin America
	Belize	Latin America	Non-OECD Americas	Rest of Latin America
	Bermuda	Latin America	Non-OECD Americas	Rest of Latin America
	Bolivarian Republic of Venezuela	Venezuela	Non-OECD Americas	Rest of Latin America
	Bolivia	Latin America	Non-OECD Americas	Rest of Latin America
	Brazil	Latin America	Brazil	Brazil
	British Virgin Islands	Latin America	Non-OECD Americas	Rest of Latin America
	Cayman Islands	Latin America	Non-OECD Americas	Rest of Latin America

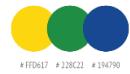
Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
	Chile	Latin America	Chile	Chile
	Colombia	Latin America	Non-OECD Americas	Rest of Latin America
	Costa Rica	Latin America	Non-OECD Americas	Rest of Latin America
	Cuba	Latin America	Non-OECD Americas	Rest of Latin America
	Curaçao	Latin America	Non-OECD Americas	Rest of Latin America
	Dominican Republic	Latin America	Non-OECD Americas	Rest of Latin America
	Ecuador	Latin America	Non-OECD Americas	Rest of Latin America
	El Salvador	Latin America	Non-OECD Americas	Rest of Latin America
	Falkland Islands (Malvinas)	Latin America	Non-OECD Americas	Rest of Latin America
	French Guiana	Latin America	Non-OECD Americas	Rest of Latin America
	Grenada	Latin America	Non-OECD Americas	Rest of Latin America
	Guadeloupe	Latin America	Non-OECD Americas	Rest of Latin America
	Guatemala	Latin America	Non-OECD Americas	Rest of Latin America
	Guyana	Latin America	Non-OECD Americas	Rest of Latin America
	Haiti	Latin America	Non-OECD Americas	Rest of Latin America
	Honduras	Latin America	Non-OECD Americas	Rest of Latin America
	Jamaica	Latin America	Non-OECD Americas	Rest of Latin America
	Martinique	Latin America	Non-OECD Americas	Rest of Latin America
	Montserrat	Latin America	Non-OECD Americas	Rest of Latin America

Region	Country	Oxford Economics country grouping	IEA country grouping	GECO country grouping
	Nicaragua	Latin America	Non-OECD Americas	Rest of Latin America
	Panama	Latin America	Non-OECD Americas	Rest of Latin America
	Paraguay	Latin America	Non-OECD Americas	Rest of Latin America
	Peru	Latin America	Non-OECD Americas	Rest of Latin America
	Puerto Rico	Latin America	Non-OECD Americas	Rest of Latin America
	Saba	Latin America	Non-OECD Americas	Rest of Latin America
	Saint Eustatius	Latin America	Non-OECD Americas	Rest of Latin America
	Saint Kitts and Nevis	Latin America	Non-OECD Americas	Rest of Latin America
	Saint Lucia	Latin America	Non-OECD Americas	Rest of Latin America
	Saint Pierre and Miquelon	Latin America	Non-OECD Americas	Rest of Latin America
	Saint Vincent and the Grenadines	Latin America	Non-OECD Americas	Rest of Latin America
	Sint Maarten	Latin America	Non-OECD Americas	Rest of Latin America
	Suriname	Latin America	Non-OECD Americas	Rest of Latin America
	The Turks and Caicos Islands	Latin America	Non-OECD Americas	Rest of Latin America
	Trinidad and Tobago	Latin America	Non-OECD Americas	Rest of Latin America
	Uruguay	Latin America	Non-OECD Americas	Rest of Latin America

6.6. Annex VI: Examples of other logo designs



Redesign Logo 1



option 1c



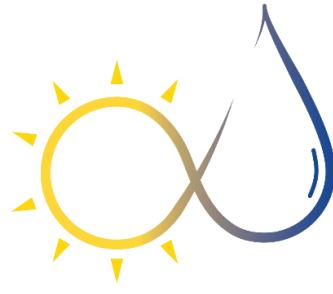
option 1d



Redesign Logo 2

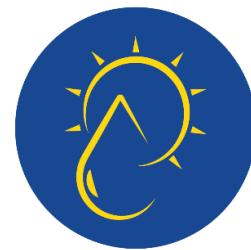


option 2a



option 2b

Planes instead of lines



Title integration 1

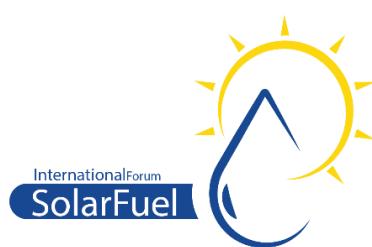


Title integration 2

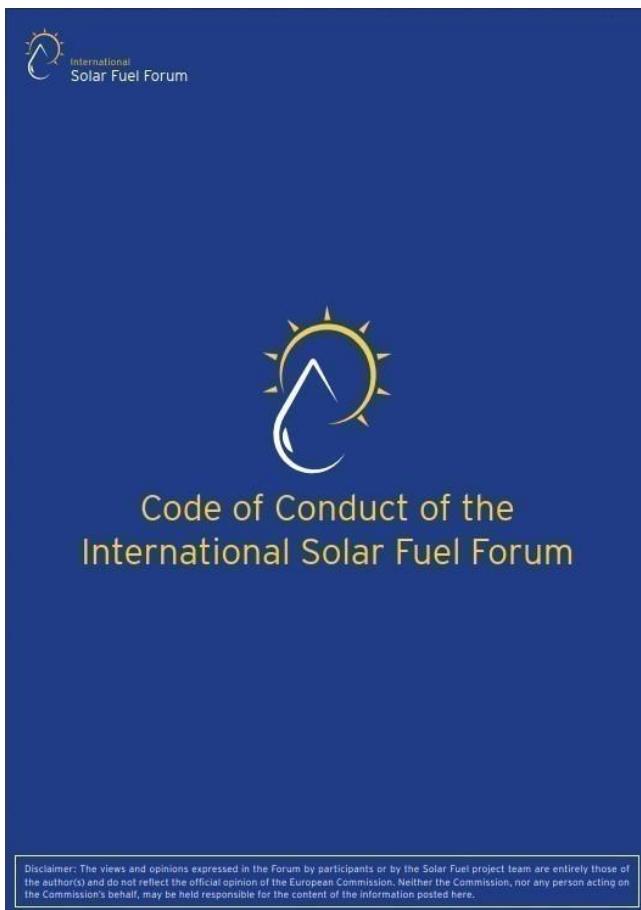


International
Solar Fuel Forum

Title integration 3



6.7. Annex VII: Forum Code of Conduct and Welcome Banner



The image shows a preview of the Forum Code of Conduct. At the top left is the International Solar Fuel Forum logo. The main title "Code of Conduct of the International Solar Fuel Forum" is centered in white text. Below the title is a small disclaimer in a black-bordered box: "Disclaimer: The views and opinions expressed in the Forum by participants or by the Solar Fuel project team are entirely those of the author(s) and do not reflect the official opinion of the European Commission. Neither the Commission, nor any person acting on the Commission's behalf, may be held responsible for the content of the information posted here." To the right of the preview is a larger section of the document. It features the same logo at the top. Below it is a detailed list of rules for the forum, starting with "This Space is for professionals who are experts and stakeholders in solar fuel. It is for constructive discussion and networking to build on the study findings." The list continues with several bullet points about registration, language, communication, and posting guidelines.

The International Solar Fuel Forum is a moderated space for discussion and a series of workshops, created in support to the European Union's study on 'Solar Fuels Research & Invest: Defining and developing the global solar fuel value chain: techno-economic analysis and pathways for sustainable implementation.' By being a member of this Forum, you agree to abide by the Code of Conduct stated in this document.

The Forum is composed of scientific experts and stakeholders in the area of solar fuels, who have registered for the Forum through the Solar Fuel project team, led by EY. @EYSolarFuel is the moderator of the Space, to ensure that the space is a suitable environment for a virtual meeting point of professionals to discuss the subject of solar fuels. The moderator will supervise the Space to guarantee that the Code of Conduct is respected and that the Forum can be a place for open discussion.

This Space is for professionals who are experts and stakeholders in solar fuel. It is for constructive discussion and networking to build on the study findings.

Access to the forum is by registration. Members cannot add participants to the Forum, however if you do have colleagues who would like to join, please message @EYSolarFuel directly or email the team at info.solarfuel@de.ey.com with the interested colleague in copy, so that the project team can add them to the discussion.

Language and communication used in the Forum shall remain professional at all times. Inappropriate, harmful or abusive language by text or other types of communication (images, gifs, stickers, etc.) will be removed by the Moderator and the person will be removed from the Forum.

Keep your communication in the Forum Spaces related to solar fuel technology, research and investment. Avoid sharing unnecessary personal information. Please do not post sensitive information in the Forum.

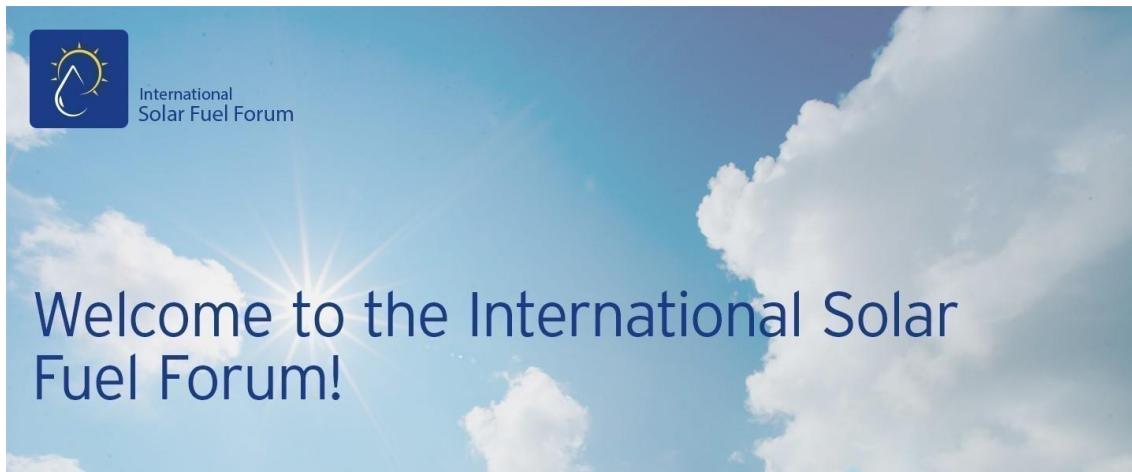
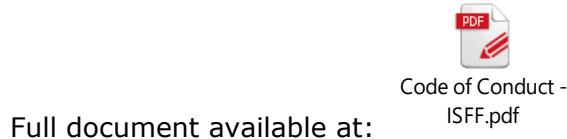
Any posting of commercial content, advertisement, or unrelated content to the subject of the Forum will be removed by the Moderator and the person will be removed from the Forum.

Do not edit or change the Space itself. Do not use or add bots, or make any other additions to the space.

Tips on how to use Webex Teams:

- The main Forum is called 'International Solar Fuel Forum.' This contains all the registered experts and stakeholders.
- If you want to mention someone by name, write '@name' to tag them in a message.
- To make sure you receive notifications from the space, click on the settings cog at the top of you page besides the Space title, and check that you have 'Global' enables to receives all the updates.

Figure 127 - Preview of Forum Code of Conduct



This Forum was created in support to the European Union's study on '**Solar Fuels Research & Invest: Defining and developing the global solar fuel value chain: techno-economic analysis and pathways for sustainable implementation.**' It is a central virtual meeting point for you to engage with fellow experts and stakeholders in solar fuel technology around the world. This Forum is moderated by the Solar Fuel project team, led by EY (@EYSolarFuel).

Figure 128 - Welcome banner for the Forum on Webex Teams

6.8. Annex VIII: Solar Fuel Survey Study Guide

Building on the EU's commitment to becoming a worldwide champion in renewable technologies and decarbonizing its society and economy, the European Commission has selected a consortium led by EY, with CEPS, IMEC and RINA Consulting, to conduct a study on 'Solar Fuels Research & Invest: Defining and developing the global solar fuel value chain: techno-economic analysis and pathways for sustainable implementation'.

The aim of the study is to perform:

- a techno-economic analysis of solar fuel value chains,
- a technology development roadmap for 2030 and 2050, and
- a market outlook for 2050 and 2100.

In order to do so, we have identified different solar fuel value chains produced either by chemical, biochemical, electrochemical or thermochemical pathways. These technological pathways and value chains were carefully identified to reflect current trends in global solar fuel developments and are used as basis for our techno-economic analysis.

In this context, we wish to further discuss the categorization of our technological pathways and components with you, throughout the different stakeholder engagement initiatives that will be launched for the project. We need your expertise and insights, as scientific experts, investment stakeholders, academics, industry specialists, regulatory bodies and civil society, to develop a strong network of stakeholders interested in being at the forefront of global solar fuel research and innovation.

To facilitate this exchange, this study guide aims at presenting our definitions of each pathway and the scope of the technology components they cover.

We look forward to discussing it with you!

EY IMEC RINA

Figure 129 - Preview of Study Guide for Solar Fuel Survey



Full Document available at:

6.9. Annex IX: Timeline of emails to stakeholders

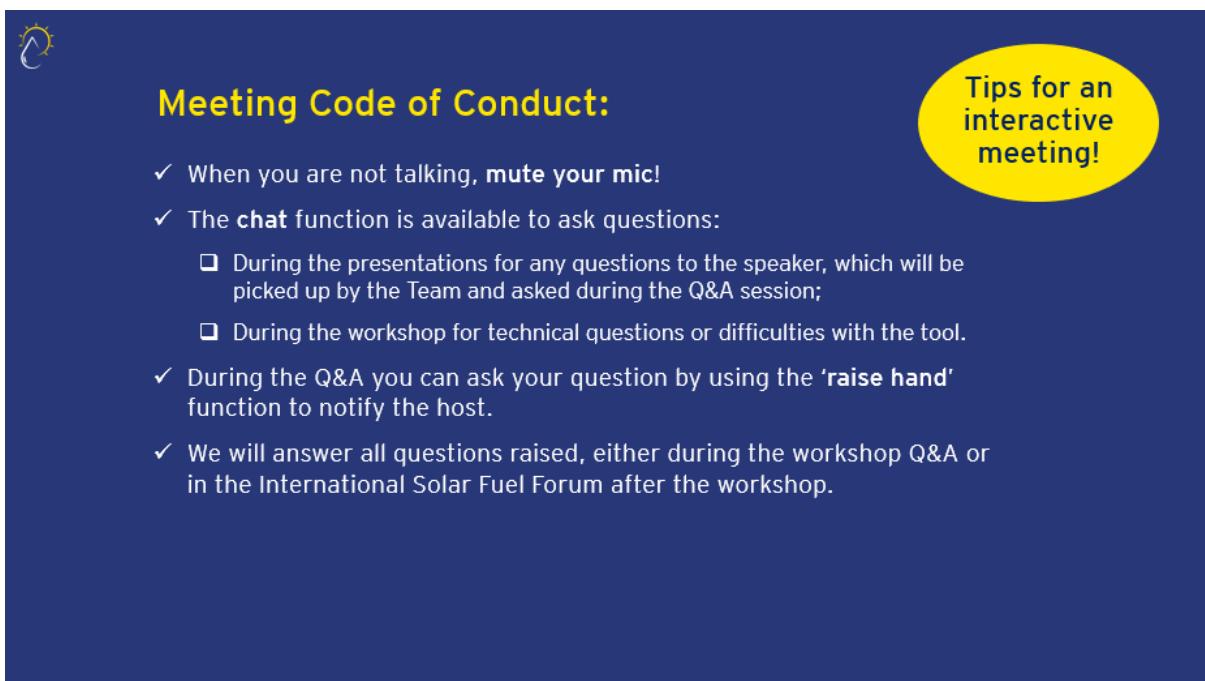
Below is an overview of the emails sent to participants with the email file attached. Please note that due to the compression of the emails into .html files, some of the formatting may have changed from the original emails that were sent out. To see the original email, please click "view this email in your browser" at the top of the email.

Table 45 - Timeline of emails sent and email files

Date	Purpose	Subject Line	Email file
28 February 2020	Introduce MI stakeholders to the study + ask them to register	(Via DG RTD email to their stakeholders) and Webex Meeting	 Solar_fuel_Study_MIS.pptx
10 March 2020	Register interest (to IMEC/RINA stakeholders)	Your invitation to join the International Solar Fuel Forum!	 International Solar Fuels Forum - invitati
19 March 2020	Reminder to register (to IMEC/RINA stakeholders)	Reminder: Don't miss your chance to join the International Solar Fuel Forum!	 International Solar Fuels Forum - remind
16 April 2020	Inform registered participants about upcoming activities	The International Solar Fuel Forum: upcoming activities	 The International Solar Fuel Forum - up
22 April 2020	Inform new registered participants about upcoming activities	The International Solar Fuel Forum: upcoming activities	 The International Solar Fuel Forum - up
28 April 2020	Reminder to register to non-registered (to IMEC/RINA stakeholders)	Your invitation to join the International Solar Fuel Forum!	 International Solar Fuels Forum - invitati
12 May 2020	How to join the Forum on Webex Teams and Webex Meetings	The International Solar Fuel Forum is ready - we are waiting for you to join!	 The International Solar Fuel Forum is re
13 May 2020	Introductory survey	The International Solar Fuel Forum: the Solar Fuel Introductory survey	 The International Solar Fuel Forum the:
18 May 2020	Reminder to non-registered for survey, register, workshop date (to IMEC/RINA stakeholders)	Solar Fuel Survey - International Solar Fuel Forum	 International Solar Fuel Forum- Invite for
19 May 2020	Reminder to fill in survey	[Reminder] Solar Fuel Survey - International Solar Fuel Forum	 Reminder Solar Fuel Survey International !
20 May 2020	Invitation to first workshop, agenda and register for Forum reminder	3 June Workshop: Solar Fuels Study and Survey Results – International Solar Fuel Forum	 3 June Workshop Solar Fuels Study and

26 May 2020	Reminder to fill in survey	[Reminder] Solar Fuel Survey - International Solar Fuel Forum	 Reminder Solar Fuel Survey International !
29 May 2020	Reminder to register for first workshop	[Reminder] 3 June Workshop: Solar Fuels Study and Survey Results – International Solar Fuel Forum	 Reminder 3 June Workshop Solar Fuels
29 May 2020	Invitation to workshop	3 June Workshop: Solar Fuels Study and Survey Results – International Solar Fuel Forum	 3 June Workshop Solar Fuels Study and
10 June 2020	Invitation to second workshop; thank you and follow up material from first workshop; survey; instructions to join Forum	17 June workshop: Electrochemical and Thermochemical Solar Fuels – International Solar Fuel Forum	 17 June workshop Electrochemical and T
16 June 2020	Reminder to register for second workshop	[Reminder] 17 June workshop: Electrochemical and Thermochemical Solar Fuels – International Solar Fuel Forum	 Reminder 17 June workshop Electrochen
23 June 2020	Invitation to third workshop; thank you and follow up material from second workshop; survey; instructions to join Forum	29 June workshop: Chemical and Biochemical Solar Fuels – International Solar Fuel Forum	 29 June workshop Chemical and Bioche
26 June 2020	Reminder invite to third workshop	[Reminder] 29 June workshop: Chemical and Biochemical Solar Fuels – International Solar Fuel Forum	 Reminder 29 June workshop Chemical a
08 July 2020	Thank you third workshop; thank you and follow up material from first workshop; survey; instructions to join Forum + conference announcement	Slides from third workshop and conference announcement – International Solar Fuel Forum	 Slides from third workshop and confer
08 July 2020	Privacy gateway - register your contact details with us	Solar Fuel conference - register your details to receive updates from the International Solar Fuel Forum	 Solar Fuel conference - register your details
15 July 2020	Final reminder for privacy gateway	[Final email] Register your details to receive updates from the International Solar Fuel Forum	 Final email Register your details to receive

6.10. Annex X: Meeting Code of Conduct and Recording Disclaimer slides



The slide has a dark blue background with a yellow circular icon in the top left corner containing a stylized sun or leaf symbol. In the top right corner, there is a yellow speech bubble containing the text "Tips for an interactive meeting!". The main title "Meeting Code of Conduct:" is in bold yellow text at the top center. Below it is a bulleted list of guidelines:

- ✓ When you are not talking, **mute your mic!**
- ✓ The **chat** function is available to ask questions:
 - ❑ During the presentations for any questions to the speaker, which will be picked up by the Team and asked during the Q&A session;
 - ❑ During the workshop for technical questions or difficulties with the tool.
- ✓ During the Q&A you can ask your question by using the '**raise hand**' function to notify the host.
- ✓ We will answer all questions raised, either during the workshop Q&A or in the International Solar Fuel Forum after the workshop.

Figure 130 - Meeting Code of Conduct slide



The slide has a dark blue background with a yellow circular icon in the top left corner containing a stylized sun or leaf symbol. The main title "Important: The workshop will be recorded" is in bold yellow text at the top center. Below it is a bulleted list of information:

- This workshop will be recorded for **internal use only** within the project team. We will use the recording to complete the minutes of the workshop.
- It will not be disseminated or distributed outside the project team.
- Once the minutes have been completed, the recording will be deleted.
- By being in this virtual meeting, you approve that this workshop will be recorded for the internal purposes outlined above. Please contact the team if you have any questions: info.solarfuel@be.ey.com
- For more information on our privacy policy and protection of the stored content and data, please visit: https://www.ey.com/en_be/privacy-statement

Figure 131 - Workshop recording disclaimer slide



Solar Fuels Research & Invest Conference

September 30th 2020 – Morning

10:00 – 10:10	Welcome address by Philippe Schild and Thomas Schleker, DG RTD, European Commission
10:10 – 10:30	Keynote speech by Professor Sophia Haussener, Associate Professor at Laboratory of Renewable Energy Science and Engineering, EPFL
10:30 – 11:00	Presentation of the solar fuels value chains and technology roadmap results - Electrochemical and Chemical pathways by Joachim John, IMEC
11:00 – 11:15	Q&A moderated by Felice Simonelli, CEPS
11:15 - 11:30	Break
11:30 – 12:00	Presentation of the solar fuels value chains and technology roadmap results - Thermochemical and Biochemical pathways by Alessandro Venturin and Andrea Leoncini, RINA
12:00 – 12:15	Q&A moderated by Felice Simonelli, CEPS
12:15 – 12:30	High level speech by Deepak Pant, Senior Scientist, VITO
12:30 – 12:40	Conclusions from the first session by Thomas Schleker, DG RTD, European Commission

September 30th 2020 – Afternoon

14:00 – 14:10	Welcome address to part two by Antonio de Rose, EY
14:10 – 14:30	High level speech by Denis Thomas, EU Regulatory Affairs & Business Development Manager Renewable Hydrogen, Hydrogenics
14:30 – 15:20	Panel Discussion: Towards industrial generation of solar fuels Panelists: Philippe Schild, Sophia Haussener, Denis Thomas, Deepak Pant Moderated by Nicholas Merriman, EY
15:20 – 15:35	Q&A
15:35 – 15:50	Break
15:50 – 16:20	Presentation of project results on Economic roadmap and Market Outlook for sustainable solar fuels for 2050 and 2100 by Nicholas Merriman, EY
16:20 – 16:35	Q&A moderated by Nicholas Merriman, EY
16:35 – 16:45	Closing remarks by Nicholas Merriman, EY



imec



Solar Fuels Research & Invest Conference

Invitation-only sessions

October 1st 2020

Invitation-only session on Electrochemical and Chemical pathways

10:00 – 10:05	Introduction
10:05 – 11:35	Presentation of results on Electrochemical and Chemical pathways and discussion on opportunities for further collaboration lead by Joachim John, IMEC
11:35 – 11:45	Conclusions by Nicholas Merriman, EY

Invitation-only session on Thermochemical and Biochemical pathways

14:00 – 14:05	Introduction
14:05 – 15:35	Presentation of results on Thermochemical and Biochemical pathways and discussion on opportunities for further collaboration lead by Andrea Leoncini, RINA
15:40 – 15:45	Conclusions by Nicholas Merriman, EY

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You can contact this service:

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- at the following standard number: +32 22999696, or
- by email via: https://europa.eu/european-union/contact_en

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Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

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<https://op.europa.eu/en/publications>. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en)

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For access to legal information from the EU, including all EU law since 1952 in all the official language versions, go to EUR-Lex at: <http://eur-lex.europa.eu>

OPEN DATA FROM THE EU

The EU Open Data Portal (<http://data.europa.eu/euodp/en>) provides access to datasets from the EU. Data can be downloaded and reused for free, for both commercial and non-commercial purposes.

This European Commission funded study provides a techno-economic analysis of global solar fuel value chains and pathways for sustainable implementation. It is structured around four key tasks providing: a techno-economic analysis of worldwide solar fuel value chains; a technological development roadmap for 2030 and 2050 and economic roadmap to 2100 as well as a market outlook mapping the full potential of solar fuels for 2050 and 2100; the International Solar Fuels Forum; and the organisation of an international conference on solar fuels. The study aims at identifying the key technological bottlenecks that need to be overcome to allow for the large-scale industrial production of solar fuels. Based on this, the cost competitiveness of a number of solar fuel technologies is assessed, together with their potential time-to-market to replace comparable fossil fuels. By forecasting the potential demand for solar fuels through 2100, the study gives an outlook on what role solar fuels could play in our future energy systems. The investments required to build capacity to meet this demand are also discussed. The report also describes the development of the International Solar Fuel Forum that was used as communication channel to disseminate study results and to encourage discussion between solar fuels experts.

Studies and reports

