SUN ERGY

Unlocking the renewable energy future

Strategic Research and Innovation Agenda

November 2022

THE CHALLENGE we are facing

Running our entire world strongly depends on fossil-based energy sources and raw materials. Their intensive use over the last decades not only depleted the Earth's resources, but also caused a significant increase of the carbon dioxide concentration in the atmosphere and therewith global warming, with tremendous consequences for ecosystems and society in general.

In the EU, the energy and transport sector generate the major part of greenhouse gas emissions, with 54 % for energy and 24 % for transport-related activities in 2016. These sectors remain central for providing welfare, industrial competitiveness and quality of life. At the same time, the electrification of society continues to grow, with the urgent need for efficient storage solutions.

SUNERGY contribution

By combining energy from renewable sources with abundant molecules (carbon dioxide, water, nitrogen) and waste, we can produce fuels and chemicals that can contribute to stopping global warming. SUNERGY proposes a pipeline of high impact technologies that boost efficiency on the supply side by making fuels as well as base chemicals for industry and agriculture next to developing negative carbon dioxide emission technologies using resources abundant in Europe to enable a circular economy.

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Executive summary[1,2]

Modern civilization thrives on a constant flow of energy and material goods obtained from natural resources such as fossil fuels. Our societies are now facing the challenge to displace fossil resources for fuels and chemicals by renewables. Different alternative routes are explored. The share of solar and wind renewable power is rapidly increasing and will soon reach the desired scale in the TW range. Together with a **massive electrification** of society and industry, this is one of the central pathways to carbon neutrality. For hard-to-abate sectors, i.e. those difficult to completely electrify, the direct use of electricity can be supported by using **molecules made from renewable resources**. Hydrogen, carbon-based compounds and ammonia can be obtained, e.g. from biomass conversion; however, the supply of sustainable biological feedstock to power the global energy system is limited. These biofuels can be complemented with renewable fuels and chemicals produced with renewable power, so-called **e-fuels** or powerfuels, or with molecules directly produced from solar energy, i.e., **solar fuels**. Carbon is either sourced from waste CO_2 from industrial sites or from the atmosphere to establish a **circular carbon economy**. The sustainable manufacturing of such renewable fuels and chemicals at the needed scale is in sight but not yet within reach.

The SUNERGY initiative aims at filling the gap between sustainable and scalable renewables and at enabling the full decoupling of economic growth from the utilisation of resources at the local, regional, national and European level. It focuses on learning how to sustainably manufacture energy carriers and chemicals while reducing cost over the **entire source to product value chain**. SUNERGY technology development and timely adaptation of energy infrastructure will enhance the manufacturing of energy carriers within Europe and reduce the need for energy import and associated geopolitical risks.

SUNERGY aims for displacing fossil fuel-based chemicals and fuels by renewables. This is enabled by novel **technologies with high overall energy and economic efficiency**. Cost reduction for renewable chemical production will stem either from high economic efficiency in **industrial sites** with economies of scale or from **decentralised business operations** integrated with suitable grids within the existing urbanised economic infrastructures.

The technological portfolio of SUNERGY is based on two main technological approaches: *indirect routes*, where renewable power is converted into fuels and chemicals through multiple steps, and the more disruptive, *direct conversion of solar energy* enabling a decentralised manufacturing of green chemicals and fuel at the highest possible yield (Figure 1). These technologies must be brought to the market with a massive deployment as

[1] This is a living document that will be developed further together with the SUNERGY community during the SUNER-C CSA (Grant Agreement no. 101058481).

[2] The views expressed in this publication are the responsibility of the authors and do not necessarily reflect the views of the European Commission nor of the European Innovation Council and SMEs Executive Agency. The identification of an area in this document does not imply that all authors or the European Commission or the European Innovation Council and SMEs Executive Agency agree with it. The European Commission or the European Innovation Council and SMEs Executive Agency are not liable for any consequence stemming from the reuse of this publication.

soon as possible. This requires a concerted, coherent and substantial research and innovation effort. The SUNERGY community is well positioned for this task, currently counting more than 300 supporting organisations from industry, academia and civil society, and working in close dialogue with EU and national decision makers.

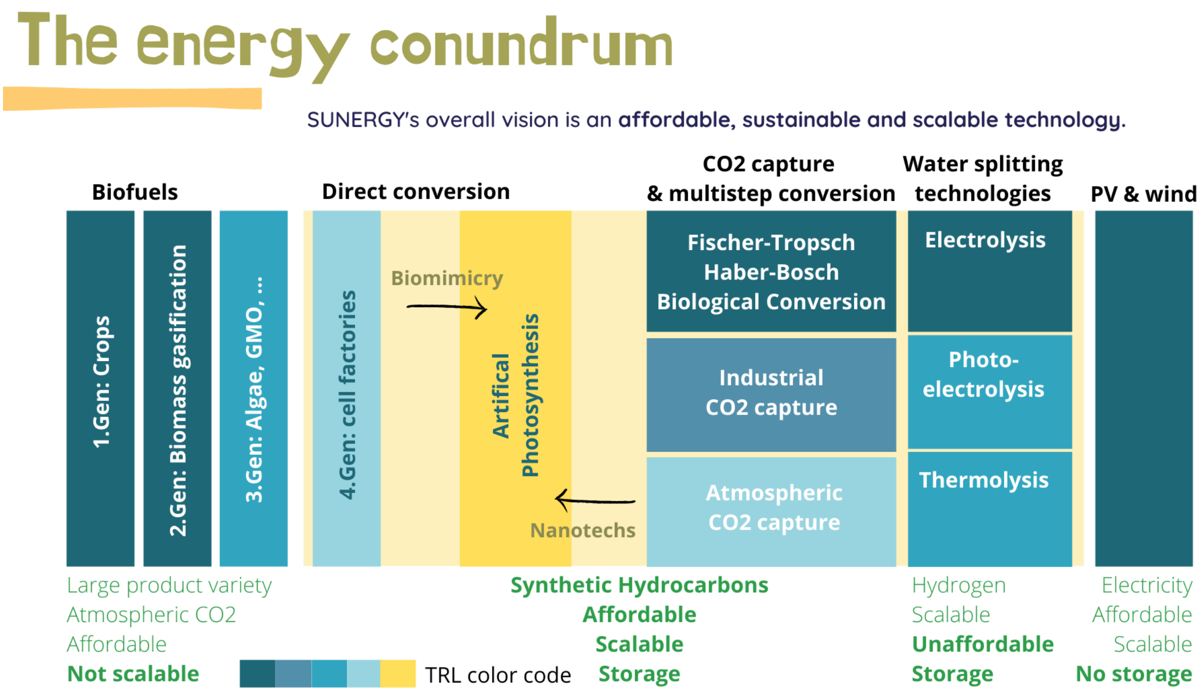

Figure 1. SUNERGY's overall goal is to provide an affordable, sustainable and scalable technology for the provision of synthetic hydrocarbons. Today, mature and affordable technologies are available to produce electricity from renewable resources - however, these technologies lack direct storage options. On the other hand, long-term storage is provided by technologies based on the transformation of solar energy into biomass. First and second generation biomass-based fuels (so-called biofuels) are affordable, but are not scalable to the entire global fuel demand because of low conversion efficiencies and consequently a high land footprint. SUNERGY focusses on technologies which merge these two concepts (middle of the scheme, yellow background). In the short term, renewable electricity is stored in the form of hydrogen and can be combined with carbon dioxide or nitrogen into diverse fuels and chemicals. These nanotech-based approaches, as well as living cell factory approaches (biomimicry), will nourish the development of technologies converting sunlight directly into an end product. This increases overall energy conversion efficiencies and will provide affordable and scalable technologies in the long-term. Source: adapted from G.J. Kramer, Utrecht University.

The present Strategic Research and Innovation Agenda[3] outlines the necessary technological steps that significantly contribute to reaching Europe's carbon neutrality within the next 30 years. Both solutions for the short-to-medium term as well as for the long-term (Figure 2) are discussed. This document provides a solid basis for the development of a full technological roadmap through broad consultation with the relevant stakeholders on the best

[3] SUNERGY's SRIA is based on the [SUNRISE technological roadmap] and the [ENERGY-X Research Needs]. It also takes into consideration the [Mission Innovation Challenge 5 Roadmap].

strategies to meet this overarching goal. It is also the basis to inform policy making of the necessary regulatory and financial support to clean technology solutions that can contribute to the ambitious EU goals.

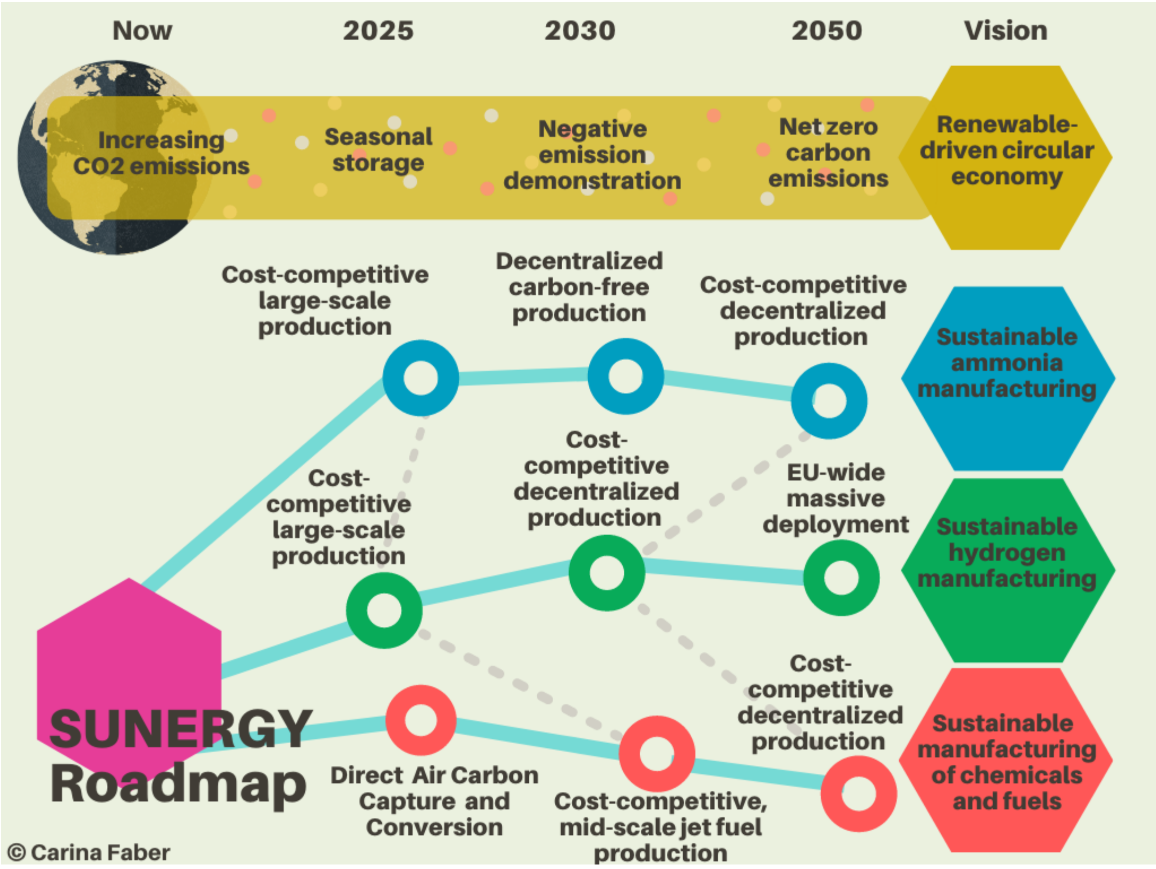

Figure 2. Principal key performance indicators of the SUNERGY Strategic Research and Innovation Agenda. Europe aims at establishing a carbon-neutral society based on a circular economy driven by renewable energy by 2050. The **sustainable manufacturing of green hydrogen, ammonia as well as carbon-based chemicals and fuels** are the industrial drivers behind the SUNERGY large-scale research and innovation initiative. Moreover, SUNERGY technologies enable the **seasonal storage** of intermittent renewable energy sources. Milestones at the short-to-medium term, as well as on the long-term are provided, enabling a **smooth transition to a renewable-driven circular economy**. A major milestone is the cost-competitive, mid-scale production of jet fuels in 2030.

From a linear to a circular economy

Today’s energy system strongly depends on fossil-based energy sources and raw materials. Their intensive use over the last decades not only depleted the Earth’s reservoirs, but also caused a significant increase of the carbon dioxide concentration (and other greenhouse gases) in the atmosphere. Among many worrisome consequences, a rise in the average global temperature is shattering. Latest reports highlight the tremendous consequences of the ongoing warming on ecosystems, resources and accordingly society at large.

A replacement of fossil-based energy sources and raw materials is crucial for Europe's vision of a zero-emission society, as well as securing Europe’s independence from imported resources and the global competitiveness of its industry. The European Commission anchored these ambitious goals on the political level through a number of initiatives including the European Green Deal and the Energy Union. However, at present technologies for the transition to a zero and negative emission society are not yet available for a fully sustainable deployment on a global scale. A coordinated effort on research and innovation is therefore crucial to provide affordable clean technologies to society for green fuel and chemical production. Large-scale implementation of these technologies matched by societal acceptance will be pivotal for establishing the circular economy driven by renewable resources.

The present document introduces the SUNERGY strategic research and innovation agenda (SRIA) for a large-scale R&I initiative dedicated to increasing the technological readiness of renewable conversion technologies for the large-scale, sustainable manufacturing of hydrogen, renewable carbon-based compounds and ammonia (Figure 3). A target of less than 50€ barrel equivalent is to be achieved by cost reductions over the entire value chain from source to product. This requires a radical transformation of the energy-chemical conversion system, adopting an integrated triple-helix approach. The latter is characterised by the symbiosis between fundamental research needs, industrial application and wide technology deployment.

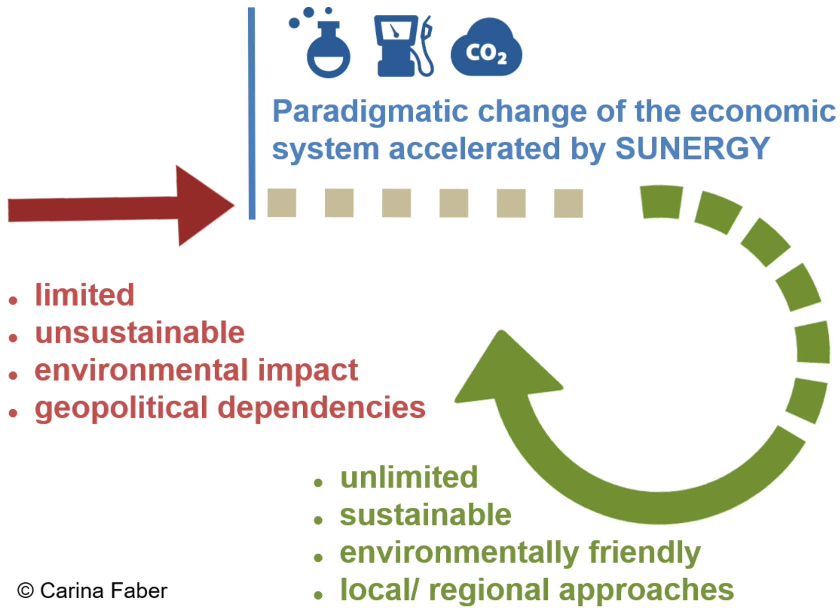

Figure 3. Drivers and long-term benefits for establishing a carbon-neutral circular economy in a systems approach employing SUNERGY technologies.

SUNERGY's Vision

Europe wants to tackle the grand challenge of defossilizing its industry to enable a transition from a linear to a circular carbon economy. SUNERGY's vision (Figure 4) is to overcome the critical hurdle of developing cost-efficient low-carbon technologies to convert renewable energy and resources that are abundant in Europe (CO_2, N_2, H_2O) into fossil-free fuels and base chemicals for industry and agriculture. SUNERGY aims to develop technologies and new value chains to substitute the massive use of fossil fuels with renewable chemicals and fuels (hydrogen, carbon-neutral hydrocarbons and ammonia). SUNERGY goes beyond green hydrogen production by utilising hydrogen as an invaluable intermediate to generate fuels and chemicals characterised by a higher volumetric energy density[4] and thus by cost-effective storage and transport.

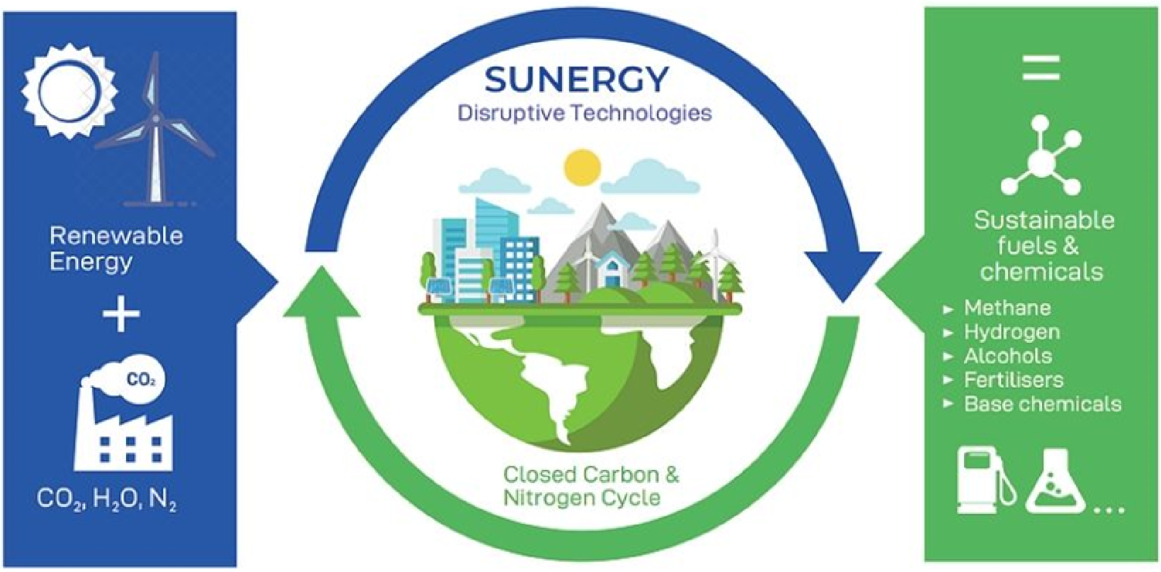

Figure 4. SUNERGY will facilitate the transition to a circular economy and a carbon-neutral society. Abundantly available molecules – carbon dioxide, water, oxygen and nitrogen (CO_2, H_2O, O_2 and N_2) – replace fossil-based raw materials to produce a broad range of chemicals and fuels. SUNERGY targets a sustainable CO_2 cycle, where the concentration in the atmosphere is decreased and then maintained at a level compatible with climate stability, committing to the sustainable use of natural resources and land.

The shift to a defossilized value chain requires technologies that convert renewable energy and abundantly available resources into green fuels and feedstock at affordable cost. Renewable energies such as wind and solar are all-around, but only in a dilute form, i.e. not concentrated in a way that they can be used to meet the ever-growing energy demand. The new paradigm pursued by SUNERGY is to concentrate and store renewable energy in chemical form which can be produced and used in any location (as opposed to current centralised production of fossil fuels and chemicals which usually requires long-distance distribution).

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[4] at ambient conditions

SUNERGY scientists believe that energy conversion should not be limited to traditional conversion technologies (e.g. thermal processes) that operate at a high rate with factoring losses. Lessons from natural photosynthesis have shown that affordable and sustainable manufacturing of energy carriers, and other products with virtually unlimited structural complexity, is feasible by decentralised renewable energy conversion beyond the slow conversion (adiabatic) limit. This provides ample opportunities to reduce manufacturing costs with high photon-to-product yield, high materials efficiency, and minimal losses in dedicated energy conversion pathways. In the long run, SUNERGY takes a systems approach towards the development and deployment of a new economy model for manufacturing of primary energy carriers and chemicals, at the base of all industrialised sectors, including agriculture. In parallel to the centralised energy supply, the decentralised manufacturing of fuels and chemicals, through realisation of the 'artificial photosynthesis' concept, will allow for smooth integration of the SUNERGY's value chain with the local resources and territory, favouring employment and reducing the environmental impact; thus, boosting environmental and societal sustainability.

The specific objectives for the SUNERGY initiative are to:

1. develop easily **replicable and scalable technologies** for the conversion of solar light into chemicals and fuels, helping to achieve CO_2 reduction targets before 2040 by:
    a. providing green hydrogen at scale,
    b. providing fuels and chemicals, beyond hydrogen, from renewable resources at scale - e.g. green ammonia or diverse hydrocarbons,
    c. providing technologies with maximised performance, including conversion efficiencies, product selectivity and yield over the full production value chain.
2. provide cost-effective, **highly flexible solutions** for manufacturing renewables, adaptable to a broad variety of energy scenarios and industrial needs,
3. develop a **systems approach** for establishing the novel full value chain infrastructure for energy conversion, with the focus on a high global-scale impact, by improving cost effectiveness and realisation of synergies between various technologies. Reducing cost requires industrial symbiosis matched by societal acceptance in regions with high economic efficiency.

The realisation of the European vision through the SUNERGY objectives will lead to improved industrial competitiveness decoupled from the environmental degradation and fossil fuel dependency. In addition, the SUNERGY initiative will contribute to climate change mitigation by increasing the share of renewables in the energy mix through long-term storage of intermittent renewable energy in the form of fuels and chemicals. By 2050, SUNERGY will contribute to a CO_2-neutral circular economy, net climate neutral mobility for people and goods, as well as affordable negative emissions technologies deployed at a significant scale.

SUNERGY Research and Innovation Focus Areas

Two main technological approaches

The overarching vision of SUNERGY is to enable the sustainable, low-emission production of chemicals and fuels. This is conceived as a gradual process, providing green technologies ready to be employed at scale at each time step from now up to 2040 (Figure 5).

The first technological approach represents a portfolio of relatively mature technologies for a large-scale centralised energy supply and uses **multiple steps** to produce alternative fuels and chemicals. The second approach takes inspiration from nature, where - through the process of **artificial photosynthesis** - solar energy, water and carbon dioxide are directly transformed into chemical energy in the form of carbon-based compounds. This is a very promising approach for a future decentralised energy conversion system, but at present it is at lower technological maturity. Besides these two core activities, the development of **key enabling technologies** is a crucial strategic element for the large-scale deployment of low-emission technologies.

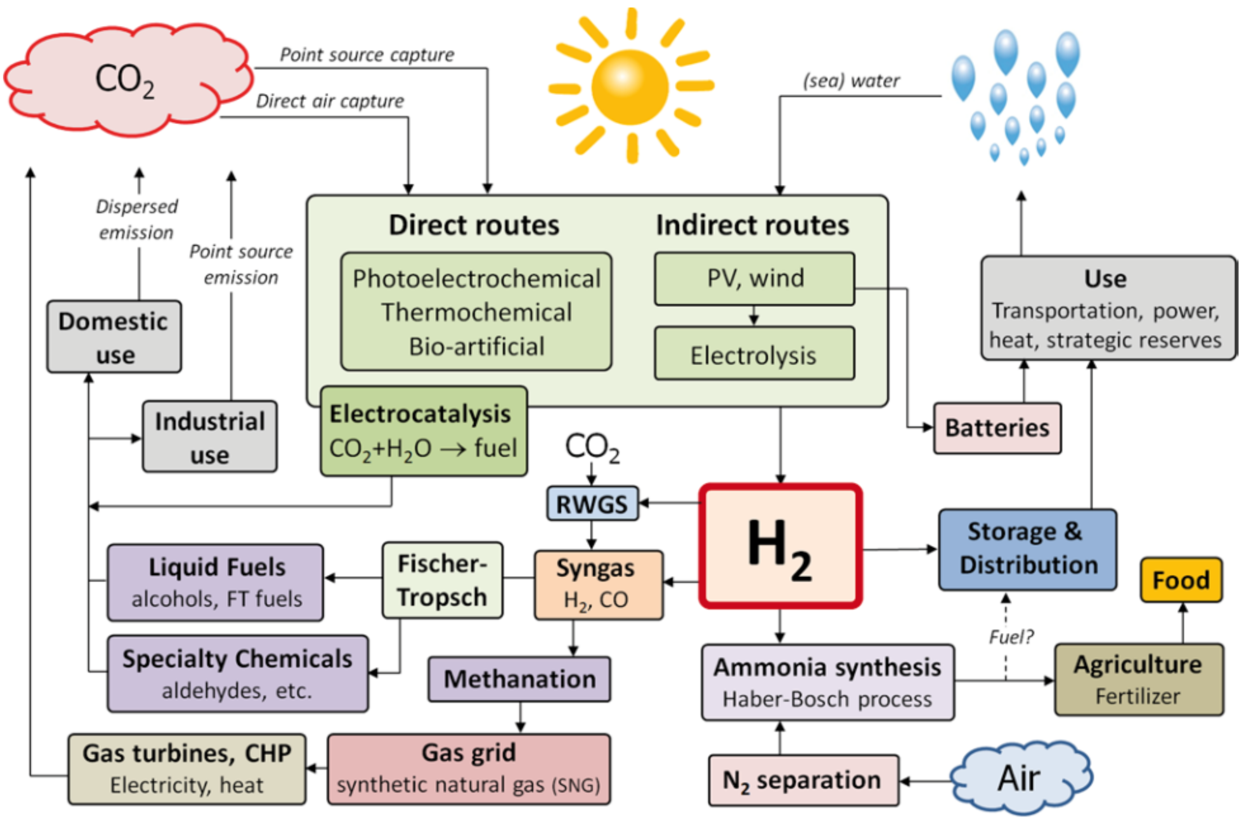


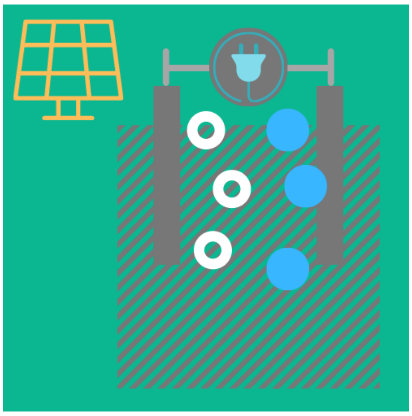
Figure 5. Future energy infrastructure based on the renewable and fossil-free conversion of renewable energy into a variety of carbon-, nitrogen- and hydrogen-based chemicals and fuels. Water splitting, either via direct or indirect routes, plays a crucial role in this scenario. The hydrogen produced via these routes can be fed into the already existing large-scale infrastructure for methanation and Fischer–Tropsch synthesis by reacting it with CO_2 to form syngas via the reverse water-gas-shift (RWGS) reaction. CO_2 is captured either from industrial point sources or from the

atmosphere. Electrocatalysis (CO_2 + H_2O to fuel) is an enabling technology for both direct and indirect routes. The areas of application of the final products span multiple sectors, including the energy sector through electricity and heat production with turbines, transportation and even the food sector by supplying ammonia-based fertilisers. Source: R. van de Krol, B. A. Parkinson (2017) *MRS Energy & Sustainability*, 4, e13.

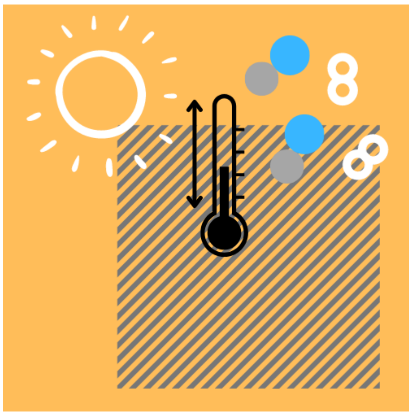
Multistep conversion: indirect route

The production of fuels and chemicals from green electricity is a **multistep approach** in two aspects: *first*, it combines the independent production of renewable power with the subsequent synthesis of intermediate products such as green hydrogen via water electrolysis. *Second*, these intermediate compounds serve as energy-rich building blocks for the production of renewable fuels and chemicals e.g. through conventional conversion processes. These include the industrially well-developed Fischer-Tropsch process for the production of fuels for transportation from syngas or the Haber-Bosch cycle for ammonia production from green hydrogen (Figure 6). Also less-industrially developed upgrading routes are promising, such as taking green methanol as a feedstock for drop-in fuels or the biological conversion of hydrogen and CO/CO_2 to ethanol or methane.

Upstream processes: from simple molecules to valuable intermediate products



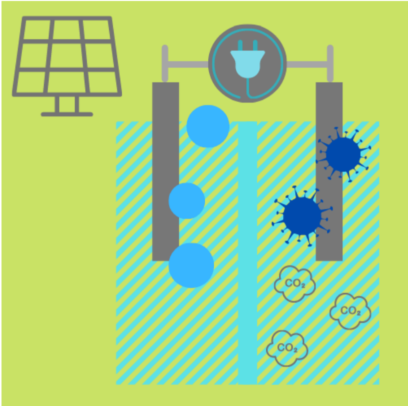
E-fuels: from green electricity to fuels and chemicals
In this approach, electricity provides the needed amount of energy to drive a given chemical reaction. The electrochemical conversion of water, the so-called water electrolysis, produces oxygen and hydrogen gas, a key enabler in the SUNERGY vision. By using renewable electricity sources, hydrogen production becomes free of carbon emissions. Beyond water electrolysis, also CO_2 and water can be directly transformed into chemical feedstock via the so-called co-electrolysis[5] or direct CO_2 electroreduction technologies.[6]



Alternative fuels and chemicals from solar heat
As an alternative to electrochemical routes, solar thermochemical approaches are another appealing pathway for multistep CO_2 conversion and H_2O splitting. These approaches require an input of heat instead of electricity to produce either hydrogen or syngas (a mixture of hydrogen and carbon monoxide). The heat input can be delivered renewably by concentrated solar power approaches. This represents again a multistep pathway,

[5] Avoiding the separate production of H_2 and a distinct thermocatalytic step through a direct electrocatalytic conversion unit could largely increase energy efficiencies and thus reduce costs and energy losses, with a benefit in lowering the carbon footprint.
[6] In addition, plasma-assisted synthesis is an alternative for chemical conversions using electrical power.

where the produced syngas is later on converted into fuels and chemicals using conventional production processes.



PV-driven bioelectrosynthesis

A promising strategy is to power a microbial cell reactor with solid-state photovoltaics. Recently, such hybrid systems have combined advantages of the metabolic versatility of microorganisms and the efficiency of inorganic solar energy capture devices to drive the reduction of CO_2 into fuels and other C_n compounds. The concept is based on the utilisation of external sources of green electricity for the generation of reducing equivalents (electrons and protons) that are then acquired by the autotrophic biocatalyst (microbial cells) present in the cathodic chamber for reducing CO_2 into fuels or other target chemicals. There are many examples of PV-driven microbial electrosynthesis reactors with promising yield and product versatility (e.g., methane, liquid fuels, high value chemicals, plastic precursors or nutrients).[7] Even though bioelectrosynthesis is still at low to medium TRL (depending on the targeted product), these systems carry a high potential for industrial applications. Methane production is for example showing pilot developments (Electrochaea).

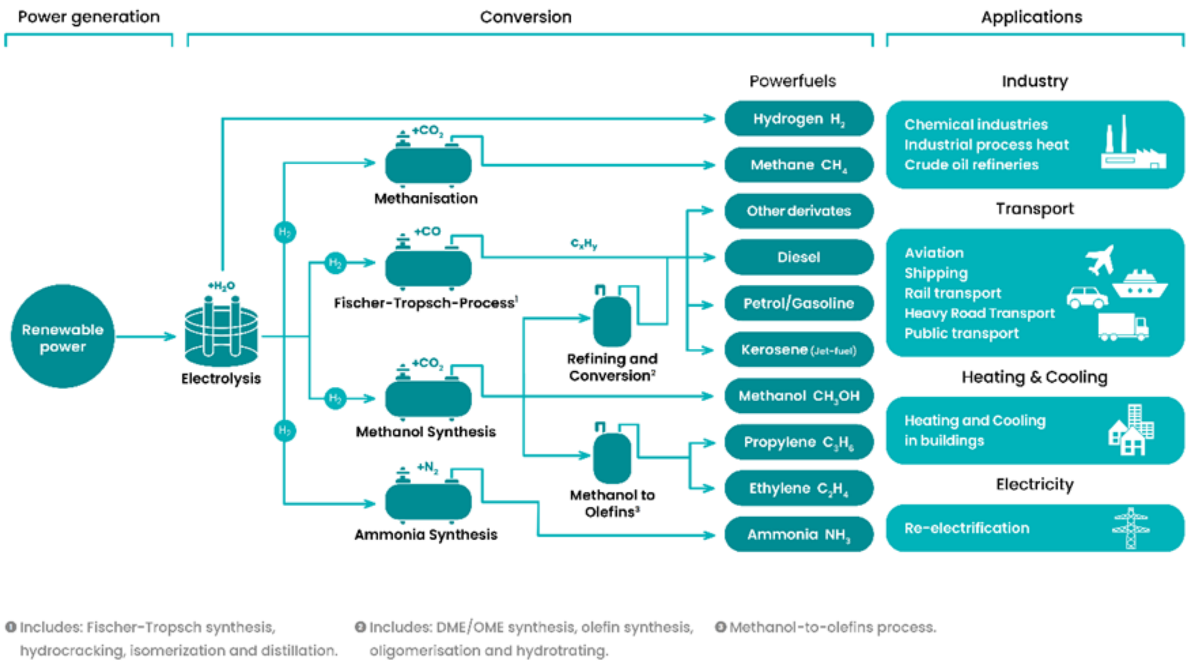


Figure 6. Illustration of a sustainable energy system based on multi-step renewable power conversion. Several components are industrially well-developed at present. E-fuels are produced from renewable power, driving the splitting of water into hydrogen and oxygen. In subsequent conversion

[7] including systems where the biocatalyst was an acetogen, a Fe^{2+}-oxidising bacteria, the ammonia-oxidizer *Nitrosomonas europaea*, the electrogenic bacteria *Geobacter sulfurreducens,* or the bioplastic producer *Ralstonia eutropha* - see e.g., T. Zhang, P. L. Tremblay (2017) *Biotechnol. Biofuels* 10, 249.

steps, green hydrogen can be combined with other molecules, e.g. carbon dioxide, to form diverse end products, such as e-methane or e-diesel. Source illustration: powerfuels.org

Downstream processes: from energy-rich feedstock to advanced, ready-to-use products

Fischer-Tropsch process for synthetic e-fuels

The defossilization of hard-to-abate sectors such as long-distance transport or chemical industry necessitates the introduction of alternative carbon-neutral fuels produced from green electricity, ready to be employed within the existing infrastructure. Synthetic fuels can be produced from a syngas feedstock following the so-called Fischer-Tropsch process. This conventional industrial process can be made sustainable by using e-syngas as a feedstock instead of its fossil-derived counterpart (Figure 7). Today, e-syngas can be produced via multiple routes (electrochemical, thermochemical and photocatalytic conversion), but some uncertainties remain on the most promising pathway from a techno-economic perspective. The Fischer-Tropsch process results in a variety of hydrocarbon cuts with different chain lengths, where e.g., jet fuel represents 30% of the total e-crude production in optimal conditions before product upgrading.

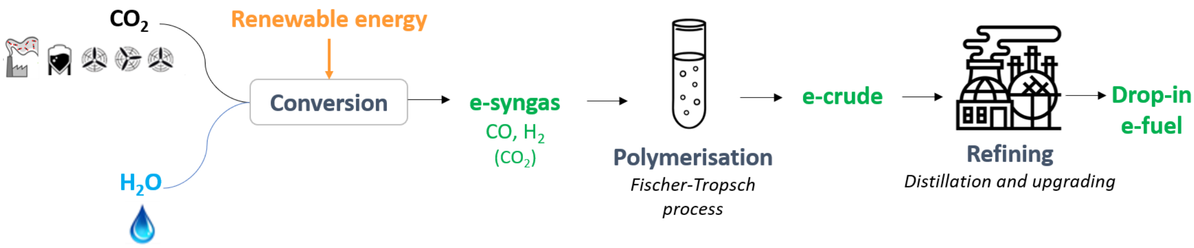


Figure 7. The conversion of green syngas into ready-to-employ e-fuels is a multistep process: starting from CO_2, H_2O and renewable energy (heat, electricity, light), renewable syngas is obtained in a first conversion step. Syngas is a mixture of CO and H_2, but depending on the type of conversion process and the operating conditions, also non reacted amounts of CO_2 can be present (which are either separated from the syngas mixture before the next step or recirculated to the conversion step). Subsequently, the syngas is polymerised into an e-crude via the Fischer-Tropsch process. To obtain a fuel compliant to current standards and norms the obtained e-crude must be refined.
Courtesy: Dr. Hélène Lepaumier, Engie.

Haber-Bosch process for ammonia production

In ammonia synthesis, energy-rich hydrogen molecules are combined with nitrogen to form NH_3. The conventional method for producing ammonia is the so-called Haber-Bosch process. Based on the utilisation of hydrogen from fossil resources, producing one ton of ammonia causes the release of around 2 tons of carbon dioxide.[8] With a yearly global production volume of 235 Mtons, decarbonizing 1% of the ammonia production processes would already result in around 4Mtons avoided CO_2 emissions.

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[8] Including direct emissions of around 1.4t of CO2 per ton of ammonia, and 0.2-0.4t of CO2 of indirect emissions.

A challenge for the production entirely based on green electricity is to ensure process flexibility and operational continuity through efficient management of intermittent renewable energy sources (Figure 8). Today, ammonia plants are optimised for continuous operation based on fossil fuel feedstock. R&D is crucially needed to find the optimal trade-off between the continuous operation of this conventional production process and the intermittent character of renewable energy sources such as wind or solar. A first step in industrial e-ammonia production is to add electrolysis capacity at existing fossil-fuel-based ammonia plants in low percentages and then to gradually increase the share of green hydrogen throughout the continuous system operation. Even though demonstration can provide a clear insight into the possibilities of renewables integration into the conventional Haber-Bosch loop, very few demonstration projects of green ammonia plants have been implemented because of cost and safety issues. Another more disruptive pathway is the redesign of the conventional process to make it more flexible by lowering the temperature and pressure in the fully operational system.

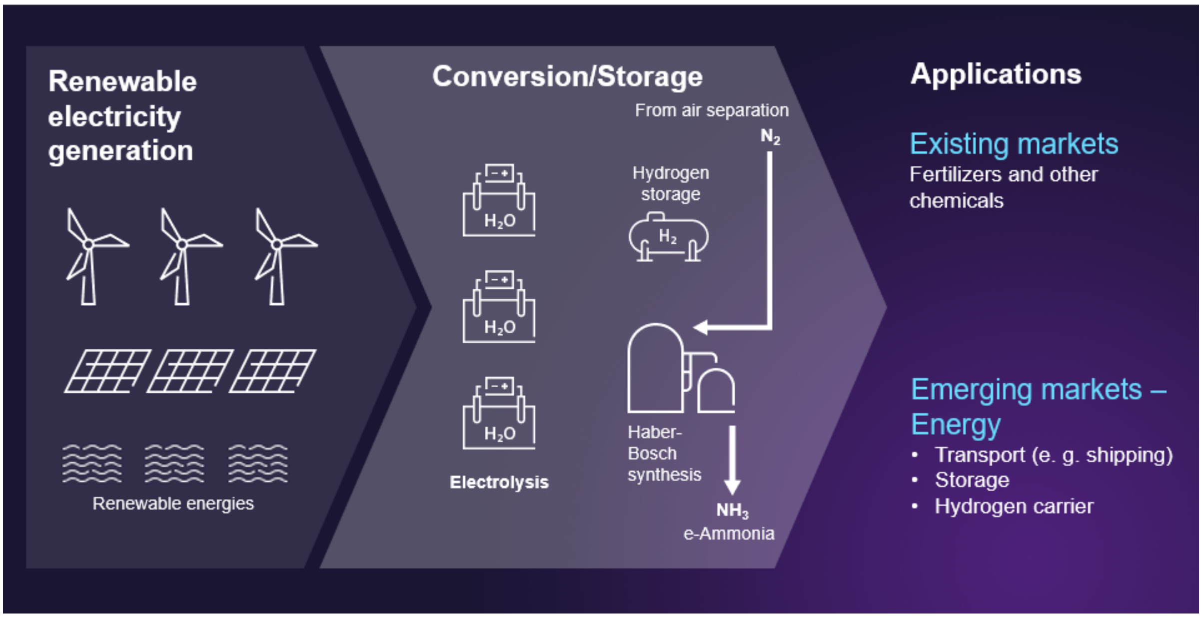


Figure 8. Green ammonia production: Renewable electricity powers the production of green hydrogen, the central ingredient of the conventional Haber-Bosch process for ammonia production. Nitrogen is sourced from the air. E-ammonia has a huge market potential, not only in existing markets such as fertiliser production, but also in emerging markets such as the energy sector (as a carbon-free fuel for transport, for long-term energy storage and as a hydrogen carrier). Source illustration: Siemens Energy, see also: White paper | Power-to-X: a closer look at e-ammonia, 2020.

Gas fermentation by biological pathways

Intermediate feedstock products such as C1 molecules (CO or CO_2) and hydrogen can be upgraded to advanced carbon-based products through biological conversion. In these so-called gas fermentation processes, the feed gas is dissolved in an aqueous medium containing living organisms which serve as biocatalysts. This bioconversion requires energy-rich agents (reducing equivalents in the form of electrons) coming from the oxidation of CO and/or H_2. The circularity of this approach is strengthened by using CO_2 from a biogas plant as a feedstock for the bioconversion. Fermentation processes are exothermic and the produced heat can be used for other industrial processes including catalysis. The gas biofermentation processes are sustainable as they rely on self-reproducing microbial biocatalysts and do not require rare metals for the bioconversion. In addition, this type of conversion system can integrate green hydrogen used in this case as a renewable electricity storage molecule (Figure 9).

The TRL of these technologies is globally low, except for syngas conversion (CO, H_2) to ethanol, with Lanzatech being the dominant global player. CO_2/H2 biological methanation shows several players competing on a lower scale, centred on Europe. The reasons for this geographic focus are the synergy between biological methanation and methanation in biogas plants for which Germany is the world leader. Indeed, biogas plants already have a source of CO_2 and a methane injection point and can thus increase their production via biomethanation. Electrochaea, the market leader, is growing rapidly on a commercial scale with several 20 MWe projects in North America and the EU.

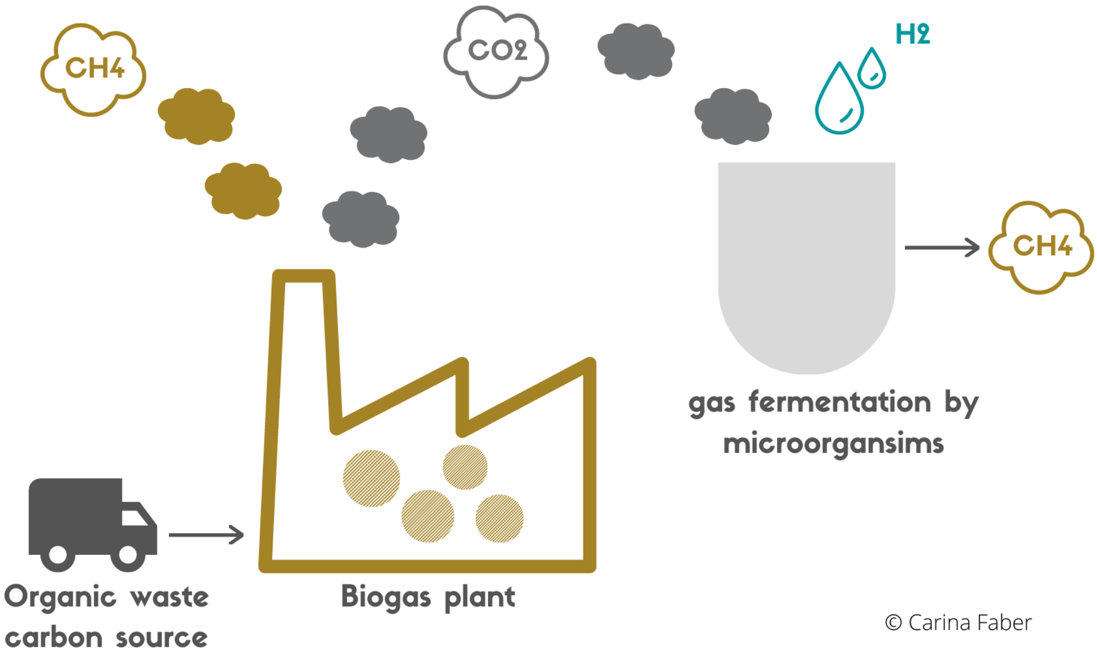


Figure 9. Synergy between biological methanation and methanation in biogas plants. In a biogas plant, the source of carbon are organic substances which are broken down by microorganisms - without oxygen and without light (dark fermentation). The result is a gas that consists of 60% methane (CH_4) and 40% CO_2. This gas can be easily filtered to obtain not only methane, but also a stream of almost pure CO_2. This CO_2 can be used, along with hydrogen, as the basis for another gas fermentation step for the production of methane.

Alternative feedstock for drop-in fuels

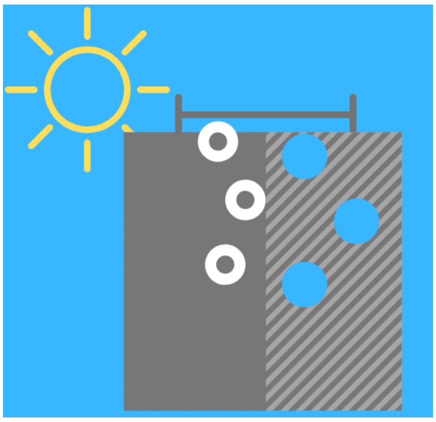
Besides green hydrogen and CO, other base chemicals produced from green electricity can serve as a valuable feedstock for advanced carbon-based products. As an example, green methanol bears significant advantages related to its easy storage (liquid) and its straightforward synthesis compared to green hydrogen. Following the German Energy Agency,[9] green methanol is expected to become the new central bulk chemical in the global chemicals industry. Instead of following the Fischer-Tropsch route from syngas to drop-in

[9] Powerfuels in a Renewable Energy World – Global Volumes, Costs and Trading 2030 to 2050, Global Alliance Powerfuels and LUT University, 2020

fuels, methanol and DME are also promising source compounds for the production of synthetic hydrocarbons through a selective methanol to olefin process.

Solar Fuels: renewable fuels and chemicals directly from solar energy

The second SUNERGY approach takes inspiration from nature, where the energy of the sun is directly used to produce complex chemicals and fuels out of simple building blocks: atmospheric carbon dioxide, nitrogen and water. Rather than using electricity from solar cells to enable the electrochemical production of hydrogen and carbon compounds, these technologies combine everything necessary in an integrated conversion system to go directly from sunlight to the final chemical product of choice. This offers a genuine route to minimising losses over value chains. In SUNERGY, we explore two approaches: the direct conversion of sunlight using synthetic systems and the conversion via living microbial cell factories.



Photo(electro)chemical systems

Photoelectrochemical and photochemical systems aim to combine everything necessary to go directly from sunlight to stable chemical products without necessitating a beforehand production of electricity. At the core of the SUNERGY technologies is the 'artificial photosynthesis' concept which takes inspiration from nature in the design principles to minimise energy losses when converting solar light to chemical energy. Different levels of device architectures are explored to this end, all aiming to target functional limitations associated with energy losses (Figure 10).[10]

Photochemical devices use the energy of the light to perform photosynthesis, i.e. drive thermodynamically forbidden reactions to store light energy in carbon-based fuels or other chemical compounds (e.g. ammonia). They must suppress thermodynamically favourable back reactions and recombination losses from charged intermediates. Photoelectrochemical processes are limited in preventing back transfer and recombination due to their low level architectures. Photochemical systems, on the other hand, offer the highest level of integration and suppress adequately back reactions and recombination losses.[11]

[10] At a low level, photoelectrochemical and photochemical devices may operate as solid-state monolithic systems (buried junction cells) or photoelectrochemical cells with separate anodic and cathodic half-cells (schematically shown in Figure 10). Liquid phase suspensions of photocatalytic nanoparticles are also explored to facilitate thermodynamically downhill steps. Another promising route is offered by approaches hybridising solid-state and molecular components (catalyst and light-absorber), including biological (photo)electroactive molecular systems extracted from living cells, to form high level architectures in the form of photochemical (semi-synthetic) supramolecular nanoassemblies.

[11] Photochemical processes (including natural photosynthesis) offer the highest level of integration and allow to cover the solar cell potential drop, the catalyst overpotential and the overpotential for thermoneutral operation in one limited overpotential, in part because the free energy losses at intermediate stages can be negative, with the overall process subject to detailed balance for net energy storage. With photochemistry, back reactions and recombination losses can be adequately suppressed. In contrast, photoelectrochemical systems (PEC) perform multiple steps over electrical

Photochemical and photoelectrochemical technologies show different sensitivities to specific surface area, carrier mobility and charge-transfer kinetics. Optimisation of these parameters together with maximum utilisation of the solar spectrum for catalytic reactions will be the major focus of SUNERGY.

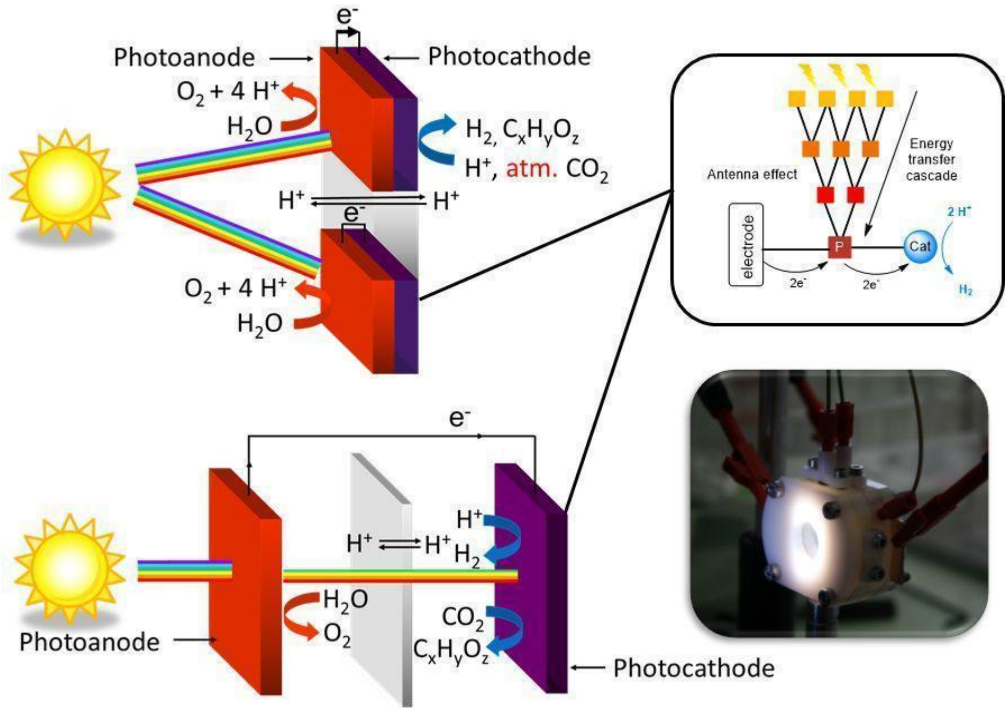
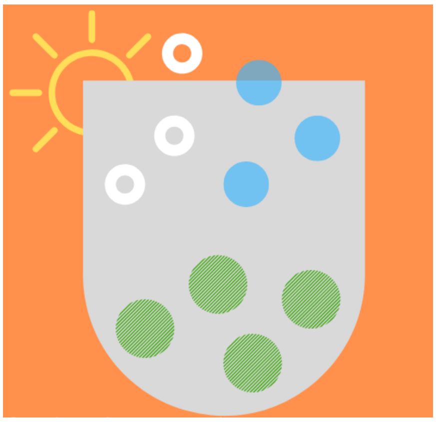


Figure 10. SUNERGY's R&I Focus Area of direct solar conversion via integrated artificial photosynthetic systems. SUNERGY addresses the conversion of CO_2 into a variety of products, the transformation of atmospheric nitrogen with green hydrogen to produce ammonia for fertilisers and, more generally, the direct solar-powered production of fuels and chemicals. Graphics: courtesy of SolHyCat.



Biological and biohybrid approaches: living cell factories

Photosynthetic organisms use sunlight as an energy source and raw materials such as carbon dioxide, water and mineral nutrients for the production of oxygen and organic building blocks. Thanks to photosynthesis, algae and cyanobacteria can produce diverse chemicals that can be used as fuels or feedstock for industry. Such biological production systems are dubbed 'living photosynthetic cell factories'.

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connections in a constant volume, which allows for limited integration (e.g. through tracking of the maximum power point of the internal PV cell by the electrochemical stage for optimal performance with varying light intensity). Preventing back reactions and charge recombination in PECs is difficult and has been a showstopper in the past. Finally, for photocatalytic systems (e.g., semiconductor particle-based systems for plasma-assisted water splitting) there is no net energy storage and these accelerate exothermic reactions with light.

Biohybrid systems employ photosynthetic and non-photosynthetic living microbes wired to inorganic components (electrodes and/or light-absorbing nanoparticles) to drive solar-driven biosynthetic pathways for CO_2 and/or nitrogen conversion into chemicals (Figure 11). The photosynthetic microorganisms fuel the biosynthetic pathways directly with the captured solar energy, whereas some non-photosynthetic microorganisms are capable of utilising sunlight (in the form of water-derived reducing equivalents obtained from the nearby photoactive synthetic systems) to drive efficient atmospheric CO_2 or nitrogen conversion into the target, often highly complex chemicals under mild conditions.

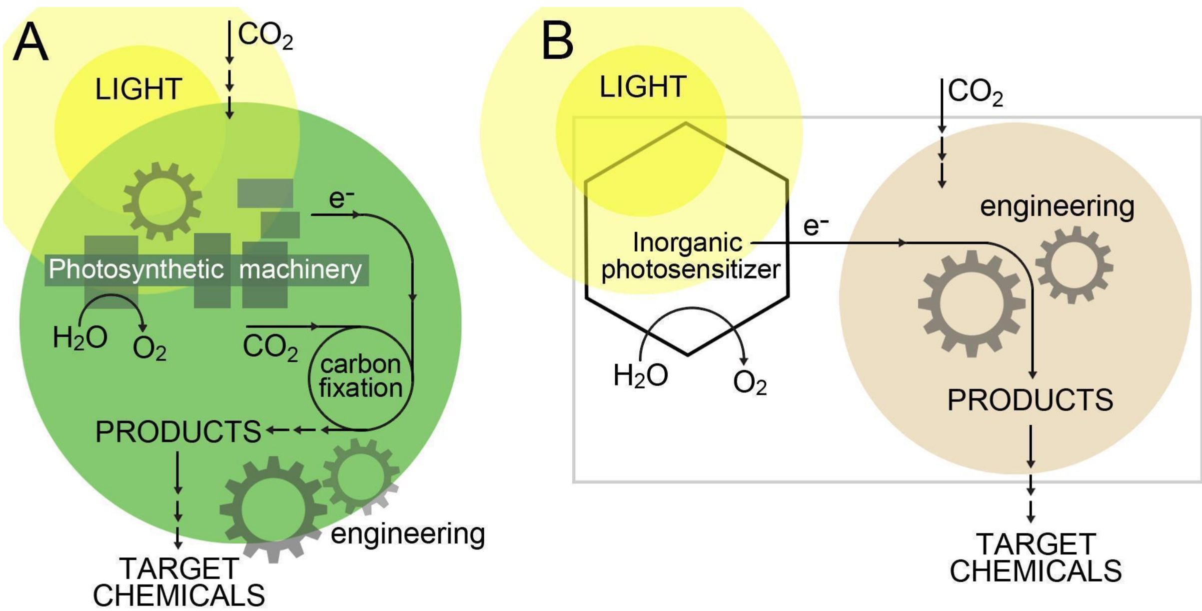

Figure 11. SUNERGY's R&I Focus Area of direct solar conversion via biological and biohybrid systems. A unique characteristic of biological conversion is that simple feedstock molecules, such as water and carbon dioxide, are transformed into complex carbon-based end products - often in a single process and in a simple reactor. **A**, Photosynthetic cell factories (cyanobacteria and microalgae) can be modified using the synthetic biology toolkit to acquire the desired metabolic pathways for solar-driven water splitting and atmospheric CO_2 (and N_2) conversion into target chemicals. **B**, Non-photosynthetic microbes can be photosensitised with inorganic photosensitisers (e.g. metal/ semiconductor nanoparticles) or immobilised on the photoactive electrode materials to carry out solar-driven atmospheric CO_2 reduction into desired chemicals. Graphics: courtesy of Dr. Pauli Kallio (Turku University).

Key enabling technologies

In line with the SUNERGY vision for the full transition to a solar-driven circular carbon economy, the considered key enabling technologies span from energy capture and conversion, to the entire energy systems and even to the societal level. The key enablers of SUNERGY will play a pivotal role in the technology development, technology integration into the value chain and ultimately, the robust business model development for integrated energy scenarios. The key enablers will allow for:

- both intense and multiscale deployment of SUNERGY technologies,
- integration of various technological approaches to reveal: i) pure technical synergetic benefits and ii) new business models,
- large infrastructure investments based on the robust decision-making modelling of energy scenarios on a medium-to-long timescale.

SUNERGY key enabling technologies target the following aspects:

Energy conversion from nano- to macroscale

Materials innovation will allow cost-competitive, efficient and durable solutions across the two main technological approaches of SUNERGY. Novel materials[12] with high robustness and high energy conversion efficiencies will be developed through new concepts.[13]

Multi-scale computational simulation supports advanced experimental setups, such as *operando* characterization of novel materials[14] and integrated systems to avoid tedious sequences of trial and error in the lab, and thus significantly speeding up the innovation process.

Knowledge and methodologies for bridging the scales, in a unified approach is crucial to design reactors and devices from nano- to macroscale and thus optimise all levels of detail.

Novel concepts in improving functionality of catalytic materials by rational design will allow one to overcome the limitations of the Sabatier principle for high yield production processes to be energy efficient**.**

Emerging concepts in artificial photosynthesis will be key for developing the next-generation decentralised energy conversion systems.[15]

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[12] These include robust, highly active and cost-effective photocatalysts, electrocatalysts, nano-engineered semiconductors with improved light absorption/active surface area and minimised defects, colloidal materials using quantization effects in semiconductor nanostructures, novel cost-effective, permeable and highly selective membranes in photoelectrochemical systems etc.

[13] Improving catalytic materials functionality by rational design requires novel concepts in: (i) *homogeneous catalysis* and supramolecular integration of molecular (photo)catalysts into solid materials and electrodes for improvement of catalyst stability, activity, product selectivity and light utilisation; (ii) *heterogeneous catalysis*, e.g. development of nanostructured semiconductor metal oxides with enhanced light absorption and appropriate band gap positioning for photochemical water splitting in visible light; improved utilisation of photogenerated charges through development of rational strategies for improved charge separation, charge transport and surface catalysis; (iii) nanoengineering and molecular design of *bio(photo)catalysts* with improved functionalities and (iv) genetic engineering of metabolic pathways in microbial cell factories for solar-driven chemical production using the *Synthetic Biology toolkit*, which carries a high potential for the realisation of a fully automated “cell designer” platform for production of complex chemicals and fuels from the sun under mild conditions.

[14] Improved nanoscale characterization methods: e.g., terahertz spectroscopy for *operando* characterization of a single photochemical nanoconstruct; computational frameworks to predict structure–property relationships in materials and devices, including machine learning methods; *in situ* surface characterization, high-resolution imaging, ultrafast spectroscopy etc.

[15] In addition to concepts in[7] these include disruptive concepts in: development of solid-state microalgal chemical production platforms; biohybrid catalytic cascades interfaced with nanostructured electrode materials; nanotechnology-driven materials engineering for achieving high surface area and

Product separation. Separation of a mixture of chemical substances into distinct target products is a crucial operational step of an artificial photosynthetic device; in most of today's devices product separation, purification and collection represent one of the major bottlenecks due to the energy consumed for production and operation.

Energy system

Upscaling of manufacturing renewables is not fundamentally limited by the supply of natural resources but by the challenge of bringing novel technological solutions from the lab bench to a global industrial scale to reach a terawatt level infrastructure of mature SUNERGY technologies. Unconstrained manufacturing offers an important perspective on a rapid transition and for this purpose the overall sustainability, the practical availability of needed resources on a large scale and economic viability must be ensured.

Development of robust energy scenarios will allow the establishment of viable infrastructure investment plans. The evolution of the energy system is deeply uncertain, which poses a challenge for strategic investment decisions by grid operators, energy producers and public authorities. SUNERGY's long-term strategy is to create a robust investment plan that allows for cost-efficient and secure energy provision through elaborate infrastructure development.[16]

Societal level

Life-cycle, techno-economic and social impact analyses will ensure viable business models, societal acceptance of the SUNERGY technologies and ultimately, the establishment of a sustainable C-circular economy.

Sociotechnical-driven development with regular feedback from societal stakeholders will help to embrace and create a pull effect for the technologies as they are being advanced to the high technological readiness level.

Industrial drivers for the SUNERGY technologies

The above introduced technological approaches need to be researched, then the most promising conversion routes need to be scaled up; this will enable the EU industry to not only defossilize its activities, but also to stay competitive worldwide by taking a leadership in carbon-neutral technological alternatives. To support industry on this pathway to carbon neutrality, this needs to be done in a holistic way to avoid a preference of individual players

better utilisation of the solar spectrum by plasmonics and quantum effects; nanotechnology-driven improvement of multi-electron CO_2 and N_2 reduction processes; nanocatalysis for reverse combustion of CO_2 to generate hydrocarbons etc.

[16] An example of the toolkit that can be used for the long-term strategic planning of energy scenarios is described in Appendix 2.

and their bet on a specific technology.[17]

Within the defossilization of energy and industrial production, a market of unprecedented size will be generated, which will allow nearly unlimited industrial growth without the depletion of natural resources and compromising our climate. In this context, circular and symbiotic industrial concepts and CCU will play a major role.
Identified benefits and opportunities for industry include:

- the development of new economic value chains based on a carbon-circular economy together with the de-risking of new business models,
- the defossilization of chemical production processes by using green feedstock and green electricity for chemical processing,
- the defossilization of segments of transport which are hard to electrify (aviation, maritime, heavy load long-distance road transport) by the provision of green energy containing molecules,
- the defossilization of heat demand for hard-to-electrify applications, such as high-temperature industrial heat, by the provision of storable and transportable energy carriers.

Considered feedstock and products[18]

Green hydrogen
Green hydrogen is a highly important energy vector in the quest for a carbon-neutral society and a crucial feedstock for SUNERGY technologies.[19] Hydrogen represents an enabling molecule in the production of ammonia and carbon-based fuels and chemicals. A fundamental aspect of SUNERGY is that not only electricity-based hydrogen technologies with a high TRL are considered; less mature methods based on the direct photochemical and thermochemical conversion of sunlight into hydrogen have a prominent place as well. Key drivers are a significant increase of the solar-to-hydrogen yield, high demands on sustainability and circularity in the energy supply and use, and the economically viable production of green hydrogen.

Sustainable carbon dioxide
Sustainable carbon dioxide is central to the production of renewable fuels and chemicals. The sustainable large-scale production of fuels and chemicals is based on both point and distributed sources of carbon dioxide.
Large industrial emitters, including electricity and heat producers, are responsible for up to 20 Gton CO_2 / year on the global scale. For industrial CO_2 point sources, both the CO_2 concentration and the impurities present (e.g. NOx and SOx) will impact the processes of

[17] The KPIs for industry are shown in Fig. 1 driving the rapid TRL advancement in the production of hydrogen, carbon-based and nitrogen-based large volume chemicals and fuels through the four technology classes shown in Fig. A1.1.
[18] Source: SUNRISE technological roadmap
[19] Especially with respect to the transport sector; it is already a well-covered topic, with existing European large-scale initiatives such as the private-public partnership *Fuel Cells and Hydrogen Joint Undertaking (FCH JU)* and their recently released *Hydrogen Europe Roadmap*.

CO_2 capture and conversion. Currently, technologies for capture and utilisation of CO_2 from stationary point sources are already established. Depending on the type of CO_2 source, CO_2 concentration can range from almost 100% (ammonia or ethylene oxide producers, hydrogen plants, biogas upgrading) to 70% for natural gas processing and down to 3-5% for gas-fired power plants.

The ultimate goal for sustainable carbon dioxide is the extraction of this gas from the atmosphere with materials that combine concentration from the air with catalysis forming the product. However, this is technologically challenging. Several teratons of CO_2 are available from the air, but with a low concentration of about 400 ppm only. Several industrial start-ups commercialise Direct Air Capture (DAC) units for CO_2 concentration only, where the CO_2 is released at a significant energy cost. These are integrated into projects expected to deliver in 2020-2025, where down-stream chemical processes will convert CO_2 into methanol or jet fuels. To overcome the excess heat losses in such multistep cascades by integration of steps is a major focus of SUNERGY.

Nitrogen from air

Nitrogen is a harmless, odourless gas that makes up 78% of our atmosphere. Together with hydrogen, it is the main feedstock for ammonia production. Contrary to carbon dioxide, which is only present in our atmosphere in very dilute concentrations, nitrogen can be easily separated from air with the energy input negligible compared to the overall energy demand for the entire conversion process. Here a critical hurdle is to mimic natural nitrogenases and develop catalysts for producing ammonia without the large temperature cycling of the Haber-Bosch state of the art, to minimise thermal losses.

Sustainable products

There is a plethora of possible sustainable fuels and chemicals – ranging from small molecules such as ammonia to complex aviation fuel. However, there is a limited number of high-volume and low-value energy carriers and platform chemicals, which is where the high impact climate challenge lies (see Figure 12).

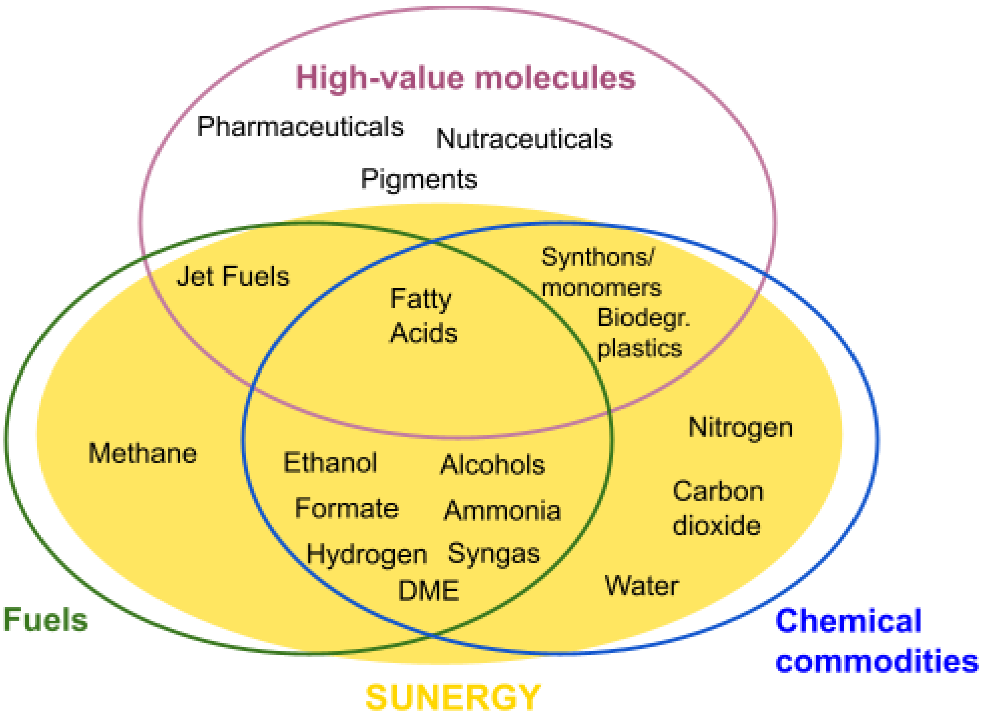


Figure 12. Key molecules considered in SUNERGY are highlighted in yellow, comprising fuels and chemical commodities, but not high-value molecules per se. The focus is on high impact on climate mitigation, that means high-volume, low-value molecules. Courtesy of Dr. Hervé Bercegol (CEA).

Figure 13 illustrates the production and final utilisation of the SUNERGY enabling chemicals and fuels. For simplicity, they are grouped in three categories: hydrogen, ammonia and carbon-based compounds. The range of products obtained from CO_2 is extended to C_{2+} products, i.e. products with two or more carbon atoms such as ethanol, to enlarge the spectrum of applications and new technology deployment.

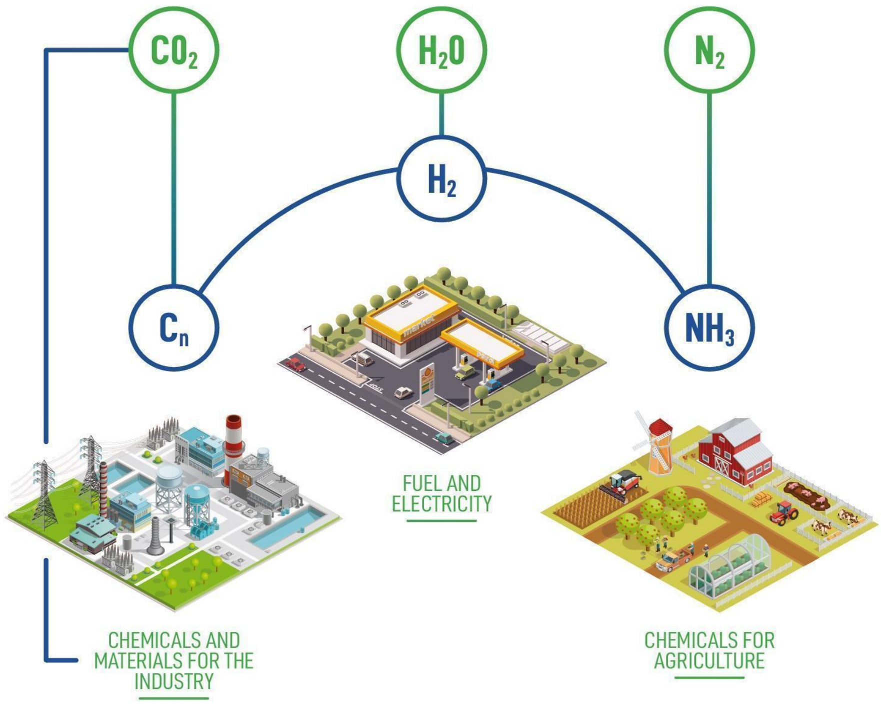


Figure 13. Production and final utilisation of the SUNERGY key enabling chemicals made with renewable energy. For simplification, three categories are shown: hydrogen (H_2), ammonia (NH_3) and carbon-based compounds (C_n). Figure Source: SUNRISE technological roadmap.

Technological milestones to be achieved

In a nutshell

Carbon, hydrogen, oxygen and nitrogen are the main atomic building blocks of commodity fuels and chemicals. We present here a comprehensive and timely plan to unlock the path towards intermediary and final products, using atmospheric gases as inputs, with a limited consumption of renewable energy flows. Water splitting is central, since molecular hydrogen, H_2, and water oxidation are key in the reduction of carbon dioxide and nitrogen (Figure 14).

Targets and timelines

The SUNERGY action will capitalise on the current maturity and deployment of green electricity and electrochemical processes, aiming at the development of innovative technological bricks adapted to the current infrastructures and business models by 2025.

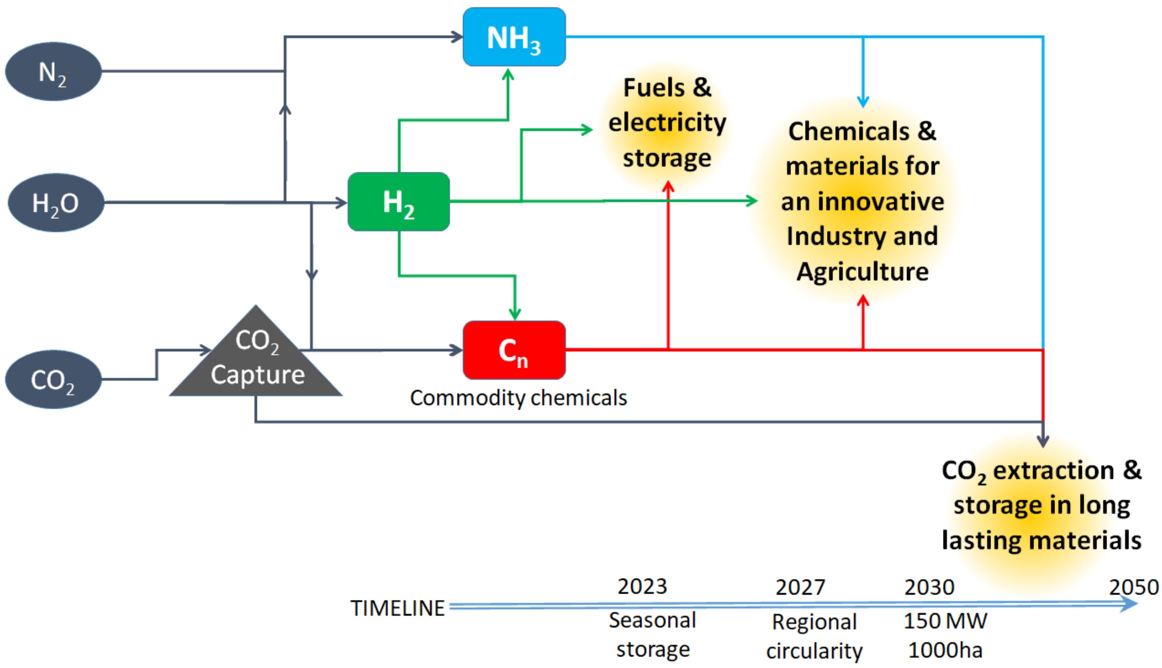


Figure 14. Earth abundant molecules (water, nitrogen, carbon dioxide) are converted using renewable energy into hydrogen H_2, ammonia NH_3 and carbon-based chemicals C_n. H_2 is central in many industrial processes. Carbon capture can be realised by physico-chemical devices or by photosynthetic microorganisms. Renewable fuels and chemicals are targeted to be reached in the next decade; future progress in CO_2 and N_2 conversion will open new ways of storing atmospheric CO_2 in long-lasting carbon materials, here envisaged to reach the market beyond 2030. Courtesy: Dr. Vincent Artero and Dr. Hervé Bercegol (CEA), SUNRISE technological roadmap.

This will encompass green processes for the production of ammonia and carbon-based fuels and chemicals. On a longer term, the development of more disruptive approaches i.e., photoelectrochemical, photochemical, biological and biohybrid systems will provide the technological basis for cutting losses with the direct conversion of solar into chemical energy with milder operating conditions, more straightforward processes, better selectivity towards specific products and in many cases, application of self-renewing/self-healing catalysts.
The capture of CO_2 and nitrogen from the atmosphere will be combined with chemical conversion processes to reach high energy efficiencies. The direct conversion processes will allow the transition from a centralised production of solar fuels and chemicals to a partially decentralised approach by 2030, bringing better resilience to the EU regions and favouring the development of a circular economy by development of the local full value chains. Such technologies will be of primary interest for the development of areas where centralised infrastructures do not exist and will allow specific solutions adapted to local resources and needs. They will provide competitive prices for fuels and compounds, establishing a circular economy, ultimately enabling the capture of excess CO_2 from the atmosphere. Concerning fertilisers, not only a low carbon-emission production is targeted, but also a decentralised production of ammonia on the small-scale and by demand (by adopting the precision farming approach); thus, by limiting the excessive use of fertilisers eutrophication and soil contamination will be ameliorated.

Beyond 2030, SUNERGY aims at providing a strong scientific and technological basis for negative emissions technologies, which will be then necessary to maintain the temperature increase below 2°C. Eventually, efficient solar energy conversion of carbon dioxide into long-lasting materials shall contribute to CO_2 removal, with the goal to reach a much lower land use than the biomass-based technologies. The concomitant decoupling of economic growth from the depletion of resources and utilising CO_2 for manufacturing long lasting materials is a much more appealing economical prospect than separate geological Carbon Capture and Storage [CCS]. Ultimately, by 2050, SUNERGY will contribute to establishing a CO_2-neutral circular economy, net climate neutral mobility of people and goods, as well as cost-effective and C-negative technologies implemented and deployed on a large scale.

Social and environmental impacts

Sustainable water supply

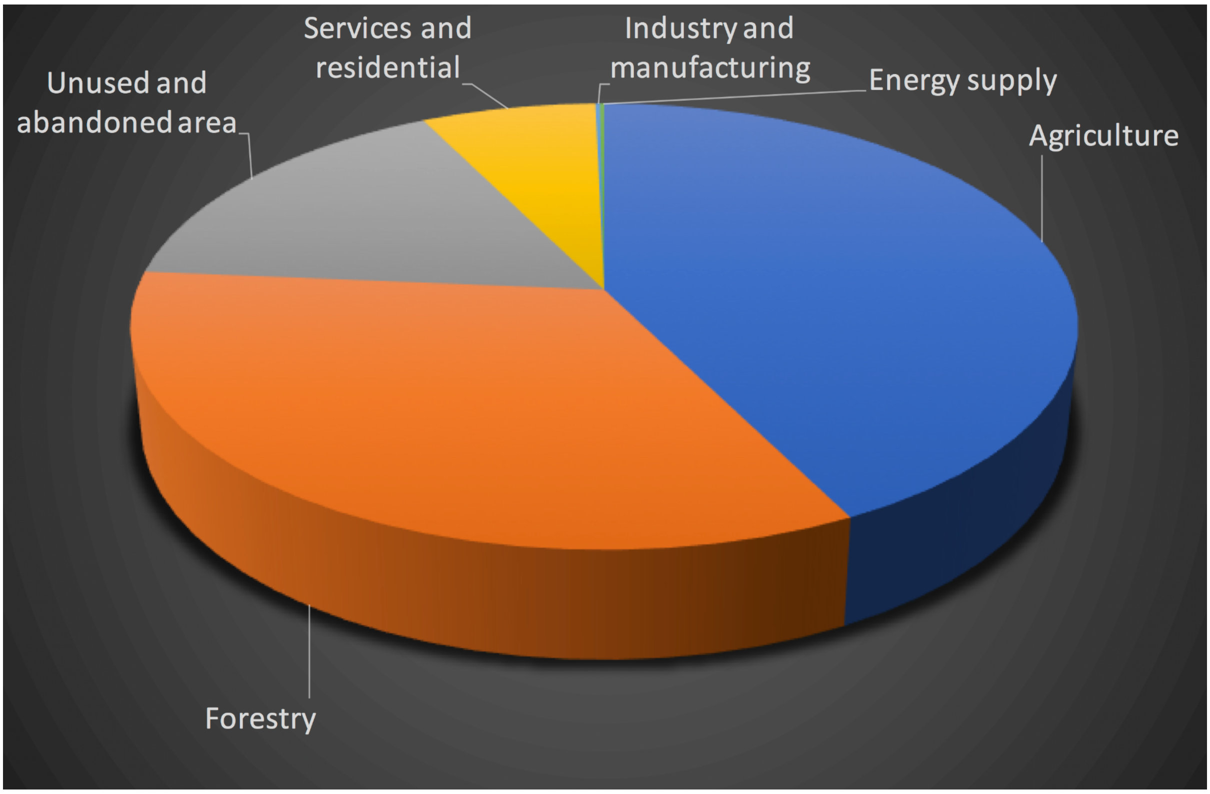
Water is the ultimate source of reducing equivalents (electrons and protons) for all SUNERGY technologies for the production of renewable fuels and chemicals. As 96.5% of global water reserves exist as brackish water and seawater, water splitting approaches utilising these sources and other impure water sources must be developed.[20] In the case of water electrolysis, apart from the cooling water requirement, ultra-pure water is required as feedstock to produce hydrogen as the key enabling molecule. The production of one ton of hydrogen requires 9 tons of ultra-pure water. The close connection between water and energy, known as the water-energy nexus, is the relationship between how much water is used to generate and transmit energy and how much energy it takes to collect, clean, move,

[20] S. S. Veroneau and D. G. Nocera (2021) *Proc. Natl Acad. Sci. U.S.A.*, 118, e2024855118.

store, and dispose of water. Therefore, the deployment of any new energy system is ultimately related to the water challenge.[21] Optimisation of renewable energy use is particularly important for the application of the SUNERGY processes and systems in the regions where water is in short supply. Regionalised life-cycle assessment should be considered to analyse the water footprint further, to take into account local water conditions and uses. Efficient water management, emphasis on water reuse circularity for chemical production and use of alternative water resources (waste water, desalinated brackish and seawater, captured water vapour from air and integrative microalgal biomanufacturing platforms and water treatment) must be developed in parallel to optimisation of technological process for solar conversion (for details on water management, see Appendix 3).

Land use demands[22]

European soil is one of the most intensively exploited in the world. High economic efficiency in urbanised regions is of paramount importance. With up to 80%, Europe has the highest proportion of land used for settlement, production systems (in particular agriculture and forestry) and infrastructure (European Energy Agency - Land use). Agriculture is the most common primary land use category in the EU-27, followed by forestry, unused and abandoned land, and services and residential. Only a small portion is dedicated to energy conversion and industry/manufacturing (Figure 15). The deployment of any new technology should carefully consider technologies with low specific area demands and consider how to integrate the new technology in the existing technological infrastructure and minimise the additional land use demand in this context.



[21] see Appendix 3 for detailed description of sustainable water supply challenges and approaches.
[22] Source: SUNRISE technological roadmap

Figure 15. Agriculture has the highest land use (41%, ca. 1 800 000 km^2), followed by areas used primarily for forestry (33%, 1 400 000 km^2), services and residential (7%, 295 000 km^2), along with unused or abandoned land (16%, 690 000 km^2), data from EUROSTAT - land use statistics. About 7 000 km² are dedicated to industrial activity for the energy sector and 7 700 km^2 to industry/manufacturing, 0.16% and 0.17%, respectively. Courtesy of Dr. Andrea Barbieri (CNR).

SUNERGY aims at storing solar energy in chemicals with yields tenfold-to-hundredfold higher than current biomass practice (Figure 16). This key target allows to reduce drastically the needed amount of production surface compared to biomass (currently the only viable renewable option for long-distance transport).

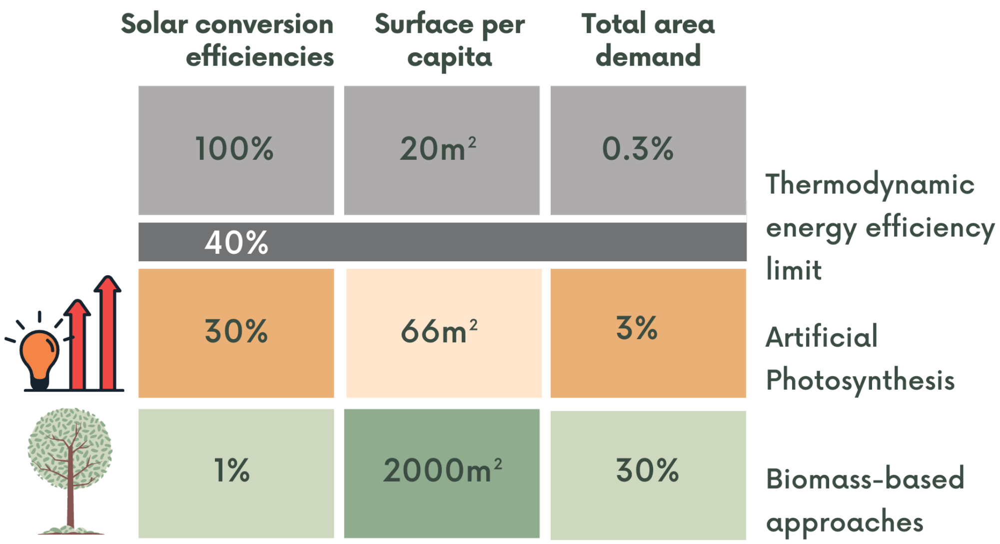


Figure 16. Land area required for solar fuel production at a meaningful scale for different energy conversion efficiency levels. SUNERGY aims at providing a 30% energy conversion efficiency in 2050. This approaches the theoretically achievable thermodynamic limit[23] and represents a massive leap forward compared to current (first, second and third generation) biomass practice. While the conversion of solar energy into biomass as occurring in nature (e.g. crops, algae) is limited to small percentages due to seasons, land area restrictions etc., artificial photosynthesis still has room for significantly improving conversion efficiencies. This can be directly translated into drastically reduced land use demands. Assuming an upper limit of 2 TW primary energy supply and 700 million Europeans, SUNERGY's approach translates into ~66 m^2 per capita of surface required, which corresponds to ~3% of the European surface (on average, 25 MWh per year are then provided for every citizen). At this level, integration into the existing technological infrastructure in industrialised or urbanised regions with high economic efficiency for reducing cost can become reality. Figure source: [SUNRISE technological roadmap](#).

[23] The thermodynamic energy efficiency limit is calculated at 40% using the following rationale. While the maximum theoretical efficiency of a silicon solar cell generating electricity, the so-called Shockley-Queisser limit, is around 30%, for a photochemical system operating around room temperature in full sunlight the thermodynamic efficiency is limited to 40% and is achieved with two light absorbers covering the solar spectrum in tandem (Ross and Hsiao, 1977).

Critical raw materials

Our carbon neutral energy transition is exponentially increasing our need for raw materials

Over the last centuries, new energy technologies have increased the need for raw materials. This is particularly true for the current energy transition towards carbon neutrality (Figure 17). When producing energy, these novel technologies do not emit greenhouse gases. Their carbon footprint is a result of their manufacture, and to a lesser extent their maintenance and end-of-life. Although they are promising in terms of combating climate change, other aspects deserve our attention and in particular, the use of critical metals or rare earths in their production. The extraction and processing of these metals and rare earths can be a source of major environmental or social concerns. Examples include pollution caused by mining and/or processing, the deplorable working conditions of miners and the consequences of toxic waste on the health of local populations.

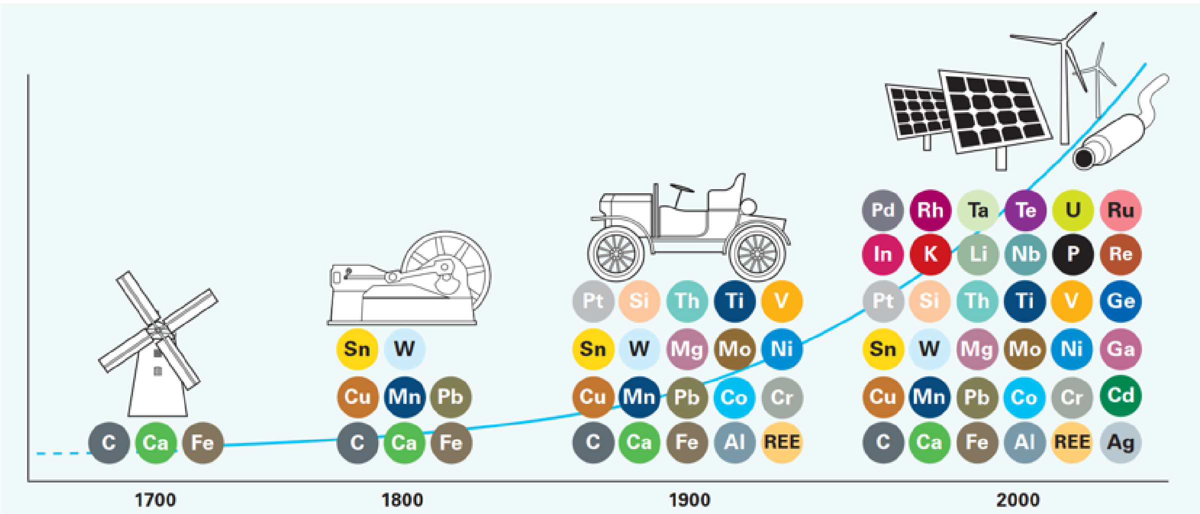


Figure 17. Materials widely used in energy technologies over the centuries. Source: Volker, Z., J. Simons, A. Reller, M. Ashfield and C. Rennie, 2014. Materials critical to the energy industry — An introduction.[24]

A distinction should be made between "rare earths" and the so-called "conflict minerals" and "critical metals". Rare-earth elements comprise 17 metals (scandium, yttrium and the fifteen members of the lanthanide family), whose thermal, electrical and magnetic properties have made them indispensable for the development of energy transition and digital technologies. Contrary to what their name indicates, they are not rare in absolute terms in the Earth's crust; rare refers in fact to the small number of economically viable deposits. The term "conflict minerals" refers to minerals whose extraction conditions violate human rights, as they come from mines located in conflict zones or areas controlled by armed groups and their extraction often makes use of forced labour. The main metals in this category are cobalt, tungsten, tantalum, gold and tin. As for "critical metals", the term corresponds to

24 https://www.drvolkerzepf.de/app/download/11633904993/2014+ESC_Materials_handbook_BP+2nd+edition.pdf?t=1607953267

those elements that present supply risks (geological, technical or geopolitical) and for which a possible shortage would have major economic consequences. Figure A6.1 (see Appendix 6) shows the current critical raw materials identified following the EU procedure[25] in which the supply risk and the economic importance of each of the materials is evaluated. The materials are considered as critical when they fall above a defined threshold on both axes.

Let us take some examples. In the production of renewable energies, rare earths (mainly dysprosium, neodymium, praseodymium and gadolinium) are only used in wind turbines equipped with permanent magnets (as opposed to electromagnets), mainly employed for off-shore electricity generation. The associated issues are not so much related to their availability as to environmental concerns. As they are only present in low concentrations, a large amount of ore must be extracted and processed, which requires large quantities of water, energy and chemicals and can produce toxic waste in significant quantities. Photovoltaic and battery technologies require little or no rare earths and the nature of the challenges and the metals in question are not the same. For the former, the materials concerned are silicon, indium, silver, selenium and tellurium; cobalt, lithium and graphite for the latter.

Cobalt is particularly critical, because of the high geopolitical and social risks associated with its areas of supply (mainly in the Democratic Republic of Congo). As for lithium, its criticality is rather linked to economic questions, because 85% of lithium resources are located in Argentina, Chile and Bolivia with a very limited number of market players.

For many of the chemical catalytic processes discussed in greater detail in this report, metal catalysts are required. The Platinum Group Metal (PGM) catalysts dominate today's applications. The IEA has recently published a report on the topic of critical raw materials[26] and alerts on a mismatch between the need of critical minerals to meet our climate ambitions and the predicted supply of some important critical metals, as depicted in Figure 18.

[25] Critical Raw Materials for Strategic Technologies and Sectors in the EU A Foresight Study. https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf

[26] IEA, WEO special report, 2021. The Role of Critical Minerals in Clean Energy Transitions. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

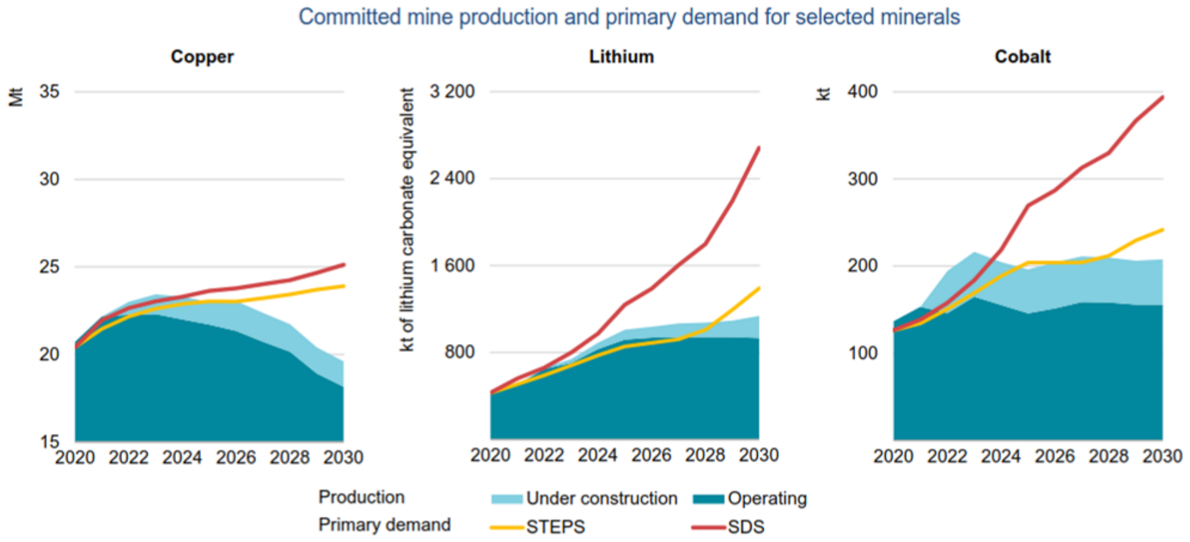


Figure 18. Mismatch between the need of critical minerals to meet our climate ambitions and the predicted supply of some important critical metals (Copper, Lithium and Cobalt) according to IEA, 2021. Notes: Primary demand is total demand net of recycled volume (also called primary supply requirements). Projected production profiles are sourced from the S&P Global Market Intelligence database with adjustments to unspecified volumes. Operating projects include the expansion of existing mines. Under-construction projects include those for which the development stage is indicated as commissioning, construction planned, construction started or pre-production. Mt = million tonnes. Source: IEA analysis based on S&P Global (2021).

How can we get past these difficulties? Reduction of the use of these metals in our energy technologies is a first crucial solution: for PV panels a reduction in the thickness of silicon wafers logically leads to a reduction in the amount of silicon required, for batteries, in case of Li-ion batteries, a great reduction in the use of Cobalt is going on whilst at the same time other technologies are emerging such as solid electrolyte batteries or redox-flow batteries. In particular these latter have demonstrated a lower environmental impact than Li-ion batteries and are therefore a promising technology for large scale grid storage of electricity.[27] The development of recycling is also key to limiting the need for raw materials. Today, 98% of the mass of a wind turbine (foundations included) can be recycled and 95% of the PV panels. However, this is the total mass and mainly refers to glass and metals such as Iron and Aluminium but a lot of the critical and rare metals are not yet recycled.

Substitutivity of these critical or rare-earth or conflict metals is another solution and a quest on replacing them by earth-abundant metals is currently on-going (Figure 19) and is expected to increase.

[27] Ligia da Silva Lima, Jan Mertens, et al., 2021. Life cycle assessment of lithium-ion batteries and vanadium redox flow batteries-based renewable energy storage systems. *Sustainable Energy Technologies and Assessments*, 46, https://doi.org/10.1016/j.seta.2021.101286

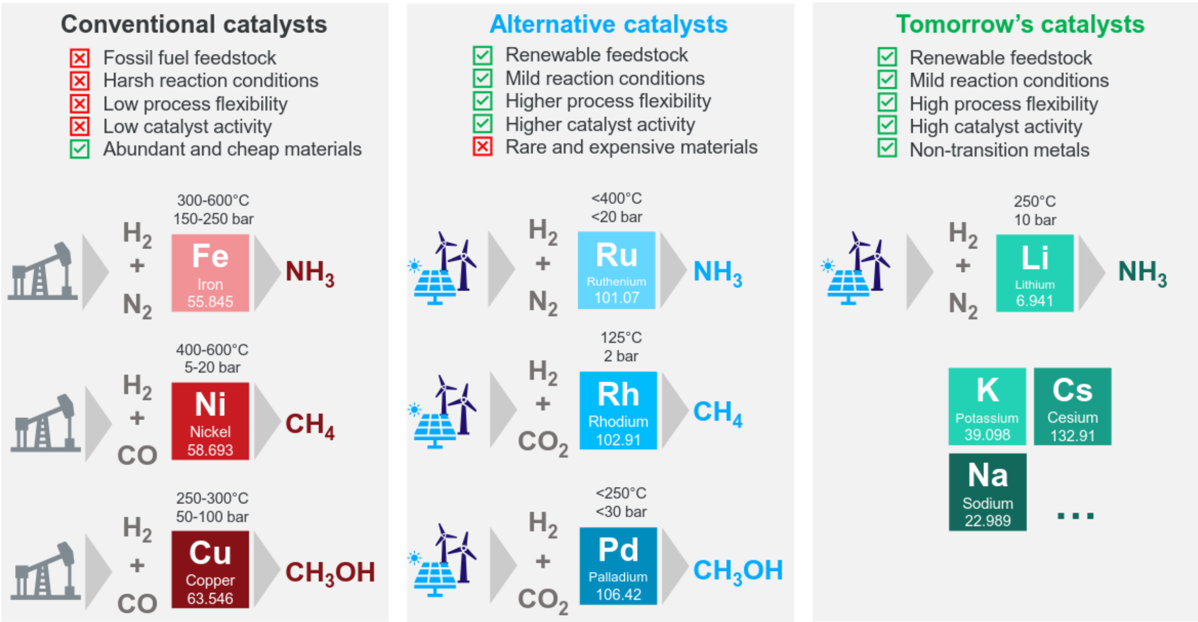


Figure 19. Quest for earth abundant catalysts. With its short-to-long term perspective, SUNERGY works on solutions for the three classes of catalyst materials - from conventional, to alternative up to tomorrow's catalyst. Source: [ENGIE *Emerging Sustainable Technologies: collaborate to reach carbon neutrality* report].

Distributed production and prosumer approach: Transversal challenges

Solar conversion technologies: a paradigm change from consumers to prosumers

We live in hedonistic societies, where the collective wellbeing is derived from the individual wellbeing. In the end, what people want is more important than what technology can do, since technology can do a lot. In a sustainable energy system citizens have a dual role, they are both consumer and producer. While decentralised energy supply requires broad engagement of citizens, it also offers a return at the individual level. The energy provision is often taken for granted, many people prefer the energy system not to be noticed in daily life and energy ethics is very limited beyond "I do not know what it is and I am against it". In view of this background, the idea of decentralised manufacturing of fuel and chemicals providing a form of revenue, a contribution to financial independence, lining up with other forms of professional pride is a new dimension, a route to make hedonism a principal positive driver towards a sustainable society. This prosumer concept may be one out of very few possibilities to overcome the critical hurdle of how to make the transition to a massive industrialization of our entire habitat without compromising human dignity. For this to proceed well, it is essential to offer choices, the possibility for individuals to make their own decisions on how to be involved in a decentralised conversion and manufacturing network, and how to collaborate with others. The SUNERGY R&I pipeline is suited for this purpose. At the start diverse new ideas are explored, and towards the end technologies either fly or die, depending on the public acceptance. Within SUNERGY, companies will work with designers to visualise new technology well ahead of its implementation, identifying most advanced, yet achievable (MAYA) designs for implementation, not only based on technological feasibility, but also on soft subjective grounds, such as that biomimetic or semisynthetic nanotechnology may appeal to the public for domestic application because of its natural roots and appearance. Ahead of the design, humanities researchers will set up “probes for debate” with artists, across EU MS and AS using the public debate network that has been built up in recent years with e.g. science cafe’s. SUNERGY will also identify “market mavens”, influencers that are trusted by the public, have expert knowledge, but do not have a conflict of interest regarding the technology or its R&I activities.

While in the economy of scale there is a distinct difference between citizens having economic ownership and citizens having cultural ownership, the transition to a decentralised manufacturing system or the precision farming business instead of the economy of scale will probably make for a more homogeneous distribution of economic and cultural ownership. The latter will be pioneered in this case by artists, innovators and business leaders with a strong commitment to follow their vision despite initial obstacles. This is not just about pathfinding, transitioning and accelerating the deployment of carbon-neutral technologies. It is about inducing the next level to the civilisation, the energy society, which requires establishing the strong energy ethics that does not exist yet.

Transversal challenges originating from the new paradigm

The ‘transversal’ challenges that the solar fuels paradigm will bring should not be addressed through another separate program, but instead be genuinely embedded within the same train of actions:

- **Develop smart strategies for market introduction**: avoid technology rejection/exclusion usually experienced by low maturity technologies due to their temporary unfavourable economics. Instead, favour smart ways to enter as soon as possible their industrialisation deployment in order to benefit from the possibility of early cost savings through walking down the learning curve. For example, for the organic PV one could consider upscaling manufacturing processes thanks to several niche applications based on their specific properties (flexibility, conformability, lightweight etc.) that standard Si-PV could not offer despite the very low price of the latter resulting from its massive deployment.

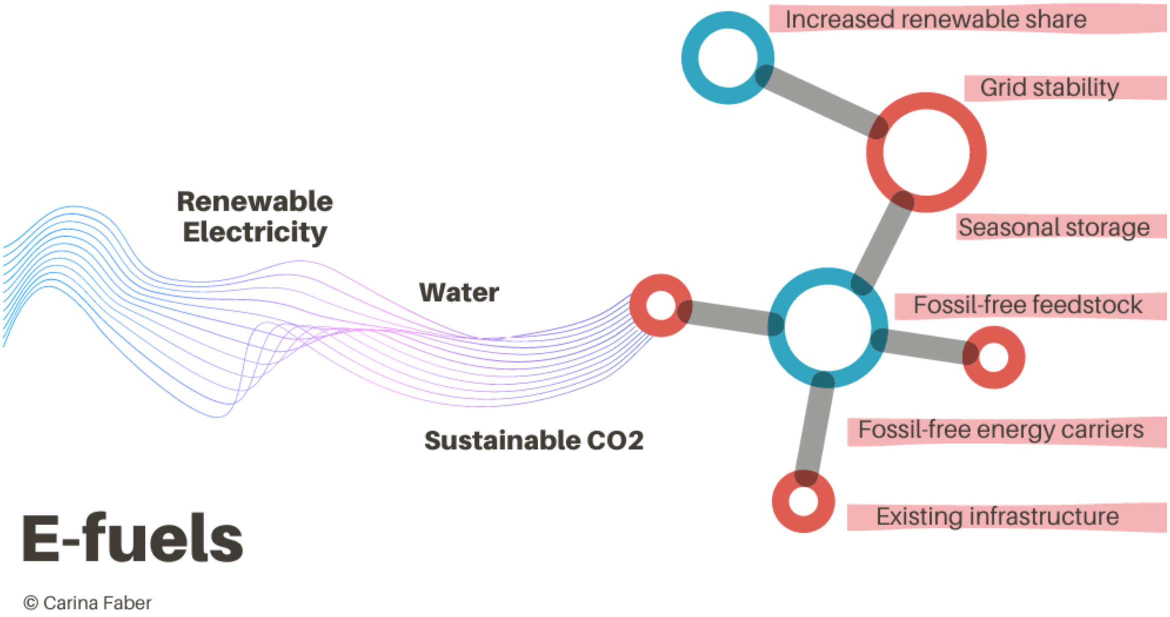
- **Create open, inclusive debate space where consensus-based rational opinions are established and stabilised, avoiding excessive voicing of single opinions**: emotions can be expressed, but then fair mechanisms should be available for rational discussion to clarify disputed matters in an open debate; with clear, constructive and simple rules for debate such as: 1) looking for didactical approaches, 2) delivering concise but rigourous reference documentation, 3) backed up by consensus of well-recognized mandate stakeholders, 4) reflecting an inclusive approach of the discussed topics. This Openspace should not only objectivise debates and techno-economic-societal outcomes reached so far during the energy transition process, but should capitalise on these to progressively reveal and ascertain medium and long term trends.

- **Unlock citizen engagement by leveraging on collaborative approaches supported by digital technologies, social sciences and humanities**: leverage on co-construction and co-design actions, Customer Experience CX approaches, avoid closed clubs of technology developers. The role of Social Sciences and Humanities (SSH) is pivotal here for reinstating the importance of social relationship through the individual and collective relationship with energy supply and use. The solar fuel roadmap should include protected “fast tracks” to address primarily fundamental societal challenges such as energy poverty.

- **Not only technology serves the society, but the society gives valuable input to the technology development**: The solar fuel paradigm will reshape our perception and relationship with (energy-related) technologies but, further, it will also reshape our direct relationship with our natural environment. It is thus also likely touching on cultural dimensions. Hence, actions on the cultural playground may be of great importance: leverage not only on education (from an early age), but also daring interactions on cultural and artistic playground could ease to position this new journey of sciences and technology (biology, chemistry, physics, green engineering etc.) as a really new inclusive journey. As an example, while artists are often strongly inspired by new technologies, their creativity should also be activated to inspire in unlocking scientific and technological deployment challenges.

R&I State of the Art and technological needs[28]

E-fuels: from renewable power to alternative fuels and chemicals



E-fuels are alternative fuels and chemicals produced with renewable electricity, water and simple molecules such as carbon dioxide or nitrogen. Carbon dioxide is sourced in a sustainable way, either from industrial emitters or directly from the atmosphere using renewable energy. The main advantage of e-fuels is that excess renewable energy can be stored during peak production times in the form of chemical energy. Therefore, a seasonal, long-term storage of intermittent renewable energy sources is enabled. This in turn allows to stabilise the electricity grid and consequently to increase the share of installed renewable power sources in the energy mix. The resulting products are fossil-free and allow for defossilization of hard-to-abate energy intensive sectors such as heavy transport, chemical or steel industry, while profiting from the use of existing infrastructure.

Overall targets

In the short-to-medium term, SUNERGY's R&I needs in this field will be focused on bringing e-fuel technologies to the market and making them economically viable and sustainable:

- Demonstrate and validate the industrial feasibility and cost effectiveness of these low-emission technologies: at pilot plant level with minimum CO_2 emissions;
- Establish local value chains: Find optimal combinations of technologies and products for a specific region minimising long-distance transport and storage issues (cost, safety) - the best suited product and technology for a location with specific feedstock and infrastructure availability is identified;
- Benchmark different conversion routes to help industry to prioritise and to

[28] See Appendix 1 for a detailed description of the SUNERGY technological portfolio.

de-risk novel business models, select best technologies and avoid "regret investments".

In parallel, SUNERGY will develop next generation technologies. While electrocatalysis is the present-day technology that is closest to industrial application for e-fuel production, other less developed electricity-based approaches (in particular, plasma-catalysis and the use of microwave technologies) should also be explored, with the focus on the limiting factors, such as scalability, long-term operability, costs, energy efficiency and product selectivity.

R&I needs in a nutshell

The SUNERGY vision fosters current technological applications that produce carbon-based compounds from renewable energies, replacing the need for fossil-based or biomass feedstocks. The actual effort, mainly driven by industry, is to combine single components with medium TRL in the fully integrated system, optimised for energy efficiency, operational stability, cost effectiveness and large-scale deployment.

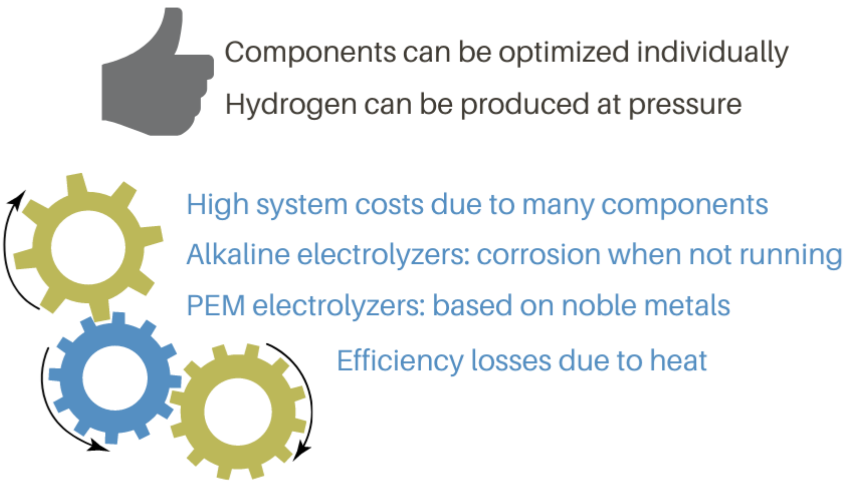


Figure 20. Advantages and challenges of e-fuel technologies, current state: advantages of electrolyzer approaches include the possibility to produce green hydrogen directly at pressure, which is in line with conventional storage methods. Furthermore, the diverse components can be optimised individually, e.g., the electricity production via photovoltaic panels and the chemical conversion in the electrolyzer. However, these many system components (at least three: electricity production with PV, DC-DC converter, electrolyzer), which must be packaged and wired, translate into high CAPEX costs. In addition, electrodes in alkaline electrolyzers are based on iron/nickel and corrode when the electrolyzer is not operated in times of variable electricity supply. PEM electrolyzers resolve this issue, but are based on noble metals (iridium, platinum) which hampers a sustainable upscaling to the TW scale. An important issue is the production of waste heat, which decreases the efficiency of the PV panels, but could on the other hand drive the electrochemical conversion in the electrolyzer. Heat transfer and system integration in general are of utmost importance.

- **System integration/Process intensification:**
  The goal is to increase product yield while minimising energy and resource demands. The production of chemicals and fuels usually implies the combination of different technologies, whereby each of them has its advantages and drawbacks. Putting together the pieces of this complex puzzle in the optimal way allows for the

development of energy-efficient processes, where e.g., the waste heat from one part of the system is used to drive a chemical reaction during another step of the production chain. Apart from these technological advantages, integration also allows for the emergence of novel profitable business models including strategic investments into new infrastructure.

- **Upscaling:**
  A rapid scale-up and prototyping of the electrocatalytic unit with improved design and engineering of the reactors is strongly needed. Intense employment and multi-scale deployment including walking down the ‘learning curve’ are crucial. Moreover, determining the right scale of application for each technology is needed: The global energy system operates at the TW scale, which sets the benchmark for the future employment of renewable energies to achieve a complete change of the energy system. The technologies themselves also represent different scales. Technologies can remain at a very low scale but can be widely disseminated. The examples of such technologies are PV or batteries for which small-scale application (e.g. 1000 W h) with high replicability is common, e.g. rooftop PV installations versus large deployments of 200 MW PV farms. While PV and wind technologies are likely to reach the TW scale by 2025, other technologies may have their sweet spot of optimal operation at smaller scales. This sweet spot is hard to predict but several multi-layer scenarios can be envisioned, in which the corresponding business models may be developed (see Appendix 2). The business models are totally different, which means that the economics requirements may also be very different.

- **Optimization of the conversion process and the operating conditions:**
  The **long-term stability** of the electrolyzer is an important bottleneck for current applications. This translates into an urgent need for materials that are robust enough to operate even in adverse conditions;
  Another important issue is **product selectivity**. Catalyst performances must be increased, and operating conditions and reactor design must be optimised to maximise the produced share of the desired chemical or fuel compared to competing chemical reactions.
  Very importantly, current **energy efficiency** of the overall process has to be maximised. Increasing the current yield and stability of the electrocatalytic process, will result in high energy conversion devices and thus both sustainable and economical viable production processes. Improving the Faradaic efficiency, materials efficiency and energy efficiency towards the thermodynamic limit over the full conversion chain is needed.

- **Sustainability:**
  Current electrode materials are based on scarce materials which hampers a sustainable large-scale deployment of these technologies. Electrodes must be developed which are not based on critical raw materials or which at least allow the recycling of critical materials. Employed materials should ideally be based on abundantly available and non-toxic resources.
- **Flexibility of power supply:**

In order to provide solutions tailored to the resources of every region, an integration within different power supply schemes has to be assured, including remote production. The current production processes must be adapted both to a continuous power supply via an existing electrical grid and local power supply directly from intermittent, decentralised sources.
Moreover, an optimal combination of intermittent renewable electricity sources with inherently inflexible conventional chemical conversion processes has to be found. Achieving operability under fluctuating power supply with volatile energy sources, largely influences electrode stability and limits the possibility of efficient heat integration (showing different dynamics). Non-adiabatic materials and processes will open the door to heat integration within catalysts for best performance under intermittent supply of electricity.
Beyond the large potential to diminish fluctuations of power supply by integrating renewable power supply with cheap and sustainable storage devices (like thermal storage systems), also annual full load operation hours can be significantly increased.

- **Sustainable CO_2 supply: from industrial point sources, to DAC and DACC:** In the short and medium term, CO_2 from industrial emitters will be the main carbon source for CCU activities, providing opportunities for lowering CO_2 capture costs and reducing the environmental impact of industrial production processes. In a long-term perspective, it is estimated that one must shift to direct air capture (DAC) technologies to provide the necessary carbon for a decentralised production of e-fuels in areas where cheap and abundant renewable energy is available. At large-scale, cost-efficient and sustainable deployment of this technology has to be enabled by drastic cost reductions and improved energy performances.

  CO_2 capture technologies have in common one major challenge: the high energy cost of liberating the CO_2 prior to catalysis. Most of the energy use is linked to the regeneration step where pure, gaseous CO_2 is released. One strategy currently considered is to avoid the sorbent regeneration step by combining in one single-step the capture and conversion of CO_2 into syngas and other base chemicals: the solvent for CO_2 capture is at the same time used as electrolyte for the electrochemical conversion step. Even though still at very low TRL, this emerging integrated concept is increasingly studied by several research groups with diverse research directions - among others amine-based electrolytes[29] or alkali liquid solutions.[30]

  In the long-term, **Direct Atmospheric CO_2 Capture & Conversion** (DACC) will enable the decentralised production of chemicals and fuels with highly efficient solar energy devices. Combining the direct capture and conversion of CO_2 in a single device is one of the primary objectives of SUNERGY. The goal is to demonstrate

[29] E. Pérez-Gallant et al., *Ind. Eng. Chem. Res.* 2021, 60, 11, 4269–4278; A. Khurram et al., *J. Phys. Chem. C* 2020, 124, 35, 188877-18885; A. Khurram et al., *J. Phys. Chem. C* 2019, 123, 30, 18222-18231;
[30] VITO NV, European Patent Application, EP 3 673 972 A1;

DACC overall conversion performances 10 to 100 times more efficient than today's biomass practices.

- **Supply and use of heat from renewable resources**: direct use of solar heat is often more efficient than prior conversion to electricity since the latter incorporates more energy conversion steps prone to energy losses. Solar heat can be directly used in a hybrid mode, where a considerable part of the needed electricity is replaced by high temperature heat from solar resources. Prominent examples are high temperature steam electrolysis and hybrid thermochemical cycles. Several thermochemical cycles, like for example redox cycles, provide directly hydrogen and/or synthesis gas, and can be uniquely operated with high-temperature heat from solar concentrating facilities - without the use of electric energy (except for minor amounts for auxiliary units). The use of energy in the form of heat enables the integration of simple and cheap storage options, opening up possibilities towards a continuously operated fuel production.

- **Electrocatalytic transformation of biomass-based feedstock:**
  Using biomass-based feedstock as a carbon source bears the advantage to already start with more complex carbon-based molecules than CO_2 and thus more efficient chemical routes to the final product. However, since biomass production on a large scale is related to high land footprints, one has to choose very wisely the field of application of this valuable resource. As depicted in Figure 21, the direct synthesis of complex chemical products from the bio-based molecules is a promising route to produce carbon-neutral alternatives to fossil-based products.

- **Direct synthesis of complex alternative products:**
  Nowadays, one can note a focus on the alternative production of simple base chemicals (such as methane or ethanol). The latter serve as feedstock for a subsequent thermo-/electrocatalytic transformation to more advanced products by conventional chemical processes (see Figure 21). In this way, the chemical industry can defossilize its production - by replacing fossil-based feedstock with the renewable counterparts, while taking advantage of its existing infrastructure.
  In the long-term, chemical processes can be intensified by avoiding the multi-step approach by the direct transformation of the bio-based intermediates into complex products. This necessitates the development of novel catalytic approaches, controlling multi-electron processes. Such a direct complex chemical transformation increases the overall process efficiency and as such, it directly contributes to a novel, distributed chemical production that is fully integrated with the local resources.

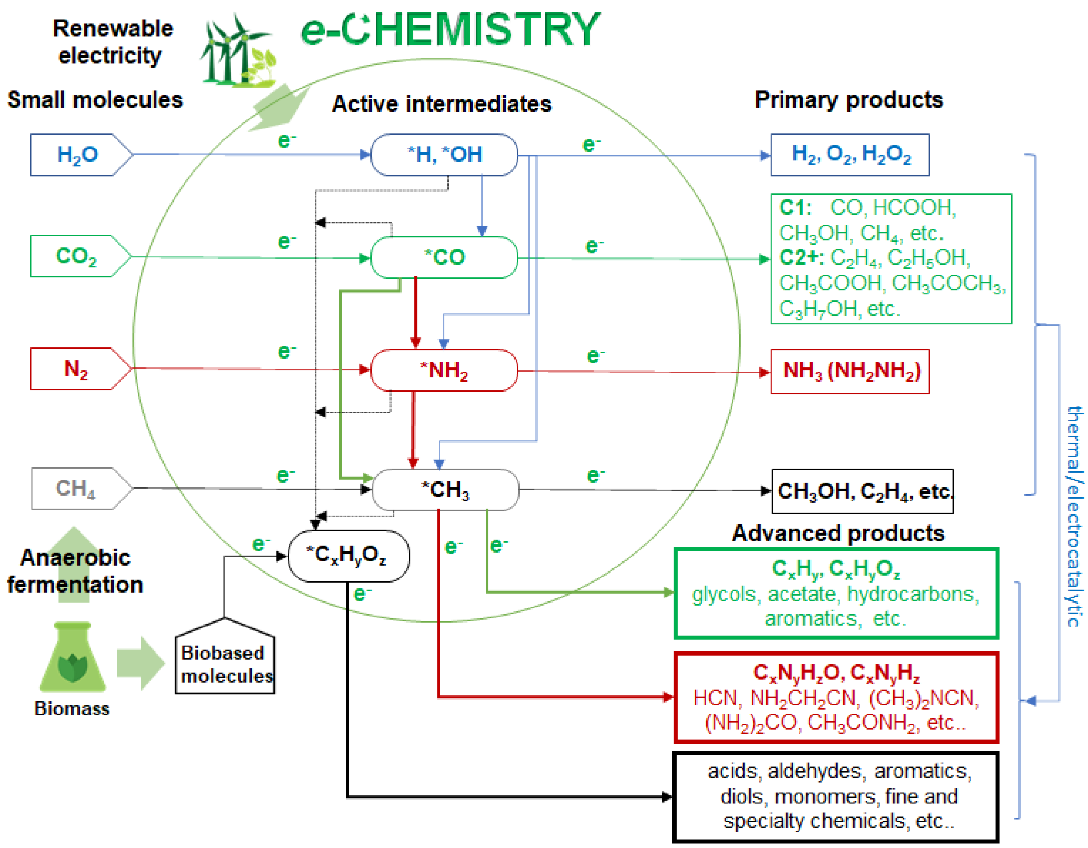
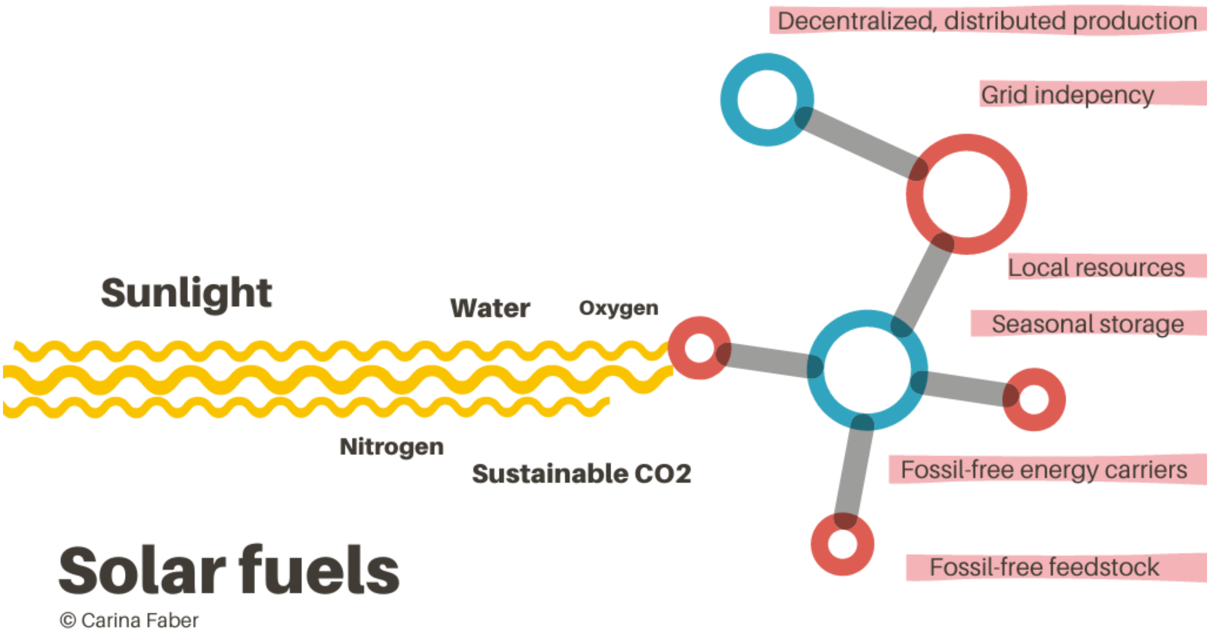


Figure 21. In SUNERGY, to reproduce the complex (petro)chemistry with solar-driven e-chemistry, the novel area of R&I at the interface between the renewable conversion of small molecules and chemical transformation of the bio-based platform chemicals into complex chemicals using intermediates (see the circle) must be explored and synergized. This novel R&I sector, together with creating the symbiosis between fundamental discoveries in catalysis and technological breakthroughs in green chemical engineering, is one of the major focuses of SUNERGY. Based on S. Perathoner (2021) *Catalyst Rev.*, 34, 8-13.

Direct conversion of solar energy for the distributed production of solar fuels and chemicals



In 'direct' photoelectrolysis routes, light absorption and catalysis are integrated in one single device. The main advantage of the direct solar conversion technologies is to offer the possibility of a decentralised, renewable production of chemicals and fuels, solely driven by solar energy for distributed supply. They do not require the connection to an electricity or gas grid infrastructure for their own supply, and can deliver into a variety of product grids. The integration of all components into a single solar-driven device can lower device costs and provide greater flexibility in the system design and deployment. Similar to e-fuels, solar fuels bear the promise of a seasonal storage of, in this case, solar energy and the defossilized production of fuels and chemicals. These technologies are key enablers to transform the linear model of production to circular manufacturing, in line with the concept of the 'Factory of the Future'[31]: synchronised with local needs and resources, avoiding negative environmental impacts through long-distance transport of chemicals and fuels.

Overall targets

The vision in this field is to establish a viable solar fuels industry by the second half of this century. In the long-term, these low TRL technologies must be brought to the market and made economically viable and sustainable. In the short-to-medium term, the goal is to bring

[31] 'Factory of the Future' is a concept on how manufacturers should enhance production by making improvements in three dimensions: plant structure, plant digitization, and plant processes. It is based on full integration of information and communication technology with automation technology across the subsectors of the entire production value chain.
https://assets.kpmg/content/dam/kpmg/es/pdf/2017/06/the-factory-of-the-future.pdf

these technologies to the pilot level within the next 5 years. To this end, the achievement of specific technological milestones will nurture the accomplishment of this long-term mission.

R&I needs in a nutshell

1. **Type: photochemical and photoelectrochemical systems**

In photochemical and photoelectrochemical systems, the diverse functionalities of an electrolyzer-based system (see Chapter: E-fuels) are integrated in one compact device. This translates into potentially more cost-effective conversion devices. The main challenge is that now the sunlight has to be collected over a large area, since the electrochemical active and the light absorption areas are poorly coupled within the same direct conversion system. Current densities are 100 times lower than in commercial electrolyzers (solar current density 10-20 $mA{\cdot}cm^{-2}$ vs. 0.5-2 $A{\cdot}cm^{-2}$ in electrolyzers). This allows the use of earth-abundant catalysts and consequently on the longer term, a sustainable upscaling of this technology. As in PV panels, also in this approach the light absorber heats up, but due to the direct contact between light absorber and catalyst the chemical reaction is directly promoted; moreover, the surrounding water also serves to cool the absorber.

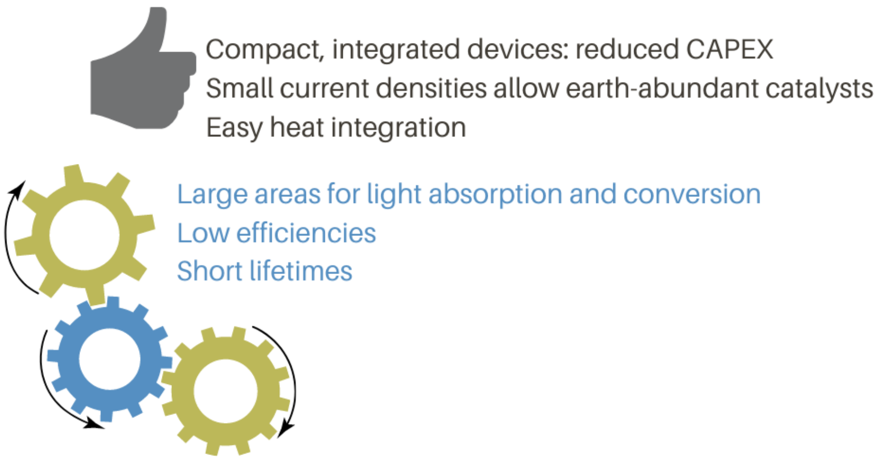


Figure 22. Advantages and challenges related to photoelectrochemical and photochemical systems**.**

In essence, photochemical and photoelectrochemical systems offer the potential for high conversion efficiency at low operating temperatures using cost-effective thin-film and/or particle semiconductor materials.[32] The main targets in this field include bringing these in general low TRL technologies to the pilot level within the next five years through continued improvements in efficiency, durability, and cost.[33] This field strongly benefits from synergies

[32] https://www.energy.gov/eere/fuelcells/hydrogen-production-photoelectrochemical-water-splitting

[33] When the water splitting reaction is the target, PV/EC and monolithic heterojunction PEC systems operating with up to 30% and 19% solar-to-hydrogen conversion efficiencies have been reported with two absorbers in tandem devices. When CO_2 or N_2 reduction are the targets, PEC performances have been low thus far due to the presence of competing side reactions. Nevertheless, catalysts grafted on solar cell surfaces have displayed high selectivity towards CO formation in combination with high current densities. Systems for generating C_{2+} compounds from CO_2 generally show low performances as the target products require multiple proton and electron processes to be orchestrated on a single catalyst surface. This design requirement lowers the quantum efficiency of such systems. For multiple electron and proton transfers to CO_2 or N_2, to yield C_n compounds, biological or biohybrid approaches and their nonadiabatic mimics offer an attractive alternative because the biological processes already

with research developments in photovoltaics, nanotechnology and computational materials science.

Substantial R&D efforts and scientific breakthroughs are needed in the following domains:[34]

- **High conversion efficiencies and product yields through enhanced sunlight absorption and better surface catalysis:**

  → development of novel chemically stable semiconductors with a band gap between 1.5 eV and 2.0 eV;

  → development of novel light-absorbing responsive matrices based on organic or inorganic materials (serving for efficient light harvesting, charge separation and direct charge transfer) coupled to molecular catalysts to form conversion cascades that operate at high forward yield thanks to vibronic coupling across the entire system.[35]

  → overcoming back reactions and recombination losses: In photochemical conversion systems, the photon to product yields are unfavourable due to the small size of the particles or delocalized charge carriers. Rational bottom-up nanostructuring of catalytic and light harvesting components within the responsive matrix in order to minimise the energy losses and improve performance towards the thermodynamic limit for uphill conversion will be one of the major focus areas of the fundamental science efforts of SUNERGY.

- **Long durability and lifetime** (with operational stability of at least 15%):
  → development of novel chemically stable semiconductors with long carrier lifetimes
  → development of novel stable catalysts based on earth-abundant elements
  → application of rugged materials and protective surface coatings

- **Novel cell designs**, with an efficient integration of both half-cells ensuring good optimised light absorption through band-gap alignment, easy and energy efficient product recovery (e.g. by condensation into liquids or solids) as well as the direct use of reactants without preliminary steps of concentration and purification;

- **Upscaling from the lab device (a few 10 cm^2) to larger area prototypes** by overcoming mass transport limitations through electrochemical engineering;

have developed the necessary chemical cascade reaction pathways and cycles needed to obtain complex desired products at high yield by nonadiabatic conversion of reactants into products. Solar-to-chemical efficiencies in some lab-scale biological systems are reported from 1% up to 10%.

[34] See: R. van de Krol, B. A. Parkinson (2017) *MRS Energy & Sustainability*, 4, e13.

[35] This design principle is aimed at minimization of energy losses (due to amelioration of wasteful back reactions and short-circuiting). Achieving much improved target current densities and Faradaic efficiency of the photo(electro)chemical cell to the levels necessary for industrialization (J> 0.2 A·cm-2 and FE > 80%). This will allow for rapid prototyping and industrial scale-up of the photo(electro)chemical technology. Novel concepts are therefore needed for formation of highly ordered photochemical nanoarchitectures operating at a minimal overpotential;

- **Reduction of fabrication costs** through materials savings (earth-abundant materials) and simplified materials processing;

- **Introduction of certification laboratories** following a developed standardised methodology for the measurement of device efficiencies and stabilities similar to those of photovoltaic devices.

2. Type: Biological and biohybrid systems

In biological and biohybrid systems, devices and reactors based on bio(photo)catalysts carry several functionalities highly advantageous for industrial applications. Purely biologically-based approaches use evolutionary optimised biological macromolecular machines from microalgae and bacteria (‘microbial cell factories’), while biohybrid approaches combine synthetic smart materials with microbial cells for the realisation of complex carbon chemistry.

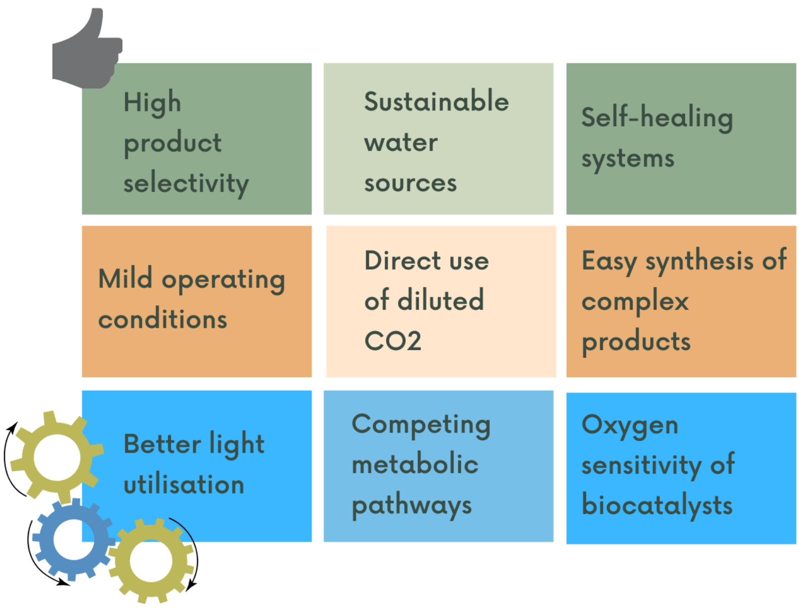


Figure 23. Advantages (two upper panels) and challenges (lower blue panel) related to direct biological and biohybrid conversion pathways

Biological and biohybrid systems work under mild operating conditions, reducing the overall energy demands. A unique feature is their capability to deal with feedstock at different concentration levels, ranging from atmospheric CO_2, to industrial flue gas up to concentrated CO_2 sources. Thanks to the natural biodiversity of microbial biocatalysts and/or the application of the synthetic biology toolkit, the biocatalyst functionalities can be selected and/or significantly improved in terms of high product selectivity and resistance to poisoning. Some microbial bio(photo)catalysts have been shown to thrive in wastewater in the presence of heavy metals or high salt present in the growth medium. Last but not least, a big advantage of bio- and biohybrid systems is their capability to carry out complex carbon chemistry, i.e. converting efficiently CO_2 into not only C_1 but also C_n chemicals in a limited

number of steps.[36] This provides an important added value over and above the synthetic artificial leaf systems or multistep solar conversion technologies, compensating for lower solar-to-product efficiencies.[37]
In the biohybrid approach, biocompatible nanomaterials are used to feed photoactivated electrons and protons to the photosynthetic microbes, thus, they represent a new paradigm to engineer microorganisms for solar-driven conversion of CO_2.[38] This is because nanomaterials often possess unique optical and electrical properties which can be functionally linked to the photosynthetic biocatalysts. In particular, inorganic semiconductor materials show an outstanding efficiency in light-harvesting with up to 20% solar-to-electricity conversion rates, multiple times exceeding that of natural photosynthesis.

The two main targets in the biological/biohybrid conversion systems are:[39]

1) **a diversification of the considered water and CO_2 feedstock**: The circular usage of water and the ability to also function with wastewater as well as brack and sea water must be pursued intensively given the great promise to reduce the related water footprint of these technologies. Exploring different CO_2 feedstocks allows one to profit from the inherent ability of the biocatalyst to function under various CO_2 concentrations, varying from atmospheric concentration up to industrial flue gas concentrations.
2) **a significant improvement of solar energy conversion efficiency and stability**: Dozens of genetically engineered photosynthetic organisms ('cell factories'), hosting novel synthetic production pathways and enzymes, are currently available for the production of desired chemicals.[40] However, most of the available systems show low solar-to-chemicals conversion efficiencies and need significant improvements to serve for industrial-scale applications in both biological and biohybrid conversion systems in which such microbial cell factories are utilised.

   For the development of the next generation biological and/or biohybrid solar conversion systems the main R&I goals are:

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[36] Wichmann et al. (2021) Trends Biotech, 39, 323-327.
[37] Although synthetic materials excel in solar capture, they do not hold the upper hand over biology regarding CO_2 fixation, with synthetic systems for direct solar CO_2 reduction suitable mainly for the C_1 products synthesis. Conversely, acetogenic bacteria live from converting CO_2 into acetic acid (C_2 product) via the Wood-Ljungdahl pathway, one of the oldest biochemical pathways for CO_2 fixation [K. K. Sakimoto et al. (2016) Science, 351, 74-77]. Another example is the soil bacterium *Ralstonia eutropha* shown to be successfully integrated with the semiconductor water-splitting system for solar-driven and highly specific CO_2 fixation into C_{2+} products [Torella et al. (2015) Proc. Natl Acad. Sci. U.S.A., 112, 2337-2342]. Similarly, some cyanobacteria (photosynthetic microbes) integrated as thin biofilms into the polymeric matrix have been proven suitable for sustainable and long-term ethylene photoproduction, with solar-to-product efficiency just over 1% [S. Vajravel et al. (2020) Green Chem., 22, 6404-6414].
[38] N. Kornienko et al. (2016) *Proc. Natl Acad. Sci. U.S.A.*, 113, 11750-11755; H. Zhanget al. (2018) *Nature Nanotech.*, 13, 900-905; C. Liu et al (2015) *Nano Lett.*, 15, 3634-3639; Y. Su et al. (2020) *Joule*, 4, 800–811.
[39] Fang et al. (2020) *Chem. Soc. Rev.*, 49, 4926-4952.
[40] S. A. Angermayr et al. (2015) *Trends Biotechnol.*, 33, 352-361; Wichmann et al. (2021) *Trends Biotech*, 39, 323-327; L.-E. Meyer et al. (2021) *Curr. Op. Green Sust. Chem.*, 31, 100496.

- selection of robust and fast-growing chassis (i.e. the elimination of competing metabolic pathways through genetic engineering and an increase in robustness of biocatalysts to impurities in the feedstock such as oxygen or heavy metals);

- redesign photosynthetic light reactions to increase production of solar-based reducing power;

- efficient coupling of solar-driven reducing power with improved CO_2 assimilation pathways;

- prolongation of lifespan of the photosynthetic cell factories (up to several months and more), where they function as self-regenerative true biocatalysts synthesising and secreting targeted solar chemicals and fuels;

- improvement and full automatization of synthetic biology tools and coupling it with systems biology technologies.;

- development of durable semiconductors, nanoparticles and other nanomaterials, which are cost-effective, energy efficient and biocompatible.

Both approaches necessitate also an **optimised reactor design ensuring:**

→ **improved light utilisation:** bioreactor designs avoiding self-shading effects. Novel concepts in microbial cultivation, and scalable photobioreactor designs will allow overcoming the inherent problems of aquatic phototrophic cultures (e.g. self-shading, diluted systems).

→ **improved integration of biotic and abiotic components at the nanoscale**: developing strategies to obtain sufficient potential required for water splitting and enzymatic CO_2 conversion, e.g., coupling the photocathode of a bio-photoelectrochemical cell with immobilised biocatalyst with a PV cell; efficient engineering of the interface between biotic and abiotic components to improve their electronic communication and biocompatibility of the light-harvesting nanomaterials;

→ **high biocatalyst loading:** e.g. development of 3D-printed nanostructures optimising loading without compromising on light penetration;

→ **cost-effective product separation:** engineering efficient strategies for significant improvement in product separation and extraction from the electrolyte medium. This technological challenge can be targeted by e.g., using integrated membrane electrolysis or microfluidics;

→ **heat integration:** low-quality, waste heat from industrial processes can speed up the reduction of CO_2 by the biocatalysts.

SUNERGY Value Chain

The SUNERGY large-scale research and innovation initiative focuses on learning how to manufacture energy carriers and chemicals while reducing cost over the entire source to product value chain. SUNERGY technology development and timely adaptation of energy infrastructure will enhance the manufacturing of energy carriers within Europe and reduce the need for energy import and associated geopolitical risks.

The energy market is the largest market by a wide margin. European energy imports are 200 B€ per year, and including base chemicals, this represents a yearly upstream market of ca. 250 B€ (Figure 24). This upstream market is currently based on fossil resources and SUNERGY aims for displacing fossil fuel-based chemicals and fuels by renewables. This is enabled by novel technologies with high overall energetic and economic efficiency. Cost reduction for renewable chemical production will stem from high economic efficiency in industrial sites with economy of scale, or from farming-type decentralised business operations which will be integrated with suitable grids (electricity or others shown in Appendix 2, Figure A2.1) within the existing urbanised economic infrastructures. This approach will allow for a concentration of products to any scale that is required in a particular location in Europe depending on the local needs.

The SUNERGY value chain can be broken down into sectors[41] based on the supporting organisations that form the SUNERGY community. An important element constituting the additional market in the SUNERGY value chain is the infrastructure which comprises the existing gas pipelines, power grids etc., but also includes the new conversion assets for large-scale decentralised terrestrial applications: e.g., solar-to-fuel reactors, microalgal bioreactors, etc., where diversification of the products is only limited by imagination (Appendix 4, Figure A4.2). The impact of a particular end product on changing the existing value chain cannot be overestimated. It is well beyond merely replacing the feedstock on the upstream side (Appendix 4, Fig. A4.3). More importantly, such renewable end products carry high potential for changing value chains by closing cycles at all levels of the value chain.
The current refinery investments on a yearly basis are ca 17 B€ per year for Europe, which provides a reasonable estimate of how large the infrastructure market is in volume. This market probably involves entirely new manufacturing and service sectors. For instance, in the early stages of development of the grids, novel sectors based on the key enabling technologies for analysis and monitoring of processes will emerge (Fig. A4.3).

[41] See Appendix 4 for an overview of technological and socio-economic sectors and services of the SUNERGY's full value chain that are represented by the existing stakeholders listed in Appendix 6.

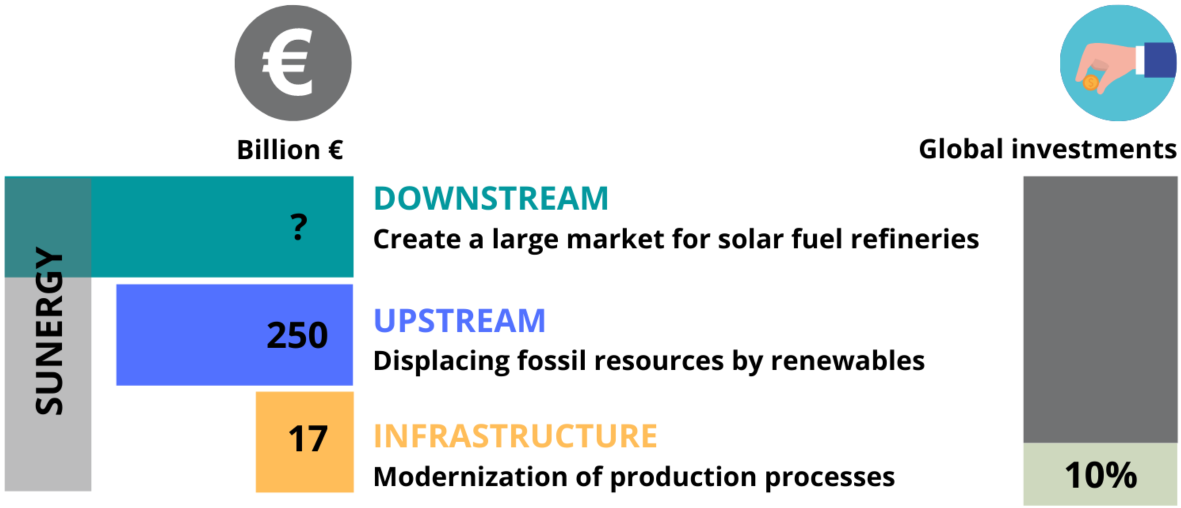

Figure 24. The value chain of SUNERGY large scale R&I initiative aims to manufacture energy carriers and chemicals at an affordable cost. The **downstream** markets are characterised by a large diversity of end products affecting almost any aspect of everyday life: comfortable housing, travel, food supply, health, security etc. SUNERGY feeds into these markets by securing the energy supply and by providing raw materials for further processing. Using the currently existing centralised infrastructure, SUNERGY focuses on the production of high-volume low-value renewable chemicals and fuels to mitigate CO_2 emissions as much as possible. For the future decentralised energy and production systems, the wide use of decentralised approaches will allow for closing the cycles with high value products at a low volume. These can be produced with on the spot refineries at farms, or in buildings and houses in urbanised areas. The **upstream** (energy) market is currently based on fossil resources and SUNERGY aims for displacing fossil fuels by renewables. The **infrastructure** market comprises the grids and the manufacturing facilities of the new conversion assets for terrestrial application on a large scale (e.g. solar-to-fuel reactors). The annual shares of the **global investments** is estimated to be 10% for all the three markets. Other EU partnerships have their pivot in the downstream markets, with the exception of the Clean Energy Transition and Clean Hydrogen partnerships that attempt to cover a minor part of the SUNERGY's value chain (technologies for green hydrogen production).

Necessary regulatory and support framework

With the introduction of the EU Green Deal, the European Commission has decided to step up and take a leading role in the fight against climate change. GHG emissions reduction of 55% by 2030 (compared to 1990 levels) and climate neutrality by 2050 are ambitious goals, the achievement of which strongly depends on a regulatory framework that is supportive of all the measures that can contribute.

A series of legislative packages are being revised and new ones are being introduced to be fit-for-purpose. **The reality of the climate urgency, the number of policy instruments and the complex interconnections between them, make this one of the most crucial climate policy periods in recent times**. Examples of important policy packages include upstream instruments like the EU Sustainable Finance Taxonomy that defines which economic activities can be considered as sustainable and thereby benefit from easier access to finance; the revision of the Emissions Trading System dealing with CO_2 emissions in different economic sectors; the communication for Sustainable Carbon Cycles that places CCU high on the political agenda for emissions reductions and carbon circularity and within it also the future Carbon Removal Certification Mechanism dealing with the definition, certification and monitoring of carbon removals; the Carbon Border Adjustment Mechanism dealing with products imported from outside the EU; but also downstream and product-specific instruments, like the revision of the Renewable Energy Directive and the associated rules for accessing and using renewable electricity, simplifying renewable energy project permitting and fostering the deployment of power purchase agreements (PPA); the Hydrogen Strategy guiding the deployment of clean hydrogen, the EU Strategy for Solar Energy that will define how to harness the solar potential in the most efficient and sustainable way; the ReFuelEU Aviation for more integration of sustainable aviation fuels; the FuelEU Maritime for emission reductions and alternative fuels in the maritime sector; the Sustainable Products Initiative and others. This list is by no means exhaustive and some of these instruments are part of the Fit-for-55 package that was introduced in July 2021 and is now under discussion in the European Parliament and the Council. One way or the other these policy packages are expected to influence the deployment of SUNERGY pathways, some more than others. **It is crucial that these regulatory instruments are not only supportive of all technological solutions that can bring us closer to our climate goals but also consistent with each other and considerate of the industrial realities**. A supportive regulatory framework will give the correct signal to industrial actors that are ready to upscale their technologies and provide alternative business models for fossil-free fuels and chemicals that will contribute to the EU's climate goals. Combination of such a framework with funding instruments like in Horizon Europe or the Innovation Fund will also give the confidence to stakeholders that support is consequent all along the TRL value chain.

Added Value of SUNERGY

SUNERGY directly contributes to the EU's and global climate and energy short and long-term goals. It supports the objectives of the *Paris Agreement*[42], most *UN Sustainable Development Goals*[43] and provides viable technological solutions to the great ambitions of the *EU Energy Union*[44], including the *EU's energy and climate targets for 2030*, the *European Green Deal*[45], the *Clean energy for all Europeans package*[46]*, the EU´s Circular Economy Action Plan*[47], the Horizon Europe framework programme[48] and to the *EU's long-term strategy*[49] of achieving carbon neutrality by 2050. It also supports Mission Innovation[50], the global initiative to accelerate clean energy innovation, in particular the Innovation Challenge 5, "Converting sunlight".

SUNERGY fosters collaboration across industrial sectors and between academia, industry, societal stakeholders and decision makers - crucial to compete with developments in other parts of the world. Europe's traditional strength in science and engineering is a critical advantage to build upon with a view of becoming the world leader in sustainable energy supply. This requires a concerted, coherent and substantial effort. SUNERGY aims at contributing to this effort, in support of Europe's competitiveness, energy independence and secure energy supply, and to position Europe in a key role for leading the world towards a more sustainable and environmentally-friendly society, creating job opportunities and welfare for future generations.

SUNERGY builds upon two previous projects (ENERGY-X[51] and SUNRISE[52] Coordination and Support Actions) funded under Horizon 2020 and. relies on established relationships across academia, industry, public institutions and other stakeholders as well as on a running organisational governance structure. SUNERGY is a growing community (recent list of supporters provided) and aims at coordinating efforts towards a pan-European large-scale research and innovation initiative (LSRI). The path and possible funding models towards such LSRI is further detailed in the section "Possible funding model for SUNERGY" below.

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[42] Paris Agreement (December, 2015): https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
[43] UN Sustainable Development Goals: https://sdgs.un.org/goals
[44] EU Energy Union: https://ec.europa.eu/energy/topics/energy-strategy/energy-union_en
[45] European Green Deal: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal
[46] Clean energy for all Europeans package: https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en
[47] EU Circular Economy Action Plan: https://ec.europa.eu/environment/topics/circular-economy/first-circular-economy-action-plan_en
[48] Horizon Europe:https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en
[49] EU 2050 long-term strategy: https://ec.europa.eu/clima/policies/strategies/2050_en
[50] Mission Innovation: http://mission-innovation.net/
[51] ENERGY-X CSA: Funded under Horizon 2020, Grant N° 820444
[52] SUNRISE CSA : Funded under Horizon 2020, Grant N° 816336

In its vision, approach and priorities, SUNERGY is complementary to other European existing initiatives, particularly the *Processes4Planet*, *Clean Energy Transition*, *Clean Hydrogen* and *Circular Bio-based Europe* public-private partnerships. SUNERGY will work in coordination with these initiatives and others, such as the recently launched EU Missions, to maximise benefits and avoid duplication of efforts.

SUNERGY's added value for Europe and its complementarity compared to other initiatives are its holistic approach enabling a systemic change of the entire value chain of sustainable energy conversion and feedstock production. Most importantly, SUNERGY combines the upstream (manufacturing of renewables feedstock for displacing fossil resources) with the downstream markets (supporting large downstream markets for solar fuels and chemicals). This is enabled by developing decentralised solutions for the energy conversion and distribution of renewable feedstock. A description of these aspects is outlined in Appendix 4.

Possible funding model for SUNERGY

The timeline envisioned for the evolution of SUNERGY towards a large-scale research and innovation initiative (LSRI) implies an intermediate step (2021-2024), the so-called "ramp-up phase" before launching the LSRI in approximately 2025. During the currently running "ramp-up phase", the overall SUNERGY initiative will be composed of common activities (coordination, community building, roadmapping and implementation of the SUNERGY roadmap via a portfolio of European and National projects, international cooperation). It will be supported by a Coordination and Support Action (CSA) project, SUNER-C[53], funded under Horizon Europe to start in spring 2022 with a total duration of 3 years. The recent granting of the SUNER-C project was an official recognition of the SUNERGY initiative as a key player on the EU level in the field of solar fuels and chemicals.

During the SUNERGY ramp-up phase (2021-2024), the implementation of the roadmap will be done via a portfolio of European projects, i.e. Research and Innovation Actions (RIAs) and Innovation Actions (RIAs), covering the key aspects at different levels of the value chain as identified and proposed by the SUNERGY stakeholders community. As part of the overall initiative and ramp-up phase, the selected RIAs and IAs will build synergies between them and with the SUNER-C CSA. A work package of the SUNER-C CSA project is dedicated to foster such interactions. Projects financed under Horizon Europe (HE) will be complemented by other funding and support instruments, including major national funding schemes and projects including industrial ones. Within SUNERGY, technologies are developed that still need some level of fundamental/disruptive research, but at the same time technologies close to application and with a short time to the market. The scope of industrial projects will be mainly focused on early demonstration and validation to create traction for an economic uptake of the developments.

[53] SUNER-C CSA : SUNERGY Community and ecosystem for accelerating the development of solar fuels and chemicals

In the envisioned timeline, the LSRI will be launched at the end of the CSA and the related "ramp-up phase", in 2025. In HE, there are at present two types of instruments for funding LSRIs: partnerships and missions. Missions rely on a strong bottom-up approach to engage citizens and the society and five missions were launched in 2021. SUNERGY could develop strong links mainly with three of them, namely "Adaptation to climate change", "Climate neutral and smart cities", and "a Soil deal for Europe". However, building an LSRI in this area requires a concerted and coherent effort: relying fully on missions is not recommended due to the risks of fragmentation of R&I actions and, as a consequence, of limited impact. The other option currently available in HE and which could support SUNERGY is a public-private partnership (PPP). More precisely, there are three different types of partnerships in HE: co-funded, co-programmed and institutionalised, each of them showing different schemes and rules for the involvement of public and private partners as well as Member States. Between these three different options, the co-programmed public-private partnership instrument could be a possible instrument for the SUNERGY LSRI (even though, as conceived now, it would support less the fundamental/disruptive research part of the SUNERGY agenda). It is the simplest type of partnership to implement and a flexible instrument. It associates public and private partners to the Commission, Member States (MS) and Associated Countries (AC) via memoranda of understanding and/or contractual arrangements. Co-programmed partnerships follow a roadmap based on a SRIA. The contribution of the EU is implemented via open calls in the HE work programmes with propositions of topics based on the roadmap - as done during the SUNERGY ramp-up phase - which ensures openness of the initiative. The partners implement their commitments (i.e. activities and contributions) under their own responsibility.

A second possibility is a co-funded partnership instrument which associates EC, MS/AC and research funders and other public authorities at the core of the consortium. Co-funded European Partnerships are based on a joint programme agreed by the partners. Funding of the partnership is ensured by a blending of EU and national public (e.g. national funding agencies) and/or other R&I funding sources. The core partners are mainly national programme owners and managers form MS & AC and thus is more public driven. The implementation is ensured based on annual work programmes with rules agreed by the partners.

The specific instrument for a future SUNERGY LSRI will be further discussed with the EC, MS and AC and with SUNERGY stakeholders, based also on the achievements of the SUNER-C CSA and the ramp-up phase, on the future developments of Horizon Europe and Europe´s funding landscape.

Wider community involvement

The main objective for SUNERGY regarding the dissemination and communication activities is to foster collaboration and coordination of activities between stakeholders across the EU and at national/local levels: academia, industry, SMEs, local/regional/national governments, societal stakeholders (e.g. NGOs) as well as European large-scale initiatives (partnerships, missions) and European/national/regional networks and clusters . Currently, the SUNERGY initiative has assembled a community of more than 300 stakeholders (see Appendix 6).

Via the SUNER-C coordination and support action (CSA), SUNERGY wants to further develop this community, aligning it around a common vision on the affordable manufacturing of solar fuels and chemicals and its implementation via a strategic roadmap.

Further involvement of the community is achieved through scientific publications, presentations at conferences and specialised events for the scientific, technological, innovation, societal and policy communities. In addition, SUNERGY interacts with its community of followers and supporters through its website, its regular newsletter (currently 4,400 subscribers) and its social media channels (i.e. LinkedIn, Twitter, YouTube, ResearchGate and Instagram) to ensure uptake, support and engagement. The website showcases SUNERGY activities, members, activities, progress on the research pipelines and recent findings. On social media channels, SUNERGY shares regular posts on e.g. project findings, new members, events and recent policy developments. A newsletter is also sent out at least four times per year and press releases are published on important milestones.

Outreach materials and demonstrators are key to attract younger generations and future end-users. Educational actions are at the very heart of SUNERGY's activities and the related SUNER-C CSA aims at promoting a generation of future leaders in renewable technologies. This includes: a) an open platform with available educational materials for students and professionals on the newly developed technologies conducted by the highest calibre experts both from academia and industry; b) attractive and interactive teaching materials for primary and high school students. Training for the business sector will focus on new business models, emerging new markets and new technology uptake strategies.

These actions also aim at having a strong citizen's engagement and the inclusion of social sciences to identify and address relevant, socio-technical cross-cutting challenges related to SUNERGY's technologies and vision. This is key to ensure a long-term success of SUNERGY and for the social acceptance of scalable renewable technologies it advocates for.

Appendix 1: Short-to long term sustainable solutions – the energy conundrum

Fuel and chemicals represent the largest global market by a wide margin. The principal industrial driver for SUNERGY is the need to displace the hydrocarbons from fossil resources and energy intensive ammonia synthesis with the Haber-Bosch process by cost efficient renewables. Only with access to large amounts of renewable hydrogen this can become reality, which is therefore an additional industrial driver to take into account (Figure A1.1).

State of the art of solar fuel and chemical production

The state of the art in the solar to fuel and chemicals R&I landscape encompasses four technology classes at different TRL, denoted A-D (Figure A1.1, central box). The class A, (biocatalysis in cell factories) aims at genetic tailoring of microorganisms for improving photon-to-chemical product value chains in conjunction with product diversification. It is enabled by synthetic biology. Technology class B comprises the visionary 'artificial photosynthesis' technologies based on direct solar conversion into chemicals. Together A and B represent the direct processes in SUNERGY. The conversion of concentrated renewable power into hydrogen in D is a step on the way to the conversion of CO_2 in the third technology class C, initially by converting CO_2 from point sources and later by capturing from the air. Technology class C is enabled by advanced, novel chemical synthesis with activated CO_2 while technology class D corresponds to either direct conversion with photoelectrochemical (PEC) systems, thermolysis, or conventional conversion of renewable electricity with electrolysis in a stepwise approach. The C and D categories represent the multistep processes, with the exception of PEC, which has characteristics of a direct process since it is a single device, while internally it is a multistep process where electricity (in the form of uncorrelated electrons) is used as an intermediate for cascading multiple photoelectric and electrochemical stages. At the lowest TRL levels are the class B direct conversion technologies, the artificial photosynthesis, which combine biomimicry and nanotechnology for decentralised high yield conversion beyond the adiabatic limit, just like nature does, with technology that is scalable for closing economic cycles at any desired level in the circular economy.

The energy conundrum – between scalability, sustainability and affordability

The biomass technologies on the left of Figure A1.1 provide a large variety of chemicals from atmospheric CO_2. Modern energy crops and secondary biofuels are affordable and renewable but are not scalable. Their supply is insufficient to cover demand with biofuels. Additionally, there is a risk that extensive biomass-based fuel production, such as that based on forestry, might prevent the realisation of other sustainability goals and, in the longer perspective, counteract climate change mitigation actions.

To the right of the SUNERGY R&I approaches (Figure A1.1) is the renewable electricity from solar conversion, directly with photovoltaics or indirectly from wind. While renewable electricity is scalable and has become affordable in recent years, it delivers transient electrical power, not the stored energy offered by chemicals and fuels. Hydrogen from power is feasible, and in principle the process is scalable, but this technology has remained unaffordable for well over a century. The sustainable conversion of atmospheric CO_2 into chemicals using green hydrogen is still a distant promise despite the successful laboratory scale trials. SUNERGY aims to reconcile sustainability and economic viability of green fuels and chemicals to overcome the hurdles that have hampered large-scale implementation of the new technological solutions in this field until now.

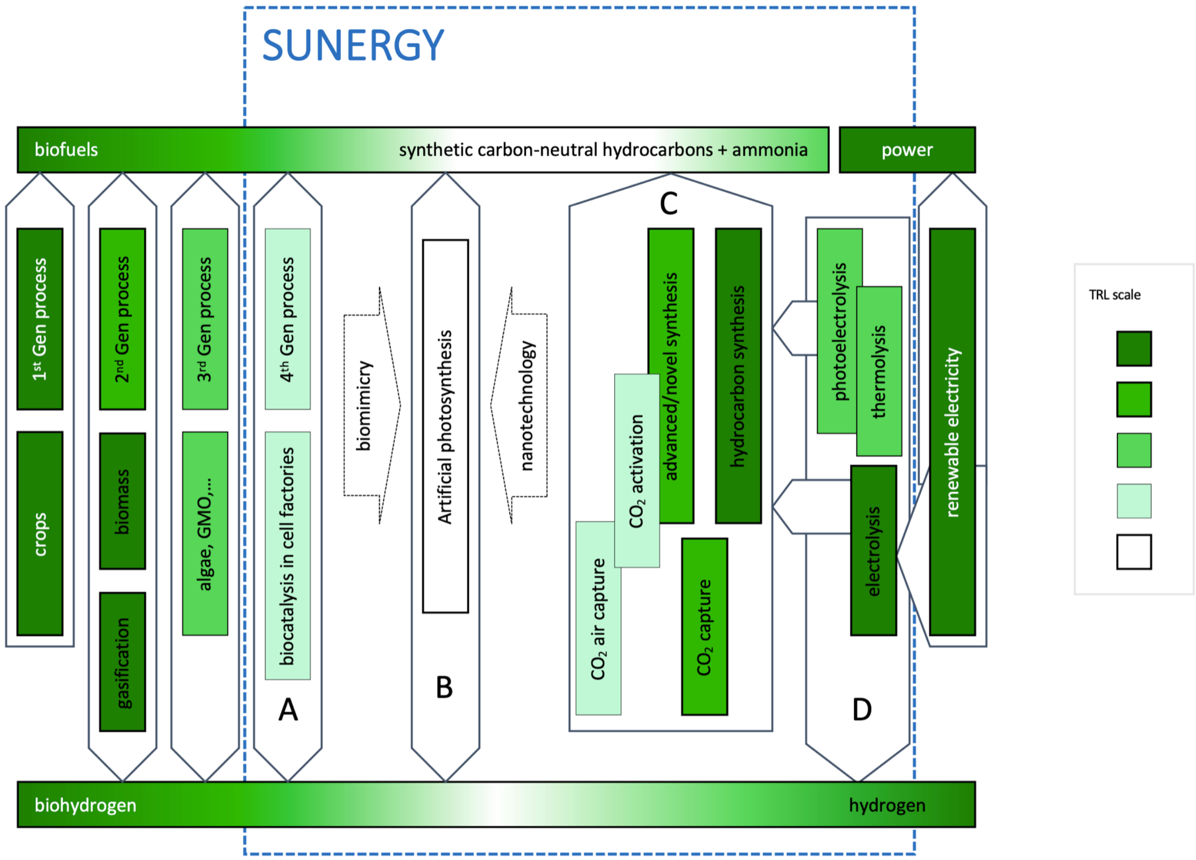

Figure A1.1. The supply of enough hydrogen, renewable carbon-neutral hydrocarbons and ammonia are the industrial drivers behind the SUNERGY LSRI for the circular economy, but halfway into the transition to a sustainable energy system we are running into a wall. On the left in Figure A1.1 there is biomass, which is affordable and can be sustainable, but is not scalable, while on the right there is PV+electrolysis, which is scalable but not affordable and sustainable. SUNERGY aims to overcome this hurdle once and for all, aiming for technology that is affordable, sustainable, and scalable (adapted from G.J. Kramer, Utrecht University).

Appendix 2: Development of strategic, flexible energy conversion scenarios

The Gridmaster approach is an example of the multilevel and multiscale energy scenario modelling toolkits which provide information for infrastructure decision-making under deep uncertainty. The approach is being developed for strategic planning of integrated energy-infrastructure. The evolution of the energy system is deeply uncertain, and this poses a challenge for strategic investment decision-making the grid operators are responsible for. The objective is to create a robust investment plan that provides timely sufficient transport capacity for the facilitation of various energy system scenarios at an acceptable risk of stranded assets. The approach uses iterative stress testing of candidate investment plans in numerous scenarios by using many computer simulations. Stress testing reveals vulnerabilities of the candidate investment plan that in a subsequent step be solved by adding adaptive investments to the plan.

Currently, the Gridmaster approach is applied to the challenge of grid planning under deep uncertainty. This approach can also be developed for other strategic decision-making problems in the context of the energy transition. The putative scenario development for the four SUNERGY technology classes A-D from a regional European perspective is depicted in Figure A2.1. On the left an exemplary European region is shown comprising many urbanised zones and operating at high economic efficiency. Following the Gridmaster approach, whereby many computational experiments are performed to create an ensemble of scenarios against which candidate actions are evaluated in order to develop robust actions[54], a myriad of energy systems scenarios can be envisaged that form a tree whereby branches are added over time that indicate possible pathways towards a zero and negative emissions energy system.

The relevant scenario space for strategic planning for a given EU region is in the order of 10^{24} scenarios, and no a priori choice can be made between the different branches from the scenario space. Three examples of development paths with different ratios of centralised and decentralised conversion assets, starting from the current status in 2021 are shown in Figure 2.1. In decision-making for strategic grid planning the deep uncertain evolution of the energy system poses a challenge. The Gridmaster approach is developing a grid planning method that can deal with these deep uncertainties. In this method candidate investment plans are stress-tested in a myriad of scenarios sampled from the scenario space. Finally, this approach results in robust adaptive investment plans that create in time sufficient transport capacity in many scenarios at an acceptable risk on stranded infrastructure assets.

It should be emphasised that the three shown grid scenarios are selected from millions of possible scenarios of infrastructure assets developing under various R&I breakthrough advances in key enabling technologies, as no *a priori* choice can be made between the different branches from the trees. By exploring the effectiveness of an investment plan in many scenarios, **robust infrastructure investments** can be identified.

[54] M. Haasnoot et al. (2013) *Global Environ. Change*, 23, 485–498.

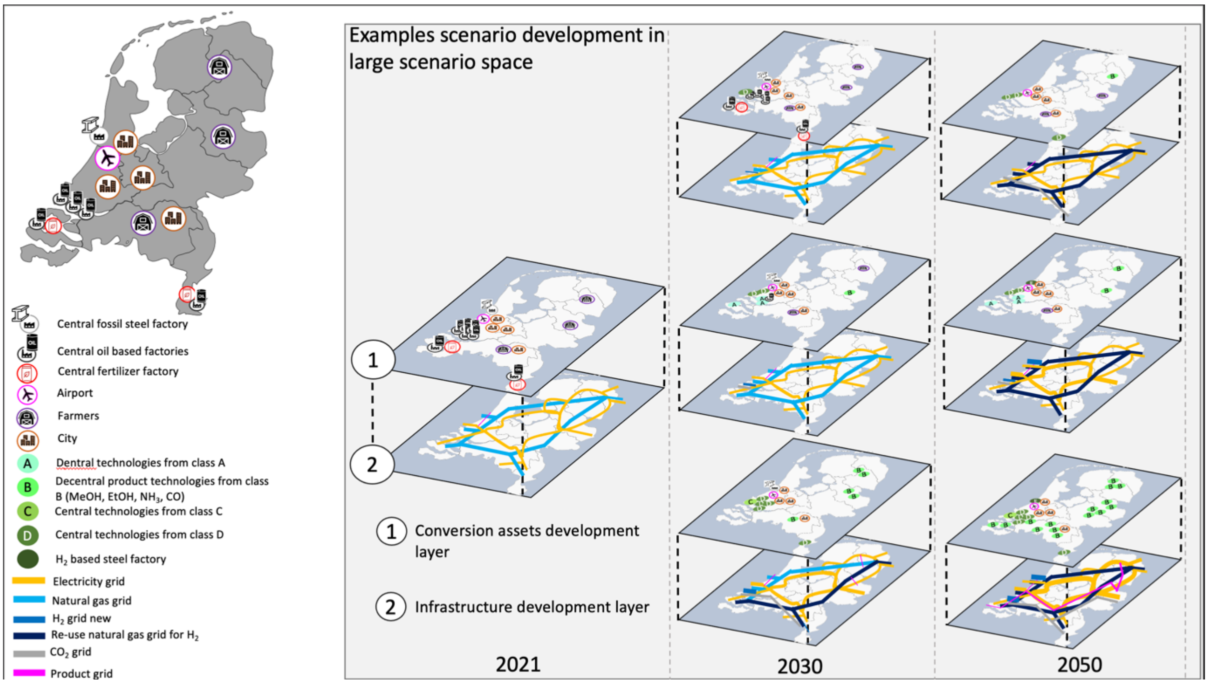

Figure A2.1. Modelling of diverse and region-specific medium-to-long term energy scenarios. Shown are the two layers; the upper one contains the conversion assets, listed in the legend on the left. Examples of high intensity centralised infrastructure assets are steel factories, oil refineries, factories for the production of fertilisers, or an airport or 'hydrocarbon fuel/energy carrier demand centre' with its planes as the conversion assets. Decentralised infrastructure assets distributed over the exemplary European region are farming conversion assets and urbanised (city) regions. The four SUNERGY technologies are indicated with different shades of green, indicating their current TRLs (see Appendix 1). Following the Gridmaster modelling toolkit for Robust Decision Making in long-term business planning, SUNERGY's technology classes A and B represent the more decentralised conversion assets, while C and D are the more centralised assets since they can be based on electric concentration (see Appendix 1 for description of technology classes of SUNERGY). Courtesy: Ton Wurth, Siemens.

Furthermore, guidelines for flexible investments that are effective in case of a particular conversion asset (infrastructure) deployment can be identified. In the legend on the left in Figure A2.1 six grids are shown. The first two, ***the electricity grid*** and ***the natural gas grid*** are presently operational. For ***CO_2 transport*** development of a new grid is necessary, and to supply all the hydrogen needed to decarbonize European economies, **a new *hydrogen grid*** is also needed. Part of the CO_2 and H_2 grids are newly constructed and another part can be realised by ***upcycling the existing natural gas grid***. Finally, it is likely that **novel renewable product grids,** which may not be fixed in the ground but can be based on flexible means of transportation, are needed to support the integration of SUNERGY technologies in the energy system.

An **adaptive investment plan** for integrated energy-infrastructure will be needed to tailor the development of energy-infrastructure to the actual evolution of the energy system by facilitating the implementation of the above-mentioned conversion technologies. The realisation of grid expansion projects is a long-term process, i.e., 5 – 10 years between investment decision and actual capacity expansion. In case implementation of centralised technologies C and D becomes dominant, the adaptive investment plan is likely to result in reusing the natural gas grid and a complementary CO_2 grid. On the contrary, in regions with implementation of decentralised more disruptive technologies, the evolution of a more diverse grid development is expected. This dynamic trade-off between efficiency and infrastructure cost derived from grid components and decentralised conversion assets is the characteristic feature of the SUNERGY approach and provides both **challenges and opportunities for new and disruptive value chains to be developed**. Robust elements of the future energy grid need to be planned immediately since they create additional transport capacity that is needed in many different scenarios. In contrast, flexible investments are planned in case it is expected that specific developments will take place in the future that will lead to transport capacity shortages.

Commonality in the millions of energy systems scenarios can provide boundary conditions leading the way into **how to focus significant investments in the specific research and innovation actions including new infrastructure for the SUNERGY's full value chain for solar fuel and chemical production**.

Appendix 3: Sustainable water supply

Challenges

The close connection between water and energy, known as the **water-energy nexus**, is the relationship between how much water is used to generate and transmit energy and how much energy it takes to collect, clean, move, store, and dispose of water. Therefore, the deployment of a new energy system is ultimately related to a water challenge. A recent IEA study has shown that '**a low carbon economy does not mean a low water economy**'.[55] Fuels or technologies introduced to achieve the clean energy transition could, if not properly managed in an integrated approach, increase water stress or be limited by it.
Water utilisation should be distinguished as:

- **Water withdrawal or water abstraction**: This is the volume of water removed from the water body. This withdrawn water is returned to the source and is available to be used again.
- **Water consumption**: This is the amount of water removed for use and not returned to its source

In its Sustainable Development Scenario, IEA has shown that thanks to the increased deployment of solar photovoltaics and wind, a shift away from coal-fired power generation and increase in energy efficiency results in lower or stabilised water withdrawal but a higher water consumption, see Figure A3.1.

As shown in Figure A3.2, if the share of conventional fossil fuels is shifted to e-fuels - fuels made from renewable electricity, water and carbon dioxide - water consumption increases tremendously, this trend being even bigger when shifted to biofuels, Figure A3.3.

Indeed, water is a major resource for the green hydrogen economy deployment. Next to the cooling water requirement, ultra-pure water is required as feedstock to produce hydrogen. The production of one ton of hydrogen would require 9 tons of ultra-pure water. According to the EU's Hydrogen strategy, at least 6 GW (of electrolysers powered by renewable energy should be installed between 2020 and 2024.[56] This would correspond to around 9 Millions m³ of water consumed per year. Even though this corresponds to a small fraction of the current water consumption by the energy sector, green hydrogen or e-fuels projects may develop in areas where water withdrawal and consumption can become a problem. Optimisation of renewable energy use may be a reason to locate processes in regions with water scarcity. Regionalised life-cycle assessment should be considered to analyse the water footprint further, to take into account local water conditions and uses.

[55] Molly A. Walton, International Energy Agency. (2019, June 12-14). Outlook for the Water -Energy Nexus [Conference Presentation]. Water Innovation Europe 2019 'Water meets Energy, Energy meets Water', Brussels, Belgium
[56] European Commission. A hydrogen strategy for a climate-neutral Europe. vol. 53. Brussels, Belgium; 2020. doi:10.1017/CBO9781107415324.004

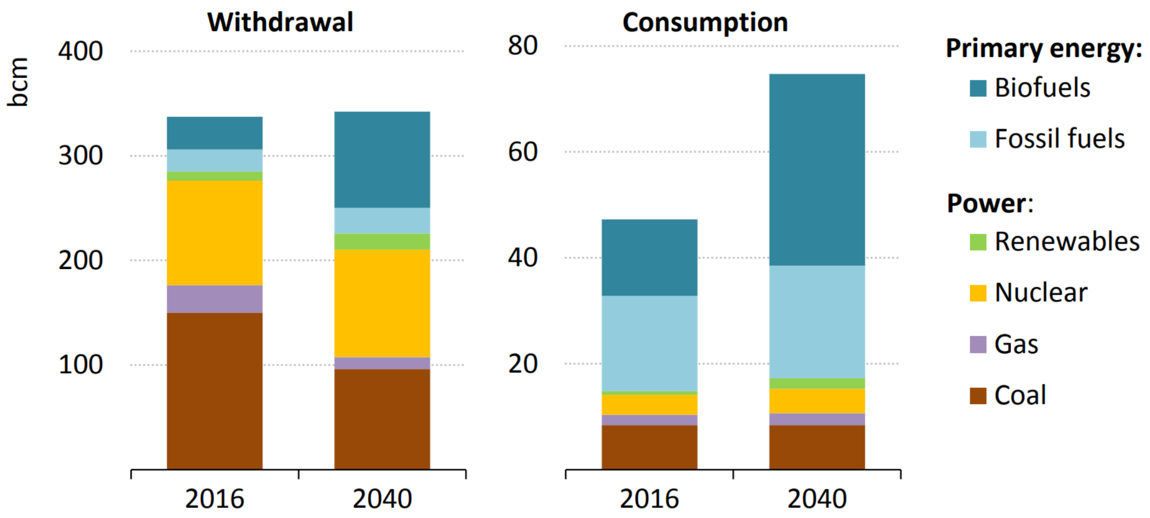

Figure A3.1. Global water requirements for the energy sector according to the IEA world main scenario: A shift to higher efficiency power plants with advanced cooling systems lowers power sector withdrawals; a rise in nuclear & biofuels in transport drives up consumption.[57]

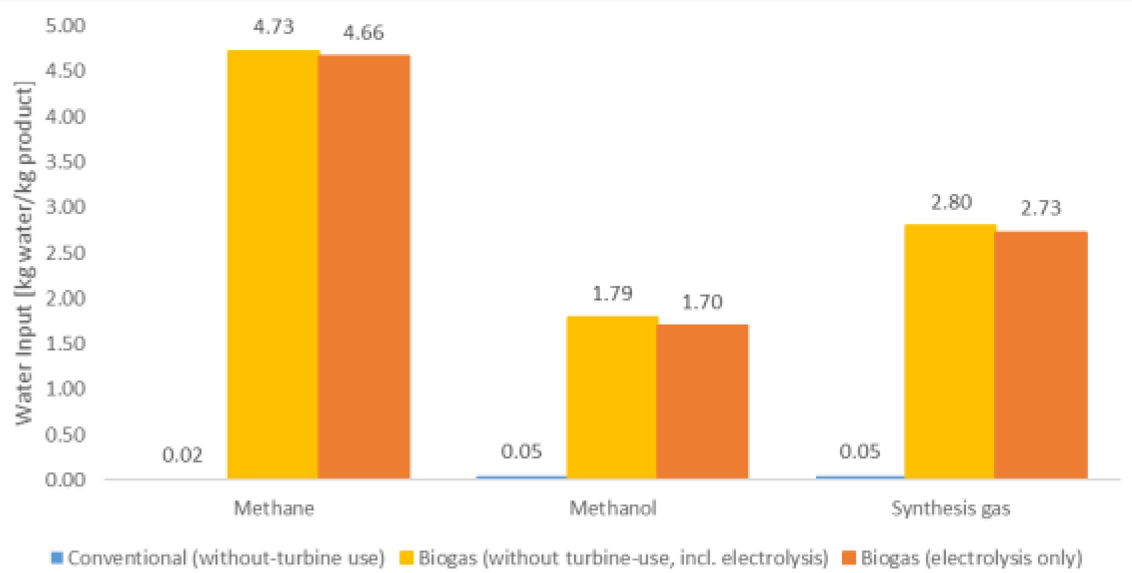

Figure A3.2. From cradle to gate water input for production of basic chemicals and polymers from carbon capture and utilisation process with biogas as CO_2 source. The water input for electrolysis is actually consumed water that is chemically transformed in the process. The electrolysis causes an increased water demand, as water is used as a raw material, which is not the case in the conventional route.[58]

[57] Molly A. Walton, International Energy Agency. (2019, June 12-14). Outlook for the Water -Energy Nexus [Conference Presentation]. Water Innovation Europe 2019 ‘Water meets Energy, Energy meets Water’, Brussels, Belgium.
[58] European Commission, Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects, 2019.

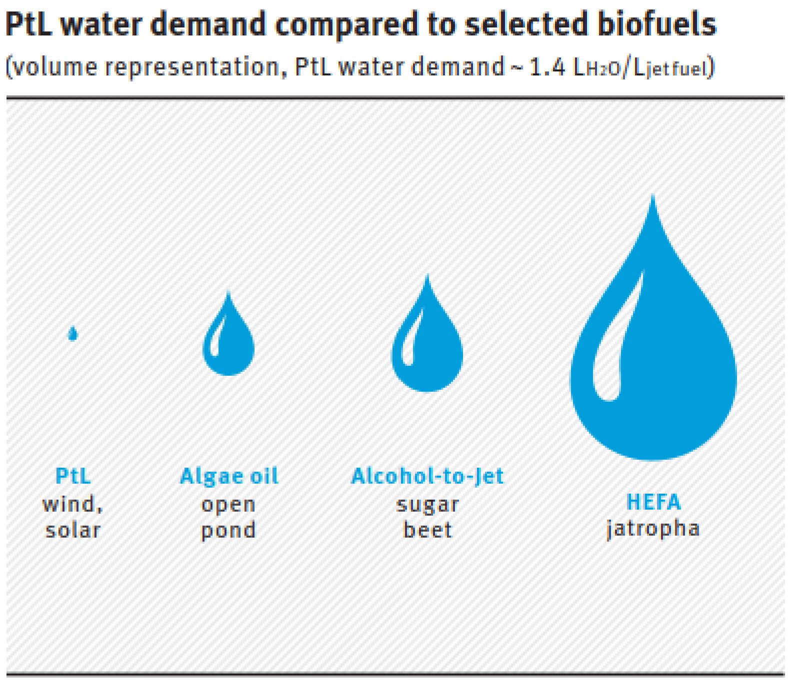

Figure A3.3. Water demand per litre of jet fuel.[59]

Water management and water circularity

An improved approach for a sustainable management of water resources is crucial to reach European requirements defined in the European Union's targets[60] and the European Commission's Resource Efficient Europe Roadmap 2050[61], indicating that by 2020 "Water abstraction should stay below 20% of available renewable water resources".

Different approaches can be considered for a sustainable water management in SUNERGY technologies:

- **Alternative water sources**
  While fresh water is the most common water source considered, only a small fraction is readily available for use: only 2.5% of water on earth is freshwater. Of that, less than 1% is accessible via surface sources and aquifers – the rest is locked up in glaciers and ice caps, or is deep underground. Worldwide increasing demand for freshwater (agriculture, energy, industries, human consumption etc.) and diminishing availability of freshwater pose challenges to ensure sustainability. Raw water sources must be diversified:
    - **Seawater desalination** is growing exponentially over the last decades. Process improvement has brought down both the cost (down to 0.5-1 USD/m³) and the energy consumption (down to 3 kWh/m³) thanks to the introduction of technology such as seawater reverse osmosis.
    - **Brackish water desalination**

[59] Schmidt, P. & Weindorf, W. Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel, 2016.
[60] Addressing the challenge of water scarcity and droughts, EC COM (2007) 414 Final
[61] Roadmap to a Resource Efficient Europe, EC COM (2011) 571 Final

- **Wastewater and water reuse**. This approach can diversify water sourcing but can be challenging depending on the water quality and availability. This is less standardised and not considered as the first option in water treatment plant design.
- **Humidity capture**, harvesting water from the air, is the ultimate solution when no other water source is available. There is a huge amount of water available as water vapour in the atmosphere. The technologies are in general scalable from low litres per day) to mid size (few cubic metres per day) and are suited to decentralised production. Due to the inherent nature of the diluted water presence, humidity capture is energy and cost intensive. Required footprint limits the development of large scale solutions. Humidity capture is less efficient in dry arid climates where water scarcity is an issue hence a penalty on its implementation. Interestingly, Low Temperature Direct Air Capture co-produces water and CO_2. Humidity capture is an unwanted phenomenon as it competes with adsorption sites for CO_2 and therefore reduces DAC performances. When DAC is coupled to e-fuel, the integration is interesting as DAC can provide enough water to cover the water needs for e-fuel production and heat from e-fuel production can be recovered to regenerate CO_2.

- **Water recycling**
Water is produced when converting hydrogen to carbon-based fuels. However, the produced water does not have the same quality to be directly recycled. Depending on the purification process, 30 to 70% of this water can be recovered back to the electrolyzer. Carbon capture also produces water from the flue gas cooling that can be recovered after purification. Large scale e-fuel projects should target maximal water recycling to reduce the amount of abstracted water.

- **Innovative water treatment processes for solar fuel and chemical production**
Reverse osmosis is the most common water treatment process. Depending on the water salinity, the recovery ratio ranges from 50% (for seawater) to 75% (for fresh water), which means that 1.3 to 2 times more water has to be pumped to produce pure water required for green hydrogen or e-fuel production. New water treatment and purification technologies are emerging allowing higher recovery ratio, higher robustness or treatment of difficult water. Those technologies are membrane distillation, mechanical vapour compression, forward osmosis etc.

- **Use of microalgae for wastewater treatment and utilisation**
Economic feasibility and environmental sustainability can be improved through integration of wastewater treatment with algal bio-production (biomass valorization) for removal of heavy metals, pharmaceuticals, recalcitrant organic pollutants present in water produced from oil and gas activities to name a few.[62] Such bio-based approaches are highly valuable for providing a sustainable pure water source for industrial applications in the technological portfolio of SUNERGY. Utilisation of wastewater and seawater in biological and biohybrid solar fuel production platforms

[62] Y. Allahverdiyeva et al. (2021) *Physiol. Plant.*, *in press*. https://doi.org/10.1111/ppl.13394

offers a highly desirable route for meeting water management challenges in the SUNERGY value chain.

Appendix 4: Technological sectors and services of SUNERGY's value chain

The value chain of the SUNERGY large-scale R&I initiative aims to manufacture energy carriers and chemicals at an affordable cost. Full optimization of the value chain may require low volume / high value hydrocarbon side streams with disruptive biological or biohybrid technologies based on microorganisms in parallel with technologically more advanced approaches.

SUNERGY aims to cover the entire value chain (from source to product) focusing primarily on the upstream and infrastructure sides and feeding into the downstream side (Figure A4.1). The SUNERGY value chain can be broken down into sectors based on the supporters that form the SUNERGY community (see Figures A4.2 and A4.3).[63] SUNERGY's full value chain will focus on high photon-product conversion efficiency (70% or better), scale of 4000 t product per year, versatility, and a large impact market.

The *downstream* markets are characterised by a large diversity of end products affecting almost any aspect of everyday life: comfortable housing, travel, food supply, health, security etc. SUNERGY feeds into these markets by securing the energy supply, providing raw materials for further processing, and by closing cycles with high value products at a low volume with highly decentralised on the spot refineries at farms, or buildings and houses in urbanised zones (Figure A4.1). Other EU partnerships have their pivot in the downstream markets (e.g. Circular Bio-based Europe, Processes4Planet), with the exception of the Clean Energy Transition and Clean Hydrogen Europe partnerships that attempt to cover a minor part of the upstream side of the SUNERGY's value chain (within technology class D, see Appendix 1). The *infrastructure* market comprises the grids and the manufacturing facilities of the new conversion assets for terrestrial application on a large scale (e.g. solar-to-fuel reactors). The *upstream* (energy) market is currently based on fossil resources and SUNERGY aims for displacing fossil fuels by renewables (Figure A4.2). An important element constituting the additional market in the SUNERGY value chain is the *infrastructure* which comprises the grids and the manufacturing of the new conversion assets for large-scale terrestrial and sea applications: e.g., solar-to-fuel reactors, microalgal bioreactors, etc., where diversification of the products is only limited by imagination (Figure A4.3).

[63] Services of the SUNERGY's full value chain are represented by the existing supporters listed in Appendix 6.

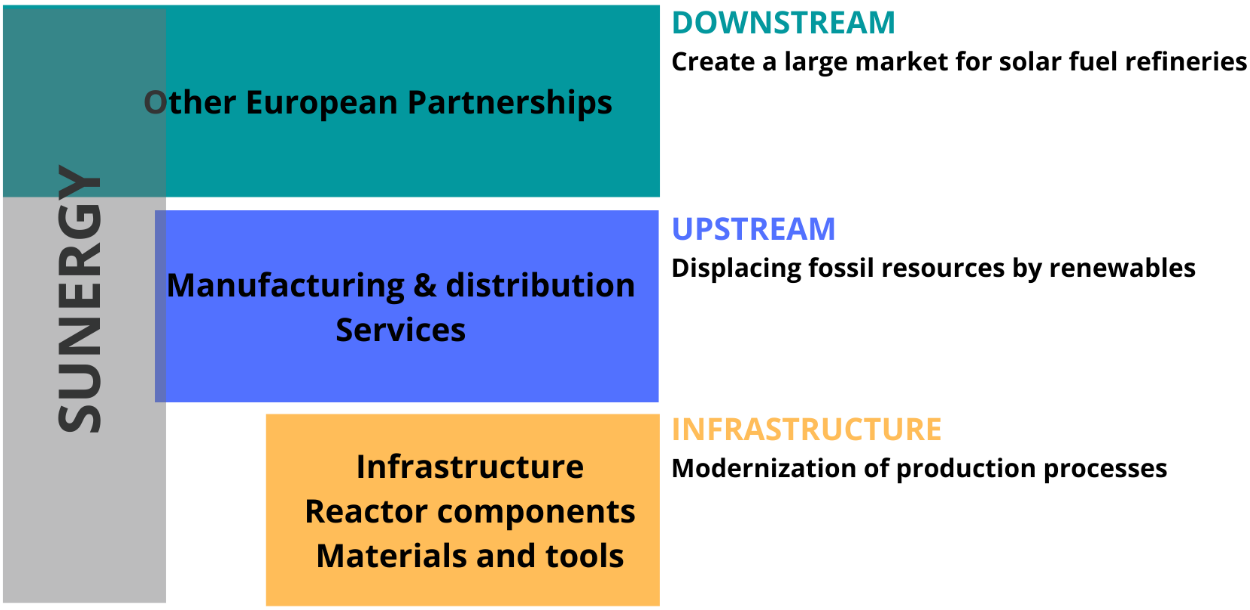

Figure A4.1. Technological sectors and services in SUNERGY's *full value chain*.

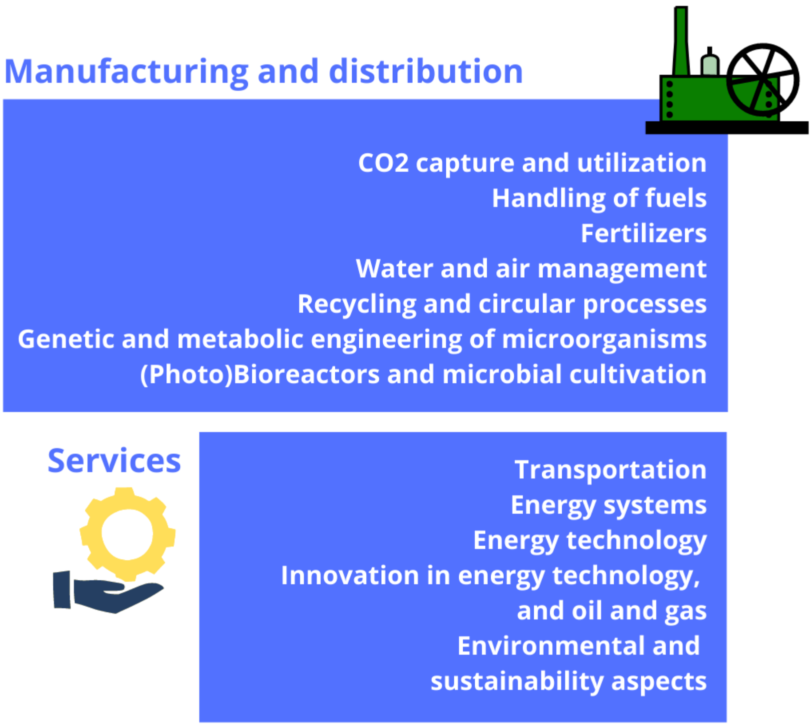

Figure A4.2. Technological sectors of the *upstream side* of the SUNERGY value chain.

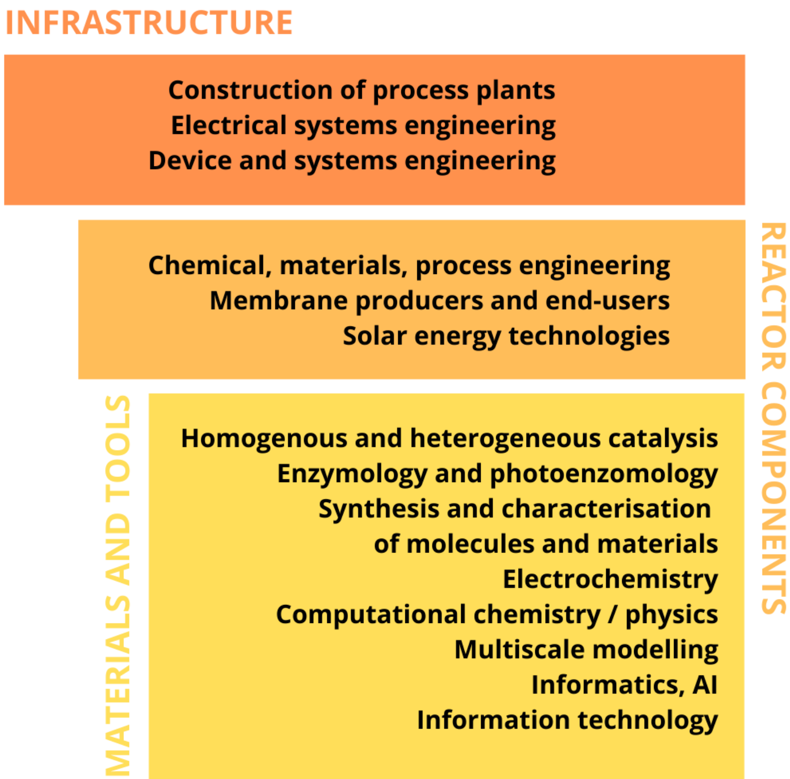

Figure A4.3. Technological sectors and services of the *infrastructure side* of the SUNERGY value chain.

Appendix 5: SUNERGY supporters

SUNERGY builds on two initiatives funded under Horizon 2020, SUNRISE and ENERGY-X. These are now united to develop a pan-European platform on sustainable fuels and chemicals, working towards a future public-private partnership in Horizon Europe. Together, SUNERGY now counts 321 supporting organisations[64] from industry, academia and civil society, and working in close dialogue with EU and national decision makers.

SUNERGY is an inclusive, steadily growing organisation. If you would like to support our journey to a solar-driven energy future, please contact us: contact@sunergy-initiative.eu.

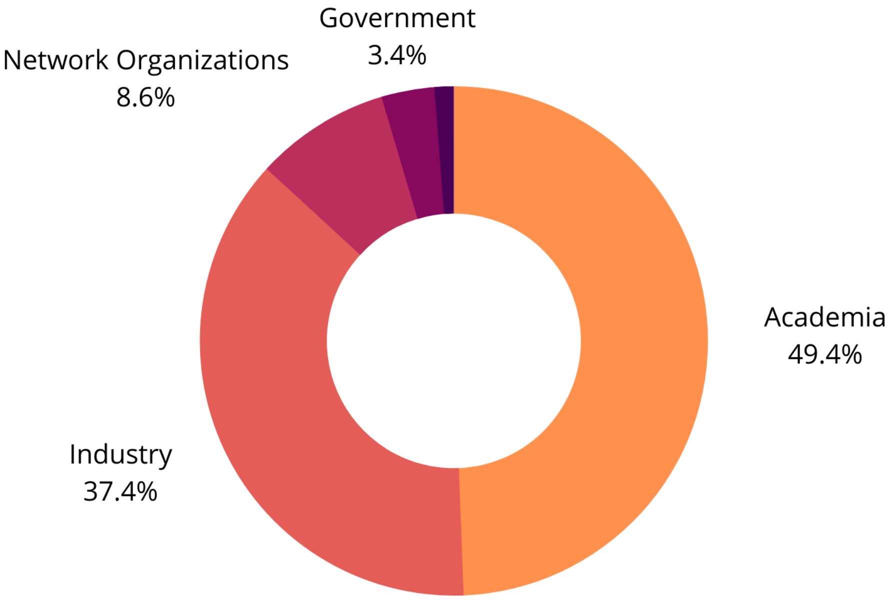

Figure A6.1. Overview of SUNERGY supporters per sector. Academia includes universities, research and technology organisations and other knowledge institutions. Industry includes SMEs, start-ups, multinationals and other types of for-profit organisations. Network organisations include national and EU-wide organisations that gather various stakeholders. Government includes local and national governmental bodies. The category ‘other (purple) includes funders and societal organisations.

[64] February 2022

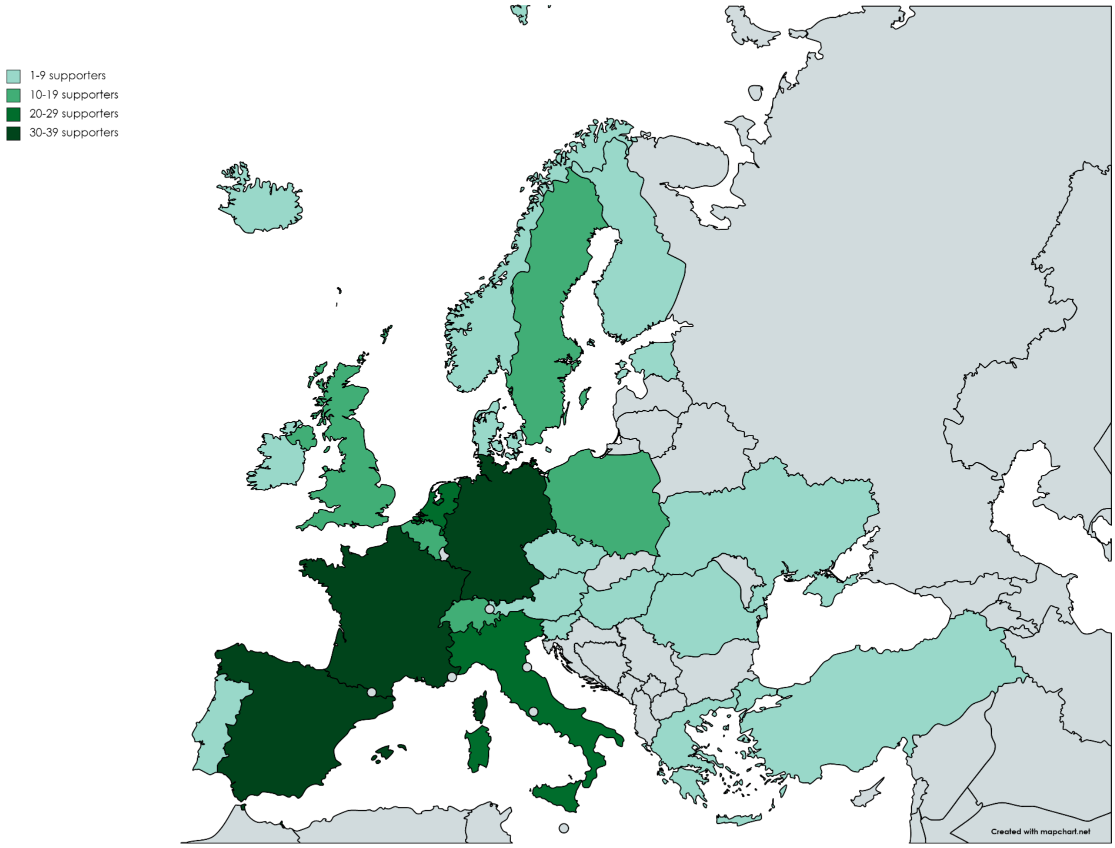

Figure A6.2. Overview of European countries with SUNERGY supporters.

Overview of SUNERGY supporters, and supporters of its predecessors SUNRISE and ENERGY-X:

Austria:

- Austrian Centre of Industrial Biotechnology (ACIB)
- Austrian Institute of Technology
- Ecoduna Eparella GmbH
- Technical University of Graz

Belgium:

- ArcelorMittal
- Certech
- Flemish Institute for Technological Research (VITO)
- Free University of Brussels (ULB)
- FRS-FNRS
- Ghent University
- GreenWin
- H2WIN
- Hasselt University
- IMEC
- INEOS
- Lhoist
- SCK-CEN
- Solvay
- UCLouvain
- University of Antwerp

- WWF Belgium

Czech Republic:

- Association of Chemical Industry of the Czech Republic
- J. Heyrovsky Institute of Physical Chemistry
- Palacký University Olomouc

Denmark:

- Copenhagen Airports
- DTU
- Danish Board of Technology (DBT)
- Haldor Topsoe
- University of Copenhagen

Estonia:

- University of Tartu

EU:

- CO_2 Value Europe
- EERA
- EMIRI
- European Chemical Society (EuChemS)
- European Materials Research Society (E-MRS)
- International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT)
- European Research Institute of Catalysis (ERIC)
- European University Association - Energy and Environment Platform (EUA-EPUE)
- ExxonMobil
- League of European Research Universities (LERU)
- Psi-K
- Toyota

Finland:

- Abo Akademi University
- Fortum Power and Heat Oy
- Neste
- ST1
- Sulapac
- Technical Research Center of Finland (VTT)
- Turku Science Park
- University of Turku

France:

- Air Liquide
- AlgoSource
- Areva H2Gen
- Arkema France
- Atmostat-Alcen
- Axane
- Axelera
- CEA
- Ecole Centrale de Lille
- ENGIE
- French National Alliance on Energy Research (ANCRE)
- French National Centre for Scientific Research (CNRS)
- Fumatech/Dupont de Nemours
- French Solar Fuels Network (GDR CNRS)
- IFP Energies nouvelles (IFPEN)

- IMT Atlantique
- LafargeHolcim
- Lyon Institute of Nanotechnology (INL)
- Marion Technologies S.A
- National Institute of Applied Sciences of Lyon (INSA Lyon)
- Polymem S.A
- Renault
- Société Chimique de France (SCF)
- Solvay-Solexis
- Symbio FC
- TEK4Life
- TOTAL S.A.
- Université Grenoble Alpes
- Université de Lille
- UniversitéLorraine
- Université de Nantes
- Université d'Orléans
- Université de Paris Université Paris Saclay
- Université de Pau et du Pays de l'Adour

Germany:

- BASF
- Bauhaus Luftfahrt
- C&CS Catalysts and Chemical Specialties
- Covestro
- Cyano Biotech
- DECHEMA
- Dr. Laure Plasmatechnologie GmbH
- Electrochaea
- Esy-labs
- Evonik
- Fev GmbH
- Fraunhofer-Gesellschaft
- Fritz Haber Institute of the Max Planck Gesellschaft (FHI)
- German Aerospace Center (DLR)
- German Energy Agency (DENA)
- Helmholtz Centre for Environmental Research
- Ineratec
- Institute of Microstructure Technology
- Johannes Gutenberg University of Mainz
- Jülich Research Center
- Julius Maximilian University of Würzburg
- Karlsruhe Institute of Technology
- Leibniz Institute for Economic Research (RWI)
- Likat
- Linde
- Max Planck Institute for Chemical Energy Conversion (MPI-CEC)
- Mügge GmbH
- Osnabrück University of Applied Sciences
- PEPperPRINT
- PlasmaAir AG
- Plasmatechnologie GmBH
- Plasmatreat GmBH

- Ruhr University Bochum
- RWE
- RWTH Aachen University
- Schaeffler
- Siemens Energy
- Subitec
- Technical University Berlin
- Technical University Darmstadt
- Technical University Dresden
- Technical University Kaiserslautern
- Technical University München
- Thyssenkrupp
- Uniper
- University of Bielefeld
- University of Hamburg
- University of Rostock
- University of Stuttgart

Greece:

- Educational Technological Institute of Crete (TEI of Crete)

Hungary:

- Budapest University of Technology and Economics (BME)
- Hungary Centre for Energy Research (EK)
- Szeged Biological Research Centre

Iceland:

- Carbon Recycling International (CRI)

Ireland:

- National University of Ireland Galway (NUI Galway)

Italy:

- Agency for Energy Efficiency (ENEA)
- Central European Research Infrastructure Consortium (CERIC-ERIC)
- EcoRecycling SRL
- European Algae Biomass Association (EABA)
- Istituto Italiano di Tecnologia (IIT)
- Italian Chemical Society (SCI)
- Kinetics Technology SPA
- National Interuniversity Consortium of Materials Science and Technology (INSTM)
- National Research Council of Italy
- Nextchem – Maire Tecnimont
- NOVAMONT
- Politecnico di Torino
- Ricerca Sisterna Energetico (RSE)
- Roma Tre University
- Scuola Normale Superiore
- University Bari Aldo Moro
- University of Bologna
- University of Camerino
- University of Firenze (UNIFI)
- University of Milan
- University of Milano-Bicocca (UNIMI)
- University of Padova (UNIPD)
- University of Perugia
- University of Torino

- University of Trieste (ITUNITS)
- WWF Italy

Netherlands:

- Antecy
- Avantium
- Carbyon
- Differ
- Everest Coatings
- Hydron Energy
- HyGear B.V.
- InCatT
- Innovation Quarter
- Leiden University
- Metabolic
- Netherlands Organisation for Applied Scientific Research (TNO)
- Opus 12
- Photanol
- Saudi Basic Industries Corporation (SABIC)
- Shell
- Skytree
- Software for Chemistry & Materials (SCM)
- Stamicarbon
- Technical University Delft
- Technical University Eindhoven
- University of Twente
- Utrecht University
- Wageningen University & Research

Norway:

- Aker Solutions
- Nel
- Norwegian University of Science and Technology (NTNU)
- Tara
- University of Oslo (UiO)
- ZEG Power A.S.

Poland:

- Adam Mickiewicz University (UAM)
- Institute of Electronic Materials Technology (ITME)
- Institute of Physical Chemistry (ICHF)
- Jagiellonian University
- Jerzy Haber Institute of Catalysis and Surface Chemistry
- Maria Curie-Sklodowska University (UMCS)
- Polish Chemical Society (PTChem)
- Polish Economic Chamber of Renewable and Distributed Energy (PIGEOR)
- Polish Ministry of Science and Higher Education
- Polish National Science Centre (NCN)
- University of Warsaw
- Warsaw University of Life Sciences
- World Oceans Day

Portugal:

- Algae for Future (A4F)
- Petrogal SA

Romania:

- University of Bucharest

Slovenia:

- Slovenia National Institute of Chemistry
- University of Nova Gorica

Spain:

- 3M
- Acconia
- Advanced Materials and Nanomaterials Spanish Technological Platform (MATERPLAT)
- ALBA-Synchrotron
- Atersa
- Autonomous University of Madrid (UAM)
- Avaesen
- Barcelona Institute of Science and Technology
- Canal de Isabel II
- Catalan Institute of Nanoscience and Nanotechnology (ICN2)
- Catalonia Institute for Energy Research (IREC)
- CEGASA
- CEPSA
- CIC Energigune
- CIEMAT
- CO_2Change
- CSIC
- DG Research & Innovation Madrid
- EDP Energia
- Enagás
- Endesa
- Feique
- Grupo Vento
- HUNOSA
- ICIQ
- ICFO
- IMDEA
- Ingelia
- Institute of Photonic Sciences (ICFO)
- Madrid City Council
- Mostoles City Council
- National Hydrogen Center Spain (CNH2)
- Oficemen
- Proheat Heattrace
- PVH Energy Storage
- QUIMACOVA
- Regional Ministry of Education and Research for Madrid
- Repsol
- Spanish CO2 Technology Platform (PTECO2)
- Spanish government
- Spanish Office for Climate Change (OECC)
- Tecnalia
- Tecnove
- University Rey Juan Carlos (URJC)
- Valladoid University Spain

Sweden:

- Chalmers University of Technology
- KTH Royal Institute of technology
- Liquid Wind
- Lund University
- Mariestad
- PowerCell
- Stena
- Swedish Energy Agency
- Umeå University
- University of Gothenburg
- Uppsala University
- Vätgas Sweden

Switzerland:

- Casale
- Clariant
- Climeworks
- EMPA
- EPFL
- ETH Zürich
- Novatlantis
- Paul Scherrer Institut
- Quantis Sàrl
- SPF Institute for Solar Technology
- University of Bern
- University of Zürich

Turkey:

- Bogazici University
- Ege University
- Mersin University
- Tampere University
- Tarsus University

UK:

- Cardiff University
- Climate-KIC Accelerator Programme
- Cristal Global
- Imperial College London
- INEOS
- Ingenza
- ITM
- Johnson Matthey
- PCM Technology Solutions
- Queen's University Belfast
- UK Catalysis Hub
- UK Solar Fuels Network
- University College London
- University of Cambridge
- University of East Anglia
- University of Salford
- University of the West of England (UWE)

Ukraine:

- Institute of Physics of the National Academy of Sciences

International:

- University of New South Wales (Australia)
- Hydrogenics (Canada)
- Xi'an Jiaotong University (China)
- JAIN University Bangalore (India)
- Bar-Ilan University (Israel)
- Tel Aviv University (Israel)
- University of Pretoria (South Africa)
- University of Witwatersrand (South Africa)
- Yonsei University (South Korea)
- Argonne National Laboratory Center for Nanoscale Materials (CNM) (USA)
- Eastman (USA)
- Marist College (USA)
- Solar Fuels Institute (Institute for Sustainability and Energy at Northwestern) (USA)
- SRG Global (USA)
- The Air Company (Air Co.) (USA)
- University of California Berkeley (UCB) (USA)

Appendix 6: Critical raw materials EU 2020

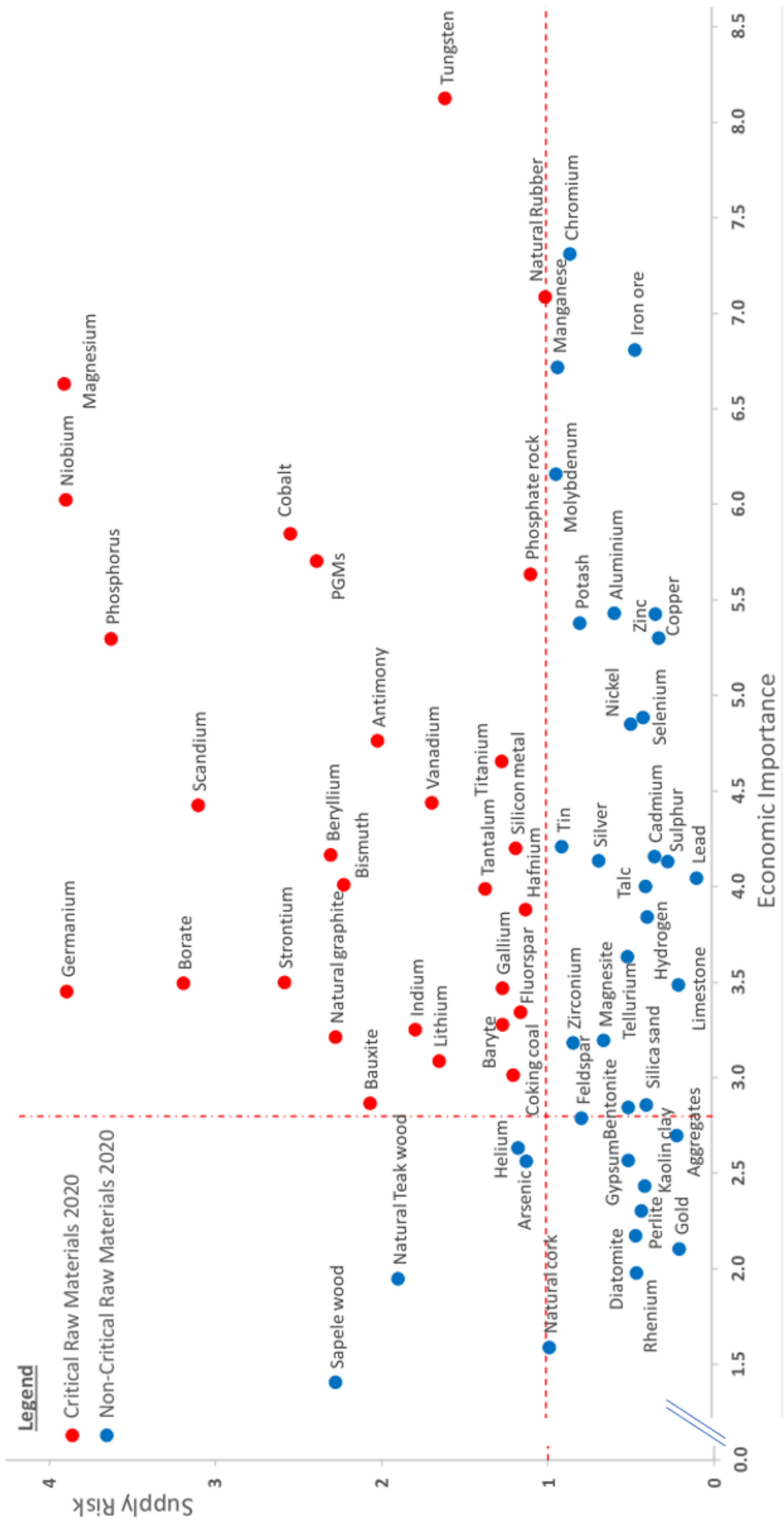

Figure A7.1. EU's recent critical raw materials.