SUNER-C

Deliverable 3.1: Technological Roadmap

Project Summary	
Project Number	101058481
Project Acronym	SUNER-C
Project Name	SUNER-C: SUNERGY Community and eco-system for accelerating the development of solar fuels and chemicals
Starting date	01/06/2022
Duration in months	36
Call (part) identifier	HORIZON-CL4-2021-RESILIENCE-01
Topic	HORIZON-CL4-2021-RESILIENCE-01-16
Type of action	HORIZON-CSA (Coordination and Support Actions)
Service	HADEA/B/03

Disclaimer

Management Information	
Final version	28 November 2023
WP	3 - Long-term technological roadmap
Lead and co-lead beneficiaries	UNIWERSYTET WARSZAWSKI (UW) & ENGIE (ENGIE)
Dissemination Level	Public
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Deliverable Number	D3.1
Deliverable Name	Technological Roadmap
Reviewers	All contributing authors, Project Coordination Team (UU, CEA, CVE & ICIQ), SUNER-C Executive Board and SUNER-C Quality and Impact Assurance (Q&IA) Board
Abstract	The SUNERGY pan-European initiative aims to enable a circular economy through fast and focused acceleration of the sustainable production of carbon-neutral fuels and base chemicals (hydrogen, synthetic hydrocarbons and ammonia) using renewable energy and abundant molecules (CO_2, water, nitrogen). The initiative was formed in 2020 in response to the urgent environmental, societal and industrial needs to defossilize energy, transport and chemical sectors by year 2050. To this end, a credible roadmap for solar fuels and chemicals is urgently needed to facilitate the implementation of the solar-to-chemical conversion technologies in a timely manner while meeting clearly defined technological timelines and milestones.

Following the International Energy Agency's guide for the development of technological roadmaps in the field of energy,[1] one of the first steps towards a well-developed roadmap is the elaboration of a brief document stating the purpose and scope of the said roadmap in order to keep the process focused throughout its evolution. In strong alignment with the said guide, in the present document, we will briefly address the following four questions:

- Purpose: why is the technological roadmap being developed?
- Scope and objectives: what is the roadmap expected to do?
- Process: how will the roadmap be developed and implemented?
- Participants: who is involved?

Document History			
Version	**Date**	**Responsible**	**Action**
Draft 1	2023	All and lead and contributing authors	Elaboration of the first draft of this deliverable
Draft 2	01 November 2023	Joanna Kargul (UW) Carina Faber (EIC) Han Huynh (ENGIE) Joachim John (IMEC)	Comments from all reviewers mentionned above received and implemented
Final version	28 November 2023	Joanna Kargul (UW) Carina Faber (EIC) Han Huynh (ENGIE) Joachim John (IMEC)	Final version is formatted and ready to submit

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[1] *Energy Technology Roadmaps, A guide to development and implementation, 2014, IEA: Drawing upon the extensive IEA experience, this guide is aimed at providing countries and companies with the context, information and tools needed to design, manage and implement an effective energy technology roadmap process relevant to their own local circumstances and objectives.*

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D3.1: Technological Roadmap

SUNERGY Roadmap: Purpose and Scope

The SUNERGY pan-European initiative aims to enable a circular economy through fast and focused acceleration of the sustainable production of carbon-neutral fuels and base chemicals (hydrogen, synthetic hydrocarbons and ammonia) using renewable energy and abundant molecules (CO_2, water, nitrogen). The initiative was formed in 2020 in response to the urgent environmental, societal and industrial needs to defossilize energy, transport and chemical sectors by year 2050. To this end, a credible roadmap for solar fuels and chemicals is urgently needed to facilitate the implementation of the solar-to-chemical conversion technologies in a timely manner while meeting clearly defined technological timelines and milestones.

Following the International Energy Agency's guide for the development of technological roadmaps in the field of energy,[2] one of the first steps towards a well-developed roadmap is the elaboration of a brief document stating the purpose and scope of the said roadmap in order to keep the process focused throughout its evolution. In strong alignment with the said guide, in the present document, we will briefly address the following four questions:

- Purpose: why is the technological roadmap being developed?
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The present deliverable covers the questions why to develop another roadmap on solar fuels and chemicals and how to achieve the most impact. It thus lays down the basis methodology of the on-going SUNERGY roadmapping exercise, supported via the SUNER-C CSA. It is at the same time used as a tool to align a vast community towards an all-agreed on vision and to foster collaboration between key players. It clearly lays down the covered technologies and the methodology to choose them, the used terminology and a working plan - all in all crucial for a solid roadmapping exercise.

A milestone for this document is the SUNERGY Roadmapping Workshop, having gathered more than 140 high-level experts from industry, academia and policy on 14/15 June 2022 in the Royal Academy of Science, Brussels (see Appendix for a short summary). The authors express their sincere acknowledgement to all the participants, who turned this workshop into a unique opportunity for an open and frank exchange between diverse communities on the future of solar fuels and chemicals. The authors

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would also like to thank the colleagues from Mission Innovation Challenge 5 - Converting Sunlight into Solar Chemicals and Fuels - for highly productive discussions on the scope and technologies selection for the solar fuels and chemicals roadmap. The mentioned workshop has been followed up by several meetings between the authors (more than 30 persons from academia, industry and policy) to extract and agree on the key results.

The field of solar fuels and chemicals is characterized by a plethora of technological approaches and a diverse group of stakeholders along the full value chain. A purely analytical assessment and, especially, foresight is highly difficult to elaborate due to the number of technologies and the complexity of the innovation ecosystem. In the SUNERGY Roadmapping process, we therefore **rely on the expertise of leaders in the field, deliberately engaging experts from academia, industry and policy sectors who represent diverse disciplines.**

Conclusions drawn by the community at the SUNERGY Roadmapping workshop and a subsequent through analysis by the SUNERGY Roadmapping Core Team and the mentioned authors on the current state-of-the-art include:

For electrochemical conversion approaches,

- it was concluded that these high TRL technologies, such as **alkaline and proton-exchange membrane (PEM) electrolyzers**, still have to overcome drawbacks and shortcomings (e.g. extending PEM lifetime and active surface for upscaling) before reaching hydrogen price objectives of <3 euros/kg.[3]

  For PEM electrolyzers, a serious threat has been identified in the urgent need of substituting iridium as an electrode material in order to achieve the performance capacities predicted in the roadmap.
- Less mature electrolyzer technologies, such as **solid-oxide electrolyzer cells (SOEC), anion exchange membrane (AEM) and Proton conducting ceramic (PCC) electrolyzers,** suffer mainly from high system costs and limited membrane durability due to the high temperatures that are required.
- The pertinence of **direct electrolysis of salt water has to be explored further**. Standard electrolysers require high purity fresh water supply, and R&I activities on the electrolysis of seawater are emerging to broaden the possibilities of a sustainable water supply. However, instead of sea water electrolysis, the two-step approach of sea water desalination followed by standard electrolysis seems the most straightforward and economically efficient pathway due to the high maturity, low cost of water desalination (< 0.5 €/m³ for large scale seawater desalination) and improved energy efficiency (< 3 kWh/m³ for large-scale seawater desalination) negligible compared to the overall cost and energy requirement of hydrogen production through electrochemical water splitting.

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[3] 2030 aim is 1.5 euros

Actually the main environmental challenge today is to increase water circularity (e.g., water recovery) and to reduce the environmental impact (e.g., brine discharge)

○ The overall conclusion was that a **hydroxyl exchange membrane solution would be the most sustainable approach for high TRL electrolysers**. Therefore, the main technology effort would be shifted from the electrodes to the development of hydroxyl exchange membranes.

For photosynthetic devices,

there was a consensus of establishing a common view and language first, quantitative milestones could not be covered during the workshop. The number of explored and conceptualized device architectures is numerous and the diversity of academic disciplines involved is significant. Photosynthetic devices offer the opportunity for new, serendipitous discoveries and to explore general phenomena of light-matter interactions.

The further development of a wide range of photosynthetic device architectures is crucial, without narrowing down the technological scope at this early stage of development. A unifying property of photosynthetic devices is that the former operate under lower current densities compared to PV-driven electrolysis (PV-EC). This avoids the need for high concentrations of carbon dioxide and alternative carbon dioxide sources with lower concentrations may be envisioned. Moreover, integrating light absorption and conversion into a single device may add additional benefits through an optimized heat management.

This less mature technological area is less known by the industries. However, related high TRL technologies, such as water electrolysis or high-temperature carbon dioxide co-electrolysis, are the fore-runners of photosynthetic devices and will provide valuable learning opportunities for future photosynthetic device solutions. **It is important for the community to present a clear and critical overview of all photosynthetic device technologies in order to ensure that industries are able to fulfill their role of giving the benchmark and framework for industrial applications of photosynthetic devices.**

For biologically-driven approaches,

it was noted that there are already very advanced conversion processes that are applied at the industrial scale. These include dark fermentation, i.e. energy- and carbon-rich gasses are converted into complex end-products. The necessary energy for conversion processes comes in the form of chemical energy, not directly from solar light - it is thus a multistep conversion process necessitating the beforehand provision of feedstock molecules. This **"it is ready now!" message** had a very positive impact on the community dealing with the less mature direct biological conversion technologies and guidance can be expected in terms of the bioreactor design or upscaling. The communities seem not to be closely connected for the moment, but the SUNERGY Roadmapping will put a focus on this issue.

For solar-thermal approaches,

it was concluded that the most promising and advanced solar thermal processes are those based on thermochemical cycles, where prototypes of core components and core production chain elements have been developed and tested at solar towers. Those cycles are attractive since they involve only a few chemical steps of low complexity, leading to high reversibility and potentially high cycle efficiency. High efficiencies are expected to significantly lower the CAPEX of related plants significantly. Still, the main technical challenges to be addressed are increasing the solar-to-fuel-efficiency through process intensification, especially through highly efficient internal heat transfer and recovery as well as the scalability of the reactor concepts to achieve high energy conversion efficiencies and high throughput. One of the central measures to reach intermediate targets in terms of efficiency and cost is the improvement of heat management. It is necessary to reuse a significant portion of the usable high temperature heat in order to achieve process efficiencies that make the systems attractive for commercial use.

For CO_2 capture,

there was a discussion on the source of CO_2 (fossil vs. biogenic) and the perspective for its sourcing for e-fuel production. CO_2 utilization can bring down GHG emissions, even when fossil CO_2 is used[4]: Up to 50% of CO_2 emission reduction (depending on GHG emissions linked to the transport, capture and conversion process) could already be achieved using process-related or combustion-related CO_2; and up to 100% of CO_2 emission reductions using biogenic CO_2. Different types of carbon capture technologies are already available, at different maturity levels. Depending on the specific application and gas stream characteristics, one or the other will be the method of choice. But there is room and necessity for the emergence of disruptive capture technologies such as direct air capture, direct air capture and conversion, or even capture from the ocean.

The kick-off of the SUNERGY Roadmapping Process have been followed by dedicated meetings of the different technological working groups[5] during the roadmapping process in order to provide a solid foresight on the considered technologies. This is on-going work. **Once the state-of-the-art will be agreed on, future milestones will be determined and summarized in a living roadmap document at the end of the SUNER-C CSA.**

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[4] Source: Mertens et al., Carbon capture and utilization: More than hiding CO2 for some time, Joule (2023), https://doi.org/10.1016/j.joule.2023.01.005

[5] SUNERGY Technological Roadmap Working Groups: Electrochemical Conversion into Hydrogen; Electrochemical Conversion into Carbon-based Fuels; Photosynthetic Devices; Biologically-driven Conversion; Solar-thermal Conversion; Sustainable Carbon Capture.

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[6] 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.

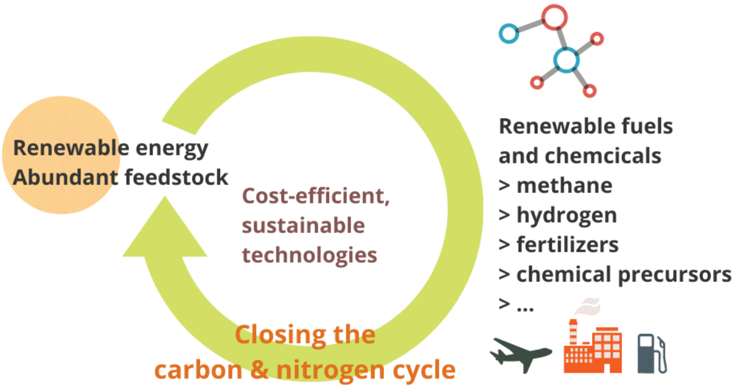
[7] This work was supported by the EU Horizon Europe SUNER-C Coordination and Support Action grant (GA 101058481).

Purpose: Why is the roadmap developed and what specific problems are addressed?

Context analysis

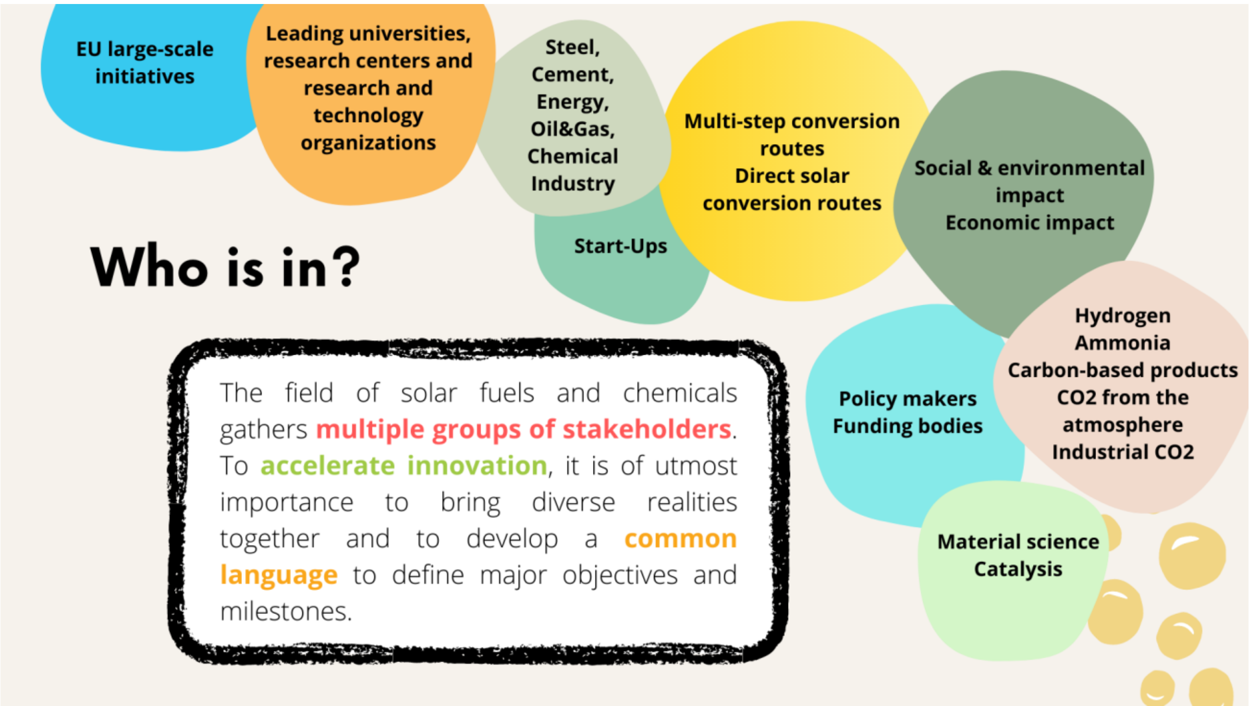
Content

A broad range of conversion technologies. SUNERGY aims at providing cost-efficient, low-carbon technologies to convert renewable energy and abundant resources into fossil-free fuels and chemicals at scale. This provides a pathway to **store renewable energy in the long-term in the form of fossil-free fuels and chemicals** and to contribute to the EU's energy security. Abundantly available feedstock such as carbon dioxide, water or nitrogen replace fossil-based raw materials to produce a broad range of products. **Carbon dioxide is turned from a problem into a valuable feedstock.** A broad range of possible technologies with different unique selling points and maturity is characteristic to this field. It is crucial to not lose focus and **concentrate on the most impactful pathways** when developing future milestones.



A solid basis of existing work. With an increasing awareness of the urgency to align and act on the national and international levels, these last years produced several high-quality documents. Among others, **scenario analysis** such as the IPCC’s Sixth Assessment Report, the European Union’ 2050 Long-term Strategy or the Global Powerfuel Alliance’s study serve as valuable guides for the SUNERGY Roadmapping process. For the first time, the 2022’s IPCC report considers Carbon Capture and Utilization (CCU) pathways in its mitigation strategy and the German Global Alliance Powerfuels study concretely estimates the impact of synthetic fuels and chemicals from renewable electricity on the energy system. Also **technological roadmaps** are available, such as the SUNRISE technological roadmap on solar fuels and chemicals and Energy-X’s Research Needs at a European level, and Mission Innovation’s Challenge 5 report at an international level.

A broad stakeholder community. An inherent characteristic of the field of solar fuels and chemicals is the **diversity** of involved stakeholders. At an academic level, researchers from different disciplines and fields such as physics, chemistry (including catalysis), biology or high throughput computing represented by often rather isolated communities have to be connected. Large-scale demonstration projects involve the **whole value chain** from the CO_2 and renewable energy sourcing, the conversion technology to the final end use. Every building block has to be optimized with respect to the other and the overall project often requires extremely high CAPEX investments. No single player can face this challenge alone, and the collaboration of different industrial stakeholders is necessary. The **financial intervention** of governmental bodies as well as a **clear and stable regulatory framework** are crucial for the de-risking of disruptive technologies. **To accelerate innovation**, it is of utmost importance to bring diverse realities together and to develop a **common language**. **Major objectives and milestones have to be defined in line with actual industrial or governmental needs, based on the best available knowledge and expertise.**



The field of solar fuels and chemicals gathers **multiple groups of stakeholders**. To **accelerate innovation**, it is of utmost importance to bring diverse realities together and to develop a **common language** to define major objectives and milestones.

Funding

SUNERGY builds on two former EU large-scale initiatives: SUNRISE and ENERGY-X. These former competitors for an EU flagship are now united as the SUNERGY pan-European platform for solar fuels and chemicals. This is made possible by EU funding, via the SUNER-C coordination and support action (CSA, grant agreement No 101058481). The latter includes among other activities, a three-year funding for the development of a technological roadmap. Following the IEA’s guide, “simply writing a roadmap is not enough — the true measure of success is whether the roadmap is implemented and achieves the organization's desired outcome”. **This is a big general bottleneck of roadmaps carried out by organizations with no direct implementation power,[8] such as SUNERGY, and this aspect has to be taken carefully into consideration when developing the scope and purpose of the roadmap.**

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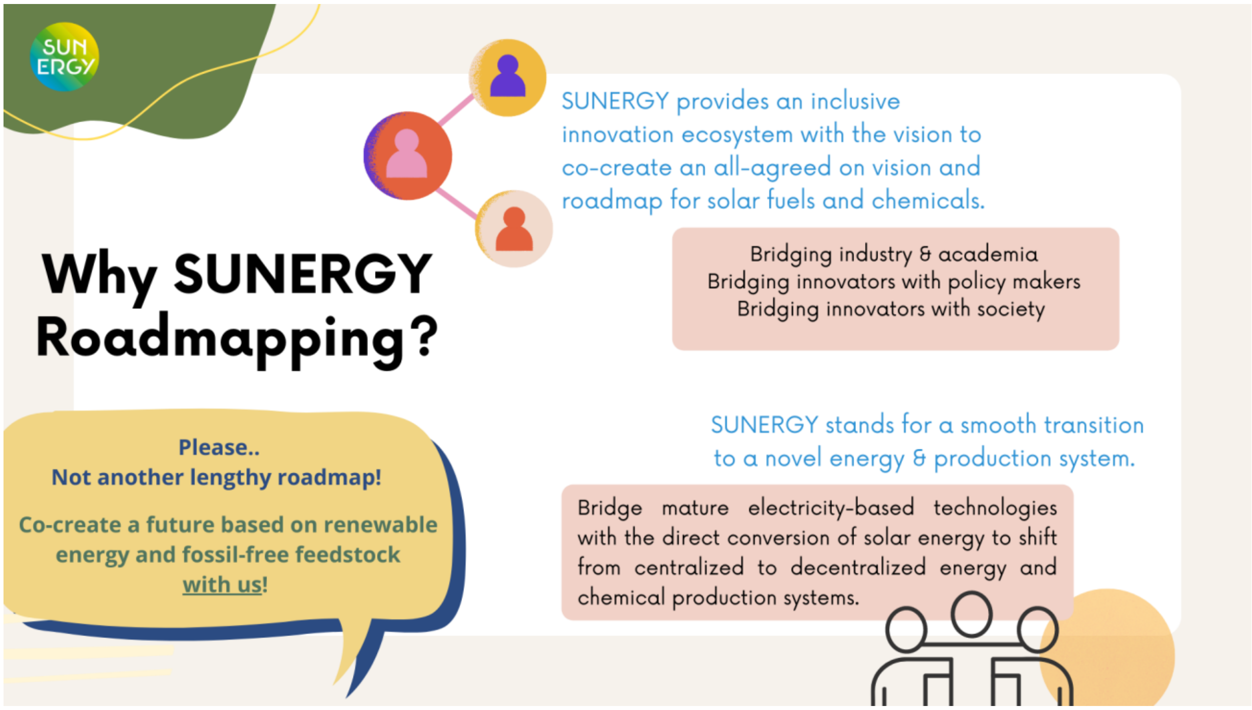
[8] Implementation power is attributed to organizations able to invest in the identified technological milestones, such as government bodies or industry. Since the SUNERGY CSA does not foresee a budget to finance R&I projects and is furthermore limited in time, it cannot be considered as an implementing body.

Deduced goals and added value



Why SUNERGY Roadmapping?

SUNERGY provides an inclusive innovation ecosystem with the vision to co-create an all-agreed on vision and roadmap for solar fuels and chemicals.

Bridging industry & academia
Bridging innovators with policy makers
Bridging innovators with society

Please..
Not another lengthy roadmap!

Co-create a future based on renewable energy and fossil-free feedstock with us!

SUNERGY stands for a smooth transition to a novel energy & production system.

Bridge mature electricity-based technologies with the direct conversion of solar energy to shift from centralized to decentralized energy and chemical production systems.

1. **Not another lengthy roadmap!** In view of the already existing work, it is important not to double the efforts. Given the significant progress in conversion technologies the last two years, e.g. on electrolyzer scales, the goal is to build on the existing state of the art and to **update and merge major objectives and technological milestones**.

2. **Co-creation and inclusiveness!** Since SUNERGY cannot be designed as a direct implementer of the developed roadmap (see Funding section), one has to **limit the roadmapping effort** to the **alignment of stakeholders**, the **identification of trends and milestones** and **dissemination**. The concrete implementation has to be left to individual organizations with implementing power (e.g. EC, national and local governments, companies, etc.). Consequently, it is of utmost importance to **create credible and influential ambassadors** helping internal decision-makers understand the new roles of companies/politics and possible new ways of investing, working and delivering for solving major societal issues.
    - **Leaders from governmental bodies and industry** have to be strongly involved and engaged from the beginning.
    - These ambassadors have to be provided with everything necessary to proceed with the concrete implementation within their organizations, e.g. information material tailored to their specific needs.

  - <u>Convivial</u> conferences are of utmost importance to get to know each other and to exchange openly.[9] A ‘closed club' approach has to be absolutely avoided.

  An incentive for their dedicated participation is the promise to get **a clear view on future milestones in an emerging domain based on the wisdom of designated leaders**. This enables the development of internal strategies. Moreover, the large SUNERGY network provides a high gain in visibility as a driver for the energy transition.

3. **A smooth transition!** An added value compared to existing initiatives is that **SUNERGY bridges mature electricity-based technologies with the direct conversion of solar energy.** This enables society to smoothly shift from centralized fossil resources to the decentralized renewables and adapt energy and chemical production systems to optimize value chains tailored to the local energy resources and needs in urbanized regions with high economic efficiencies. The ecological transition necessitates more than just new technologies; it calls for a substantial embrace of sobriety. While innovative solutions are vital, they must be complemented by a fundamental shift in human consumption patterns and a conscientious effort to reduce resource and energy use. Sobriety plays a critical role in fostering sustainability and minimizing our ecological footprint to respect the planetary boundaries and ensure that we do not exceed the Earth's capacity to support life and maintain its delicate ecological balance.

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[9] The SUNER-C CSA provides funding for two vision and roadmapping events. It is important to construct them around the principles of generative research to leave enough space for discussion and to bridge diverse communities.

Scope and objectives

This section details the boundaries of the roadmapping effort, following the IEA's guide for energy technology roadmaps.

What is the focus of the roadmap?

The SUNERGY Roadmap focuses on **technology developments**, with **overall sustainability** (e.g. materials sustainability, energy and resource efficiency etc.) and **carbon circularity** as the main criteria. It aims at accelerating the development of cost-efficient, low-carbon technologies to convert renewable energy and abundant resources into fossil-free fuels and chemicals at scale. Even though the social and political dimensions will influence its development, **the SUNERGY Roadmap represents a Technological Roadmap**. The roadmap it is intended to guide projects purely at a R&I level, with concrete technological milestones.

What is the time frame for the roadmapping effort?

Aligned with the EU 2050 long-term strategy, the current roadmap will include **milestones until 2050**. Given the increasing uncertainties with an increasing timeframe, a focus will be on near- and medium term milestones: Near-term milestones, meaning within 5 to 10 years and medium-term, within 10-20 years. These target milestones are considered reasonable considering the necessary time for:

- Pilot and demonstration project development,
- Technology industrialization and scale-up,
- First of its kind industrial project development.

Which energy sources or end-user sectors will be considered?

Energy sources. Concerning the used energy sources, **the ultimate goal is the direct conversion of solar energy into chemicals and fuels**, i.e. to store intermittent energy from the sun in the form of chemical bonds in the fully integrated system. However, **in the short-to-medium term, renewable electricity**, e.g. from PV and wind, serves as a valuable resource (see also below "Which technology classes are considered?").

End-user sectors. Even though the proposed alternative fuels and chemicals are made with renewable energy sources and abundantly available molecules (e.g. CO_2), their production is inherently related to high conversion losses compared to the direct use of green electricity. Especially in view of the currently limited amount of renewable electricity, **synthetic fuels and chemicals represent a precious resource** which can help to complement the direct electrification of industry, transport and society. **However, they have to be used only for applications where they have the greatest environmental impact (i.e. those with the highest amount of avoided CO_2) and where electrification or substitution by H_2 technologies is not possible.**

For e-fuels, i.e. molecules produced from renewable electricity, a merit order of applications has already been established (see figure below) in areas where direct electrification represents the method of choice, e.g. light-duty transport and residential space heating. However, there are also important markets where direct electrification comes to its limits, such as long-distance aviation, shipping or the supply of chemical feedstock. **For those hard-to-abate sectors, alternative fuels are indispensable.**

For the direct conversion of sunlight into molecules, such an analysis is still lacking and the establishment of a merit order of solar fuels and chemicals applications will be an important part of the SUNERGY Roadmapping efforts.

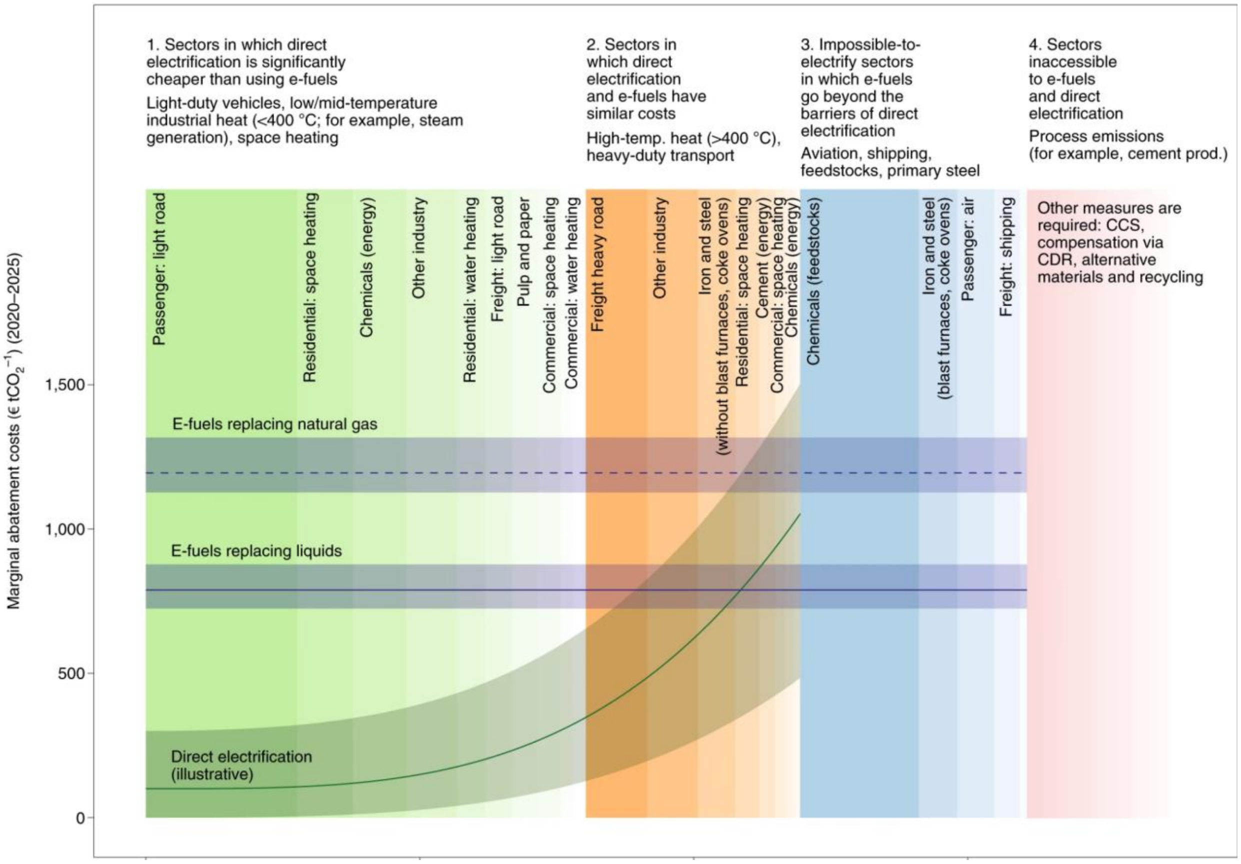

Figure: Costs of directly electrifying different energy end uses (sorting on y-axis from low to high costs of direct electrification), resulting into four categories: 1) Direct electrification is cheaper, 2) Direct electrification and efuels show similar costs, 3) Impossible-to-electrify sectors and 4) Sectors inaccessible to both efuels and electrification. Within each of the categories, the different applications, such as light-duty vehicles or feedstock provision for chemical industry, are sorted according to their size. Even in impossible-to-electrify sectors (category 3), there is a need to establish a merit order of applications. The final energy in the concerned sectors amounts to ~40 EJ across the OECD (12,500 TWh in 2014). This would require additional renewable electricity capacity of the order of 5,000 GW, together with the same amount of electrolysis capacity (global 2019 addition of renewable electricity capacity amounted to ~200 GW yr^{-1}). Source: Ueckerdt et al., Luderer (2021) Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nature ClimateChange. https://www.nature.com/articles/s41558-021-01032-7.

Which technology areas or classes will the roadmap consider?

Two main technological approaches[10]

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 2050. Considering the currently existing centralized energy infrastructure, SUNERGY focuses on the production of high-volume / low-value renewable chemicals and fuels to mitigate CO_2 emissions in the short- and medium term. For a future decentralized energy production system, SUNERGY advocates for the wide use of decentralized approaches that will allow for closing the cycles with high value products at a low volume (produced in on-the-spot refineries at farms, or in buildings and houses in urbanized areas). Indeed, the full optimization of the value chain may require low volume / high value hydrocarbon side streams with disruptive technological conversion technologies (e.g. microbial cell factories) that would be implemented in parallel with technologically more advanced approaches (such as the electrochemical energy systems).

The first technological approach represents a **portfolio of relatively mature technologies with sufficient technological or economic headroom for further improvement in terms of efficiency and cost** for a large-scale centralized energy supply and uses multiple steps to produce alternative fuels and chemicals. Given the potential of further cost reductions, continued R&D in these indirect conversion technologies makes much sense.

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 promising approach for a future decentralized 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.

The energy conundrum

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 that can combine scalability with affordability, by direct conversion of solar energy (see below figure,[11] 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

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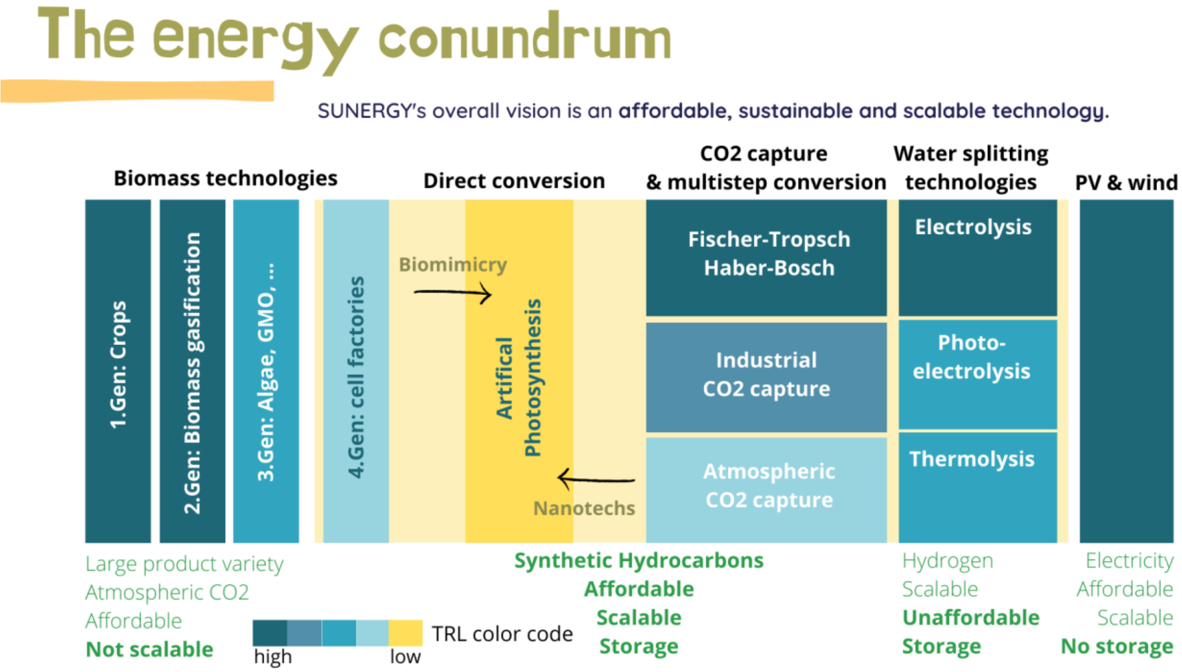
[10] Based on: SUNERGY Strategic R&I Agenda, November2022;

[11] adapted from G.J. Kramer, Utrecht University;

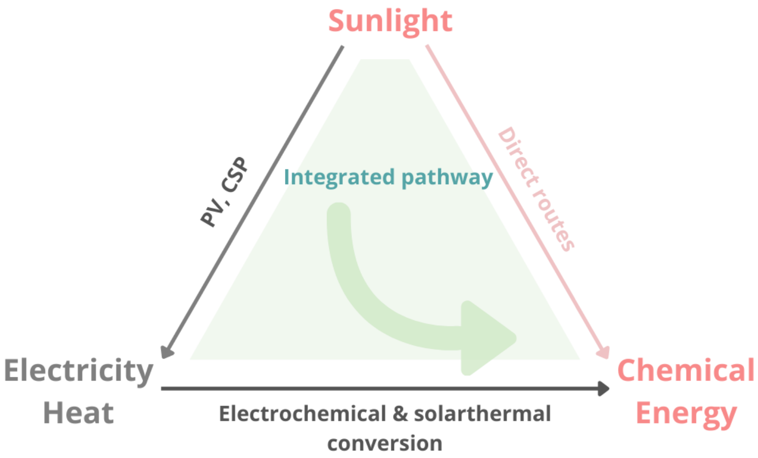
diverse fuels and chemicals. Nanotech-based approaches, as well as living cell factory approaches (biomimicry), will nourish the development of technologies converting sunlight directly into an end product. This increases overall energy conversion efficiencies and will provide affordable and scalable technologies in the long term.



Guiding principles for technology selection

Choosing the scope of technologies which will be considered in the SUNERGY roadmapping exercise is a delicate matter - reducing to a high degree the selection scope facilitates the evaluation, but one risks to neglect important bricks, especially in view of strong interfield synergies in the solar fuels domain; including too many technologies slows down the overall process and one risks to lose focus on the most impactful milestones.

The approach taken here is based on the declared overarching goal: **to store solar energy directly in the form of chemical bonds - at scale, on a time horizon from now to 2050**. This automatically includes all direct conversion approaches (purple pathway in the below figure). Moreover, mature multi-step approaches driven by industry are also considered - **however, with an additional condition: Integration**. Pathways (gray) converting solar energy into other forms of energy, such as electricity or heat, are not necessarily of interest for the SUNERGY Roadmap. They become interesting only if their integration with the subsequent conversion to chemical energy is considered (depicted in blue, e.g. PV panels connected to an electrolyzer, heat from concentrated solar power feeding directly a solar thermal conversion process). Overall process integration in the indirect routes is of utmost importance and today still a challenge. Only a few systems have already shown efficient flex operation.

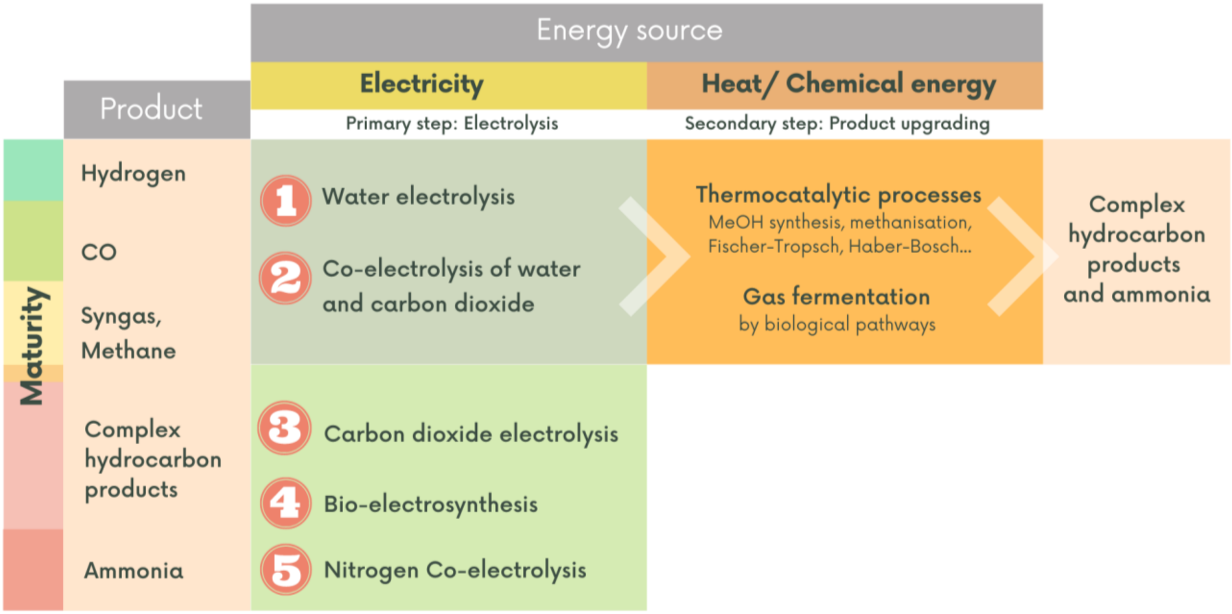


@ Bill Tumas (NREL, Mission Innovation)

Portfolio multistep conversion

Electrochemical conversion routes

The technologies considered here have one thing in common: the heart of the process is an electrochemical conversion, driven by solar electricity. It is a multi-step approach, where the light absorption process (via PV) is decoupled from the chemical conversion step. Advances in this field directly translate into advances in direct conversion approaches, where light utilisation and conversion are executed in one single step. The most mature technology is hydrogen production via **water electrolysis**. Products beyond hydrogen can be obtained either via **secondary industrial upgrading** steps, e.g. via **conventional thermochemical processes** or **novel biologically-driven gas fermentation processes**[12], or directly through **electrochemical CO_2 reduction**. In the latter case, technologies are usually less mature.



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Focus of SUNERGY: SUNERGY focuses on the primary, electricity-driven conversion step (categories 1 and 2), since cross-knowledge transfer to direct solar conversion approaches is expected. Secondary upgrading processes (e.g., via thermochemical or biological routes) on top of these electrochemical conversion steps are also important to consider, since integration and optimization have to be carried over the whole production chain in order to minimize the carbon dioxide footprint and to maximize the economic benefit.

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[12] Gas fermentation is a process in which microorganisms can fix CO_2 if sources of reducing power and metabolic energy are available. Hydrogen or CO are energy-rich electron carriers that can drive CO_2 fermentation. See for reference: Liew, F., et al. (2016), "Gas fermentation – a flexible platform for commercial scale production of low carbon fuels and chemicals from waste and renewable feedstocks", Front. Microbiol. 7:694. doi: 10.3389/fmicb.2016.00694J; Schievano et al. (2019), "Editorial: Microbial Synthesis, Gas-Fermentation and Bioelectroconversion of CO2 and Other Gaseous Streams", Frontiers in Energy Research 7, doi:10.3389/fenrg.2019.00110;

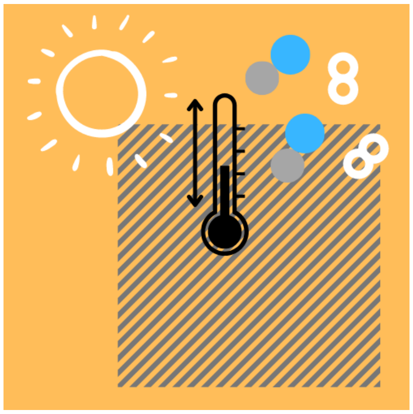
Category 3, electrocatalytic biomass transformation, differs from the other approaches in the sense that the starting point are already complex energy-rich organic molecules, instead of simple, energy-poor feedstock such as carbon dioxide or water. As a result, more complex carbon-based products can be directly obtained.

Category 4, bioelectrosynthesis, takes advantage of the maturity of conventional electrochemical conversion processes and the ability of microorganisms to synthesize complex hydrocarbon products from simple feedstock in a single step.

Category 5, the direct electroreduction of water and nitrogen into ammonia is still at a low maturity level. Recently, researchers could demonstrate electrochemical ammonia production working via both lithium- and calcium-mediated mechanisms. However, the latter require a pulsed operation to overcome the strong binding potential of these metals and to "clean" the electrode surface.

Alternatives to electrochemical routes

Besides direct electrochemical conversion routes, other pathways such as solar-thermal or plasma-driven routes enrich the technological panorama and can be used as a benchmark.



Solar-thermal or solar-driven thermochemical technologies are an alternative to electrochemical routes. First, solar energy is converted into high-grade heat via concentrated solar power (CSP). This renewable heat then drives the splitting of water and CO_2 into hydrogen and syngas in specific materials (so-called RedOx materials). Solar-driven thermochemical water- or CO_2- splitting cycles can produce H_2 or carbon monoxide with very low greenhouse gas emissions.[13] The produced hydrogen or syngas may later on be converted into fuels and chemicals using conventional production processes.

Non-thermal plasma technologies are considered as promising alternatives for CO_2 conversion due to their mild operating conditions, scalability and flexibility with fast switch on/off suitable for efficient storage of renewable energy, grid stabilization and production on-demand. These technologies enable an efficient breaking of molecules relying on the activation of gas molecules (CO_2, N_2, H-source (CH_4, H_2)) through collision with free excited electrons generated by an electrical field. Different types of plasma set-up exist, mainly Dielectric Barrier Discharge (DBD), Microwave (MW) or Gliding Arc (GA). Still at an early stage of development (TRL 1-3) for CO_2 conversion, different molecules (syngas, NH_3, C1-C5, oxygenates) can be produced, but research is still needed to increase the selectivity, energy efficiency[14] and conversion.

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[13] Converting-Sunlight-into-Solar-Fuels-and-Chemicals-MI-Challenge5-Roadmap

[14] This requires introducing a definition of the energy efficiency which allows a direct comparison to solar-to-X technologies.

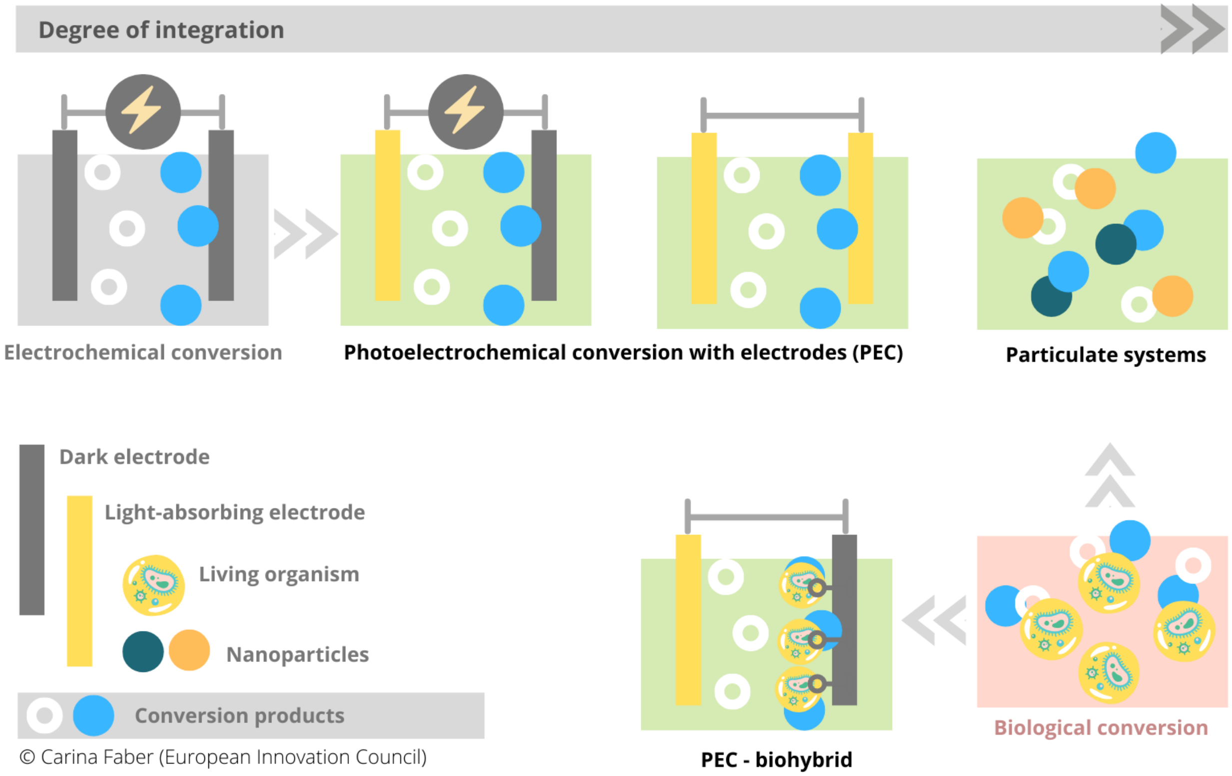
Portfolio of direct conversion technologies

Storing solar energy directly into chemical bonds includes **photosynthetic devices** and **biologically-driven technologies**. Device architectures are manifold and various conceptual approaches are explored. One way of categorizing them is by their degree of integration (see below figure): while **electrochemical conversion of solar energy** using an electrolyzer (two electrodes alimented by an external voltage) that is completely separated from light absorption constitutes an indirect conversion technology, **biological systems** completely integrate all necessary steps. Between these two extremes, researchers elaborate diverse concepts of photosynthetic devices.

Photosynthetic devices - taking inspiration from nature while providing high economic efficiency. Photosynthetic devices convert solar energy directly into fuels and chemicals. The technologies considered here have one thing in common: they are standalone devices converting solar energy directly into fuels and chemicals out of simple building blocks - carbon dioxide, nitrogen and water. They also take into account the need for high economic efficiency by minimizing use of critical materials, and by seamless integration into the existing technological infrastructure from the very beginning. Rather than transporting electricity from solar cells to enable the centralized electrochemical production of hydrogen and carbon compounds, these technologies aim to combine everything necessary in an integrated conversion system to go directly from sunlight to the final chemical product of choice, in a decentralized way. This offers genuine routes to minimizing energy losses and potentially reducing cost over entire value chains. It also poses a main challenge for scalable device designs: it requires efficient simultaneous management of photons, electrons, ions, substrates and products in a cost efficient energy systems approach.

SUNERGY focuses on photosynthetic devices, a.k.a. artificial photosynthesis.

A fundamental distinction exists between photocatalysis and photo(electro)chemical conversion: photoelectrochemical conversion uses solar energy to drive energetically uphill reactions, while photocatalysis speeds up downhill processes. This means that photo(electro)chemistry is an important approach for net energy production.



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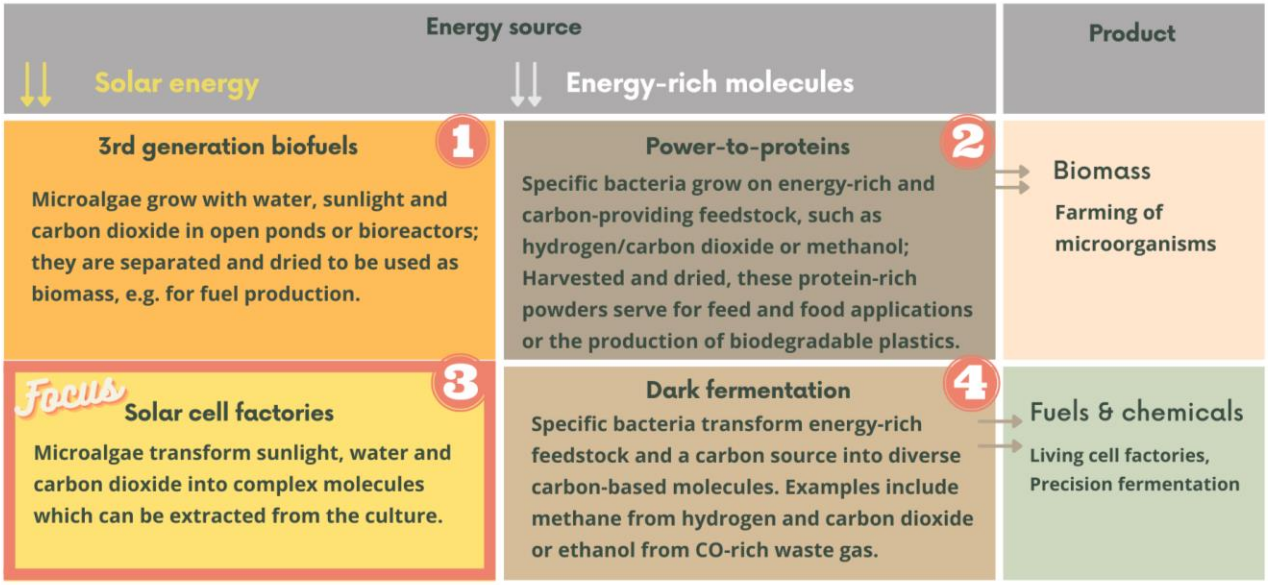
In contrast to electrochemical conversion, where an electrolyzer is driven separately by a solar cell, photosynthetic devices integrate light absorption with energy conversion in a single device. A common approach used in photoelectrochemical devices (PEC) is to include two electrodes that are light-absorbing and able to do chemical catalysis, to directly convert solar energy into a product. In such systems, the electrode materials may be tailored by attaching catalysts onto the electrodes' surface. A variety of catalysts may be used, e.g. molecular or biomolecular catalysts, or non-molecular inorganic catalysts ("inorganic" PEC). The same principle is applied in biohybrid PEC devices, but this time living cells are anchored to the electrodes. In particulate systems, photoactive particles are explored, which does not require wiring or transmission of current. This may be inspired by solar-driven biological conversion where photosynthetic cell factories produce fuels and chemicals from sunlight, water and carbon dioxide. The description here is not complete, since a mixing of the above mentioned ideas leads again to completely novel concepts trying to combine the best of different worlds, such as in bio-hybrid devices.

Biocatalytic conversion - not to be confused with traditional biofuels of first (crops) and second (biomass waste) generation. The biologically-driven technologies considered here have one thing in common: they rely on microorganisms and a renewable energy source to convert a given, non-biomass-based substrate into a valuable product. Depending on the chosen feedstock, energy source and product, the considered technologies can be divided into four distinct categories:



Energy source		Product
Solar energy	Energy-rich molecules	
3rd generation biofuels ① Microalgae grow with water, sunlight and carbon dioxide in open ponds or bioreactors; they are separated and dried to be used as biomass, e.g. for fuel production.	**Power-to-proteins** ② Specific bacteria grow on energy-rich and carbon-providing feedstock, such as hydrogen/carbon dioxide or methanol; Harvested and dried, these protein-rich powders serve for feed and food applications or the production of biodegradable plastics.	**Biomass** Farming of microorganisms
Focus **Solar cell factories** ③ Microalgae transform sunlight, water and carbon dioxide into complex molecules which can be extracted from the culture.	**Dark fermentation** ④ Specific bacteria transform energy-rich feedstock and a carbon source into diverse carbon-based molecules. Examples include methane from hydrogen and carbon dioxide or ethanol from CO-rich waste gas.	**Fuels & chemicals** Living cell factories, Precision fermentation

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SUNERGY focuses on solar cell factories, i.e. the direct production of fuels and chemicals from sunlight (Approach 3). Photosynthetic microorganisms, cyanobacteria, are fed with water, carbon dioxide and sunlight and secrete the desired products from their cells into the medium. Synthetic biology offers the possibility to genetically modify the organisms and to access a broad range of possible product molecules. Discoveries from Approaches 1, 2 and 4 can be directly translated to this focus area and are highly valuable to be considered in the roadmap development.

Dark fermentation (Approach 4) is the most mature at this stage to provide renewable fuels and chemicals from energy-rich feedstock molecules, such as H_2 or CO, in the short-term and commercial plants are close to operation (e.g. Steelanol plant in Ghent, Belgium). Microorganisms are fed with energy-rich and carbon-containing feedstock and secrete diverse product molecules from their cell into the medium. Synthetic biology offers the possibility to genetically modify the organisms and to access a broad range of possible product molecules.

Power-to-proteins (Approach 2) is based on the growth of bacteria fed with energy-rich and carbon-containing feedstock. Via the growth of the bacteria and the subsequent harvesting of the latter, simple feedstock is converted into protein-rich microbial biomass and can be used directly for food and feed applications. This approach is also at an advanced TRL. It necessitates a beforehand conversion step to access the needed energy-rich feedstock (e.g. electricity to green hydrogen) or a waste stream rich in CO or H_2 (e.g. from steel blast furnace gas). They represent indirect production routes with the potential to drive forward the less mature direct conversion into fuels and chemicals by de-risking biologically-driven conversion processes and upscaling to the industrial level.

Third generation biofuels (Approach 1) are based mainly on microalgae and cyanobacteria (rarely macroalgae) grown in water, carbon dioxide and sunlight, either in open ponds or bioreactors. The focus is on farming of microorganisms which are at a certain point separated and used as biomass for the further downstream processing to biofuels and other products (biorefinery). Solar-driven growth of microbial biomass in closed photobioreactor systems could provide valuable knowledge in bioreactor engineering for solar cell factories.

Even though the considered processes are driven by microorganisms, the fundamental difference to so-called biofuels of first and second generation is that the latter use organic matter as feedstock for the final product (e.g. fermentation of sugar cane to biodiesel). In SUNERGY, simple, non-biomass-based molecules such as water, carbon dioxide or nitrogen are considered as a feedstock for the biocatalytic production of fuel and chemicals. Traditional biofuels of first and second generation are not treated in the following, a comprehensive introduction is provided by the International Energy Agency in their Outlook for Biogas and Biomethane.[15]

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[15] [IEA]: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane

Sustainable CO_2 capture

Different types of carbon capture technologies are available, at different maturity levels. Depending on the specific application and gas stream characteristics, one or the other will be the method of choice.

Post-combustion capture refers to the separation of CO_2 from flue gasses. CO_2 capture technology based on chemical absorption (TRL 7-9, depending on the CO_2 concentration) is today the most mature process yet still could benefit from further improvements such as energy consumption per tonne of CO_2 captured, stability of the amine solvents used and efficient solvent regeneration.[16] However, alternative technologies, e.g. physical adsorption (TRL 7-9, depending on the CO_2 concentration), membrane separation (TRL 4-9, depending on the CO_2 concentration), calcium looping (TRL 7) and cryogenic separation (TRL 5-9, depending on the CO_2 concentration) may offer opportunities for cost reduction.

Capturing from the atmosphere, referred to as Direct Air Capture (DAC), involves two main types of processes linked to the temperature of regeneration: at high temperature (regeneration at ~700-900°C) by absorption on alkaline solvent vs. low-temperature adsorption on solid sorbents (thermal regeneration at ~80-100°C or humidity swing). The technology-readiness level is currently 5-6, where scale and system integration are still major issues.

Capturing from the ocean: CO_2 extraction from seawater is based on seawater acidification followed by CO_2 stripping. Acidification is typically achieved thanks to an electrochemical process. Two main technologies have been tested so far: bipolar membrane electrodialysis and ion-exchange membranes. Current TRL is 4.[17]

Direct capture and conversion is a not mature, but highly promising pathway to integrate CO_2 capture with its direct utilization. Post-combustion capture technology is of particular interest, due to the possibility of retrofitting existing industrial facilities. However, one major challenge lies in the high energy requirements for sorbent regeneration. To avoid this energy-intensive step, several universities and research institutes are currently investigating a technology allowing the direct conversion from the captured CO_2 solution. Such an approach can also be applied to capturing atmospheric CO_2 and directly converting it, the main issue being the presence of O_2 present in the air and remaining trapped at significant concentration in the captured CO_2 solution.

Pre-combustion capture refers to the separation of CO_2 from hydrogen, before its combustion or utilization. An example is the production of blue hydrogen via steam methane reforming.

Next to these main CO_2 removal processes, other possibilities can occur depending on the specific industrial process. Examples are **indirect calcination** during the production of cement (Calix's

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[16] An example is the use of monoethanolamine to capture CO_2 at a scale of 60 kton/year from the waste to energy flue gas at AVR (Duiven, the Netherlands).

[17] A prototype has already been developed and operated several years ago by the US Naval Research center and Palo Alto. Recently, the topic raises again increased interest, with the start-up Captura Corporation, a spinoff of the California Institute of Technology, having developed a 100-ton Direct Ocean Capture pilot system in the lab (https://newatlas.com/technology/captura-carbon-dioxide-ocean/).

technology[18]) or the **oxyfuel[19] combustion process** (TRL 6-7, depending on the fuel feedstock) using pure oxygen instead of air.

Focus and relevance for SUNERGY

Certain CO_2 capture technologies are already quite mature and their further development and optimization is driven by industry. Since CO_2 is a crucial feedstock molecule in SUNERGY, there is a strong need to align CO_2 capture and CO_2 conversion technology roadmaps. **The scales of CO_2 provision have to be matched with CO_2 utilization and cost reductions can be achieved by optimizing these two bricks with respect to each other.**

For the specific case of Direct Air Capture, analyses show strong synergies when it is directly integrated with e-fuel production. For certain products (e.g. e-methane), the latter produces enough heat to aliment a low-temperature DAC process for the provision of the needed CO_2.[20] Moreover, water is also produced and can be reused for an electrolysis process. Not only the e-fuel, but also some DAC processes produce water – as a by-product to the captured CO_2 (see Figure below and ref.[21]). Water is needed as feedstock for the electrolysis step, especially in arid areas. However, water co-capture is done at the expense of reduced energy efficiency for the DAC, which could be addressed in its integration with e-fuel production by recovering heat from electrolyzer and conversion process.

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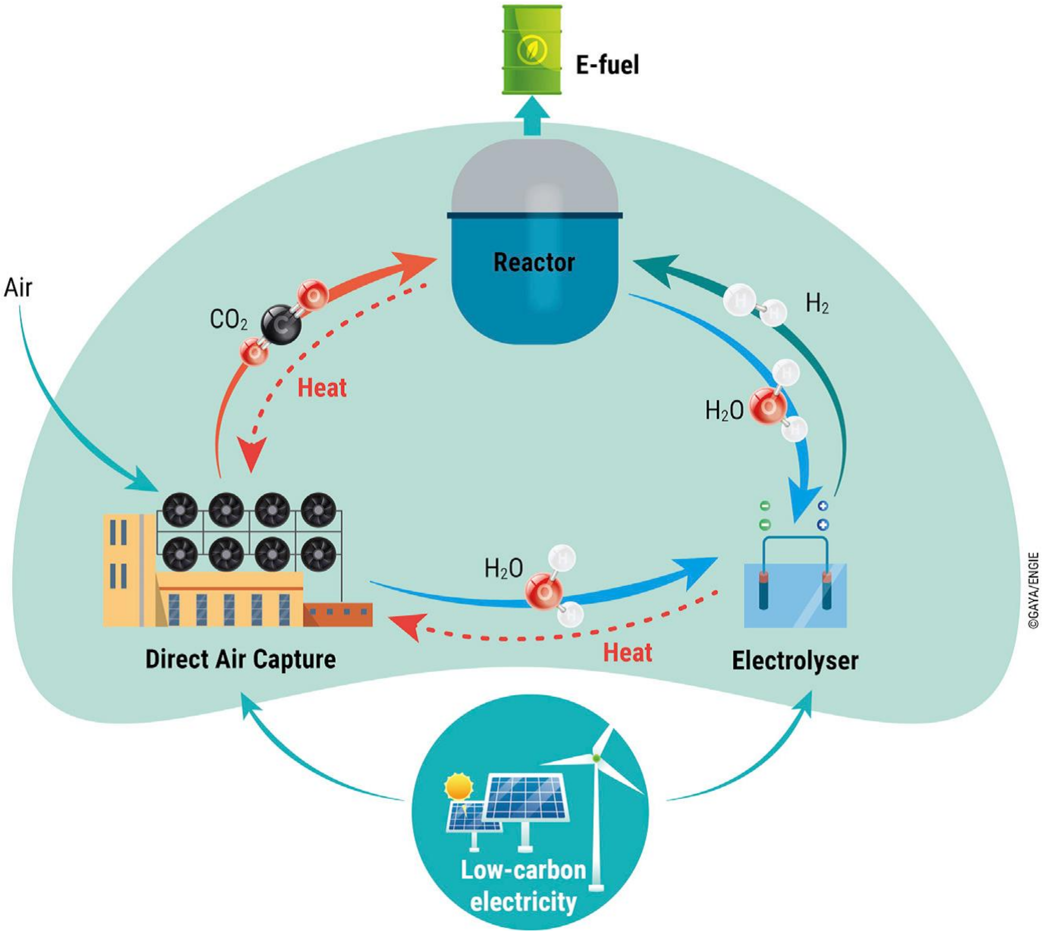
[18] Development for cement industry: indirect heating of the limestone in the calciner in an enveloping vessel, allowing pure CO_2 release from the limestone calcination.

[19] *i.e.* combustion with pure oxygen or oxygen-enriched air; The separation of the produced CO_2/steam mixture can be done by cooling. Oxyfuel capture is shifting the energy-intensive stage from CO_2 separation to oxygen separation; opportunities may arise when O_2 is available as a by-product from water electrolysis.

[20] Drechsler C. and D.W. Agar, 2020. Intensified integrated direct air capture -power-to-gas process based on H_2O and CO_2 from ambient air. *Applied Energy*, 273, 1150763;

[21] Mertens et al., Carbon capture and utilization: More than hiding CO2 for some time, Joule (2023), https://doi.org/10.1016/j.joule.2023.01.005



Main cost drivers for CO_2 capture are the characteristics of the source stream (**CO_2 concentration**, **present impurities**), **scale**, the **required CO_2 purity** specifications for the conversion process, and the **added value** of the "CO_2 as a product", e.g., in terms of sustainability (e.g. gray CO_2 vs. green CO_2). Conversion technologies are more or less sensitive to impurities in the CO_2 stream and consequently more or less expensive purification methods are necessary (ranging e.g. from formic acid synthesis with high CO_2 purity to mineralisation with impure input streams). High purity CO_2 is usually required by conversion processes with sensitive catalysts and with products that could modify its properties due to the presence of impurities, whereas less expensive pre-treatments are needed for more robust catalysts, such as biologically-driven conversion processes.

What is the current state of the technology under consideration?

Multistep conversion. Converting renewable electricity and simple feedstock molecules into chemicals and fuels, e.g. by means of electrolysis and subsequent conventional industrial processes, is an **already quite mature approach**. Significant progress over the last few years, faster than initially expected, can be noted. Installations at the 200 MW scale are currently doable and projects up to the 500 MW scale[22] are in the pipeline for the next few years.[23] Technological **challenges** are related to **integration**, **energy efficiency** and **sustainability** of the used materials. Moreover, **high financial investments** for such large-scale applications and **unclear regulation** (in terms of feedstock and end product) are major hurdles. Hydrogen may be used as an energy vector, but the transport from the centralized production place (e.g. "Hydrogen islands" with excess wind energy or places with high solar irradiation) to the application need to be taken into account. All kinds of discussed conversion to other more easily storable and transportable substances (e.g. ammonia, metal hydrides, etc.) have their pros and cons, but definitely add cost in terms of energy and economics to the value chain.

Direct conversion approaches. Storing sunlight directly in the form of chemical bonds is generally **at low technology readiness levels** in contrast to multistep conversion approaches. However, they bear important promises for future decentralized applications with minimized infrastructure needs. The distributed nature of these approaches means they are less dependent on concentrated CO_2 sources, and can effectively incorporate direct air capture in the conversion. Inherent challenges - but at the same time opportunities - are related to the fact that light absorption, and its utilization for direct catalytic conversion of feedstock molecules into products take place in the same device. These processes have to be controlled simultaneously and optimized with respect to each other, leading to efficiency challenges. In multistep conversion approaches, these steps are separated, e.g. light absorption is carried out via PV panels and chemical conversion happens in an electrolyzer.

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[22] E.g. https://www.pv-magazine.com/2022/11/25/the-hydrogen-stream-tes-rwe-plan-500-mw-electrolyzer-in-germany/

[23] For a thorough analysis of power-to-x (efuel) projects in Europe, see: Wulf C, Zapp P and Schreiber A (2020) Review of Power-to-X Demonstration Projects in Europe, Front. Energy Res. 8:191.

Process

What is a roadmap?

Following the IEA's guide, "a roadmap is a **strategic plan** that describes the steps an organization needs to take to achieve stated outcomes and goals. Roadmapping is the **evolving process** of creating and implementing a roadmap, and monitoring and updating it, as necessary. The **process is often as important as the resulting document**, because **it engages and aligns** diverse stakeholders in a common course of action."

A roadmap is a visual tool to illustrate how to go from the current state-of-the-art to a defined vision, setting priorities to determine the most efficient way.[24]

Based on Momčilo Dakić, Treasure Roadmap,https://momcilodakic.com

Key elements of the SUNERGY roadmapping process

The SUNERGY roadmap is conceived as a living document. It will be updated regularly and will help to grow, integrate and align the community around the topic of solar fuels and chemicals.

A first draft has already been worked out by SUNERGY's Strategic R&I agenda lead team. It is based on the analysis of existing work: the SUNRISE technological roadmap, Energy-X's Research Needs, SUNERGY's Strategic R&I Agenda and Mission Innovation's Challenge 5 roadmap. This summary has been provided and further developed by a broad community during SUNERGY's first roadmapping workshop (14/15 June 2022, Brussels).[25]

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[24] University of Cambridge, Roadmapping for strategy and innovation;

[25] This workshop hosted over 140 participants from industry, academia and policy. It consisted of high-level talks of leading experts to build a common ground and active work and discussions in dedicated working groups. Next to five technical working

This draft facilitates the engagement of other stakeholders. It will be widely published and will be open for review by a broad community.

We will focus on the development of technological milestones, bringing us from the state-of-the-art to the vision, while we base our analysis on existing scenarios. The state-of-the-art is determined within the SUNERGY technological working groups.

How is it done?

VISION
SUNERGY SRIA

Scenarios
IPCC
EU 2050
Global Powerfuel Alliance
CVE
...

SUNERGY Roadmap
SUNRISE Technological Roadmap
ENERGY-X Research Needs
Mission Innovation 5
...

Scenarios

Where are we now?

The SUNERGY Roadmap will be aligned to actual needs of industry, policy and society. Since SUNERGY is not the implementing body, the roadmapping development only makes sense when it meets the actual needs of implementing bodies. Before its first Roadmapping Workshop (see above), SUNERGY already started to scout for needs in industry and policy by **conducting interviews with key stakeholders**. This helped to optimally shape the workshop content and structure. Moreover, it allowed to develop tailor-made output for the participating organization, **increasing the chances for concrete implementation**.

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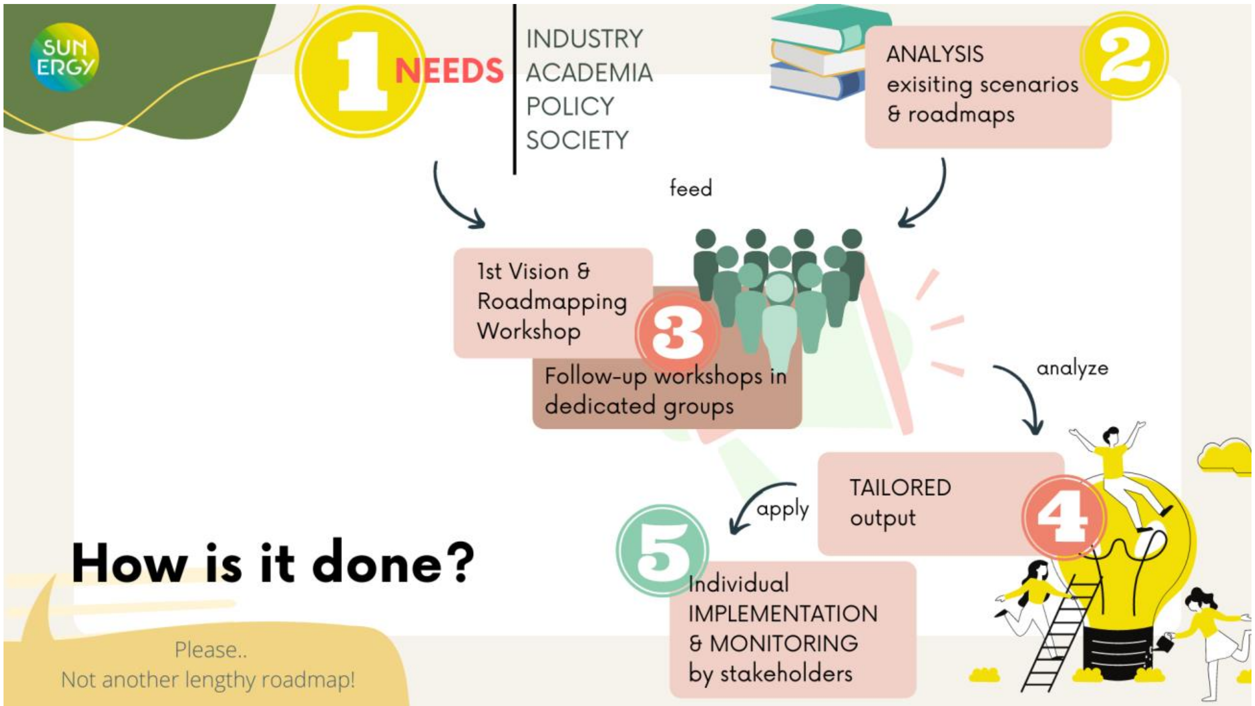
groups (Electrochemical conversion, thermochemical conversion, photosynthetic devices, biological conversion and CO_2 capture), social acceptability and the importance of future business models have been discussed.



1 NEEDS

INDUSTRY
ACADEMIA
POLICY
SOCIETY

ANALYSIS
exisiting scenarios
& roadmaps
2

feed

1st Vision &
Roadmapping
Workshop
3
Follow-up workshops in
dedicated groups

analyze

TAILORED
output
4

apply

5
Individual
IMPLEMENTATION
& MONITORING
by stakeholders

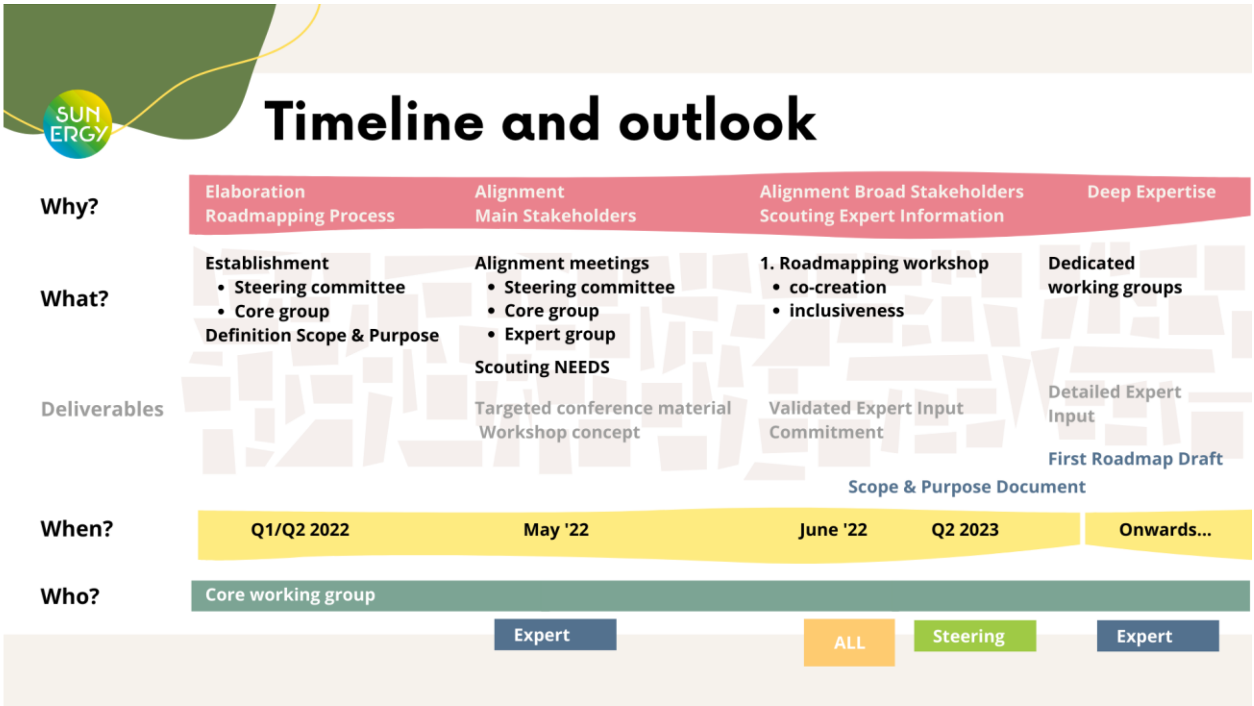
How is it done?

Please..
Not another lengthy roadmap!

Preliminary timeline and outlook

SUNERGY got started being funded in June 2022, via the SUNER-C CSA. However, extensive work has been carried out by a small, dedicated group of experts during the non-publicly funded transition period from 2020–22. The result is the SUNERGY Strategic R&I agenda on solar fuels and chemicals, directly feeding into the development of the SUNERGY Technological Roadmap. The latter represents the backbone of subsequent activities, being completed and updated in the upcoming three years in the spirit of a living document.

An urgency to act. Even though this draft is not complete, the SUNERGY Strategic R&I leaders identified the need to provide first answers and a sort of direction as soon as possible (see Appendix, SWOT analysis). Given the current political circumstances, the local production of fuels and chemicals with renewable energy could provide an important brick to the EU's energy security. However, industry and policy decision makers urgently need answers on when technologies will be ready for a sustainable large-scale deployment, especially considering the enormous financial and regulatory efforts related to such kinds of projects. **Missing the right timing and neglecting the current political momentum will threaten the implementation of the roadmap.**



Timeline and outlook

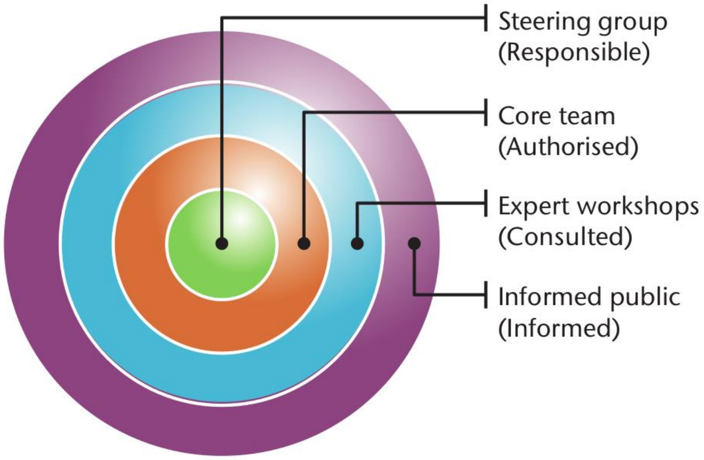
Why?	Elaboration Roadmapping Process	Alignment Main Stakeholders	Alignment Broad Stakeholders Scouting Expert Information	Deep Expertise
What?	**Establishment** • Steering committee • Core group **Definition Scope & Purpose**	**Alignment meetings** • Steering committee • Core group • Expert group **Scouting NEEDS**	**1. Roadmapping workshop** • co-creation • inclusiveness	**Dedicated working groups**
Deliverables		Targeted conference material Workshop concept	Validated Expert Input Commitment Scope & Purpose Document	Detailed Expert Input First Roadmap Draft
When?	Q1/Q2 2022	May '22	June '22 Q2 2023	Onwards...
Who?	Core working group	Expert	ALL Steering	Expert

Participants

The overarching goal of the SUNERGY initiative is to **group all the actors of the innovation ecosystem** of solar fuels and chemicals. It is designed as an **inclusive** network and counts on the expertise of stakeholders from **diverse backgrounds**. The SUNER-C CSA allows its consortium partners to play an active role in the SUNERGY Roadmapping process; but: the roadmapping is open for any participation, also from outside the consortium.

As detailed before, **a strong engagement of policy makers and industry leaders right from the beginning is of utmost importance** - to steer the development towards industrial and societal needs and to ensure an actual implementation of the roadmap.

The chosen stakeholder involvement strategy follows closely the recommendations of the IEA's roadmapping guide. The roles and responsibilities of organizations and individuals have been identified using a RACI[26] chart (see figure below, taken from the IEA guide).



Steering group

This group is composed of senior representatives from policy, industry and research. This high-level engagement **assures not only the quality of the final product, but also the concrete implementation of the roadmap afterwards**. Its members serve as **credible and influential ambassadors** helping internal decision-makers understand the new roles of companies/politics and possible new ways of investing, working and delivering for solving major societal issues.

Regular, but light intervention.

Core team

The core team is actually undertaking the vast majority of the work; it mirrors the composition of the steering group. The team is amongst others responsible for developing the overall roadmapping strategy, providing the background and working material to the working groups, guiding the groups towards the defined goals and taking care of dissemination and stakeholder engagement.

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[26] RACI = Responsible, Accountable, Consulted, Informed

Dr. Carina Faber (European Innovation Council)	Roadmapping strategy, working material
Prof. Joanna Kargul (UWarsaw)	Stakeholder engagement and alignment of R&I needs and breakthroughs
Han Hunyh (ENGIE)	Delivery manager
Dr. Laura Lopez (ICIQ)	Dissemination
Dr. Joachim John (IMEC)	Roadmapping and work group guidance
Prof. Huub de Groot (ULeiden)	Vision alignment
Dr. Ann Magnuson (UUppsala)	Vision alignment

Expert group

Following the IEA's guide, "this group channels the input from the broad group of stakeholder experts participating to the workshops and ensures the quality of their input; This group typically includes expert representatives." **Mandate: Attend workshops, provide reports, review roadmap drafts.**
Within the SUNERGY Roadmapping, the expert group is organized into working group leaders and participants to dedicated working groups. Working groups are preferably led by a team of experts, in the best case a mix of leading academic and industry/RTO representatives to access both **front-end knowledge and industrial applicability**.
Important: all working groups are open for your participation![27]

Electrochemical Conversion	Prof. Maximilian Fleischer (Siemens Energy) Dr. F. Pelayo Garcia de Arquer (ICFO) Dr. Moritz Schreiber (TotalEnergies)	Dr. Joachim John (IMEC) Dr. Deepak Pant/ Dr. Yuvraj Birdja (VITO) Dr. Arne Roth (Fraunhofer)
	Dr. Francesco Matteucci, Alexander van der Made (SHELL), Joost Smits (SHELL), Ruud Kortlever (Differ), Paramaconi Rodriguez (IKERBASQUE), Nicolas Nouvel (Aster Fab), Julien Poillot (VICAT), Tamas Ollar (Centre for energy research), Domenico Grammatico (Austrian Institute of Technology), Isabel Francois (Waterstofnet),	

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[27] You can express your interest under: https://sunergy-initiative.eu/sria/

	Holger Ihssen (Helmholtz Association), Samantha Michaux (Ineratec GmbH), Han Huynh (ENGIE), Sofia Derossi (NWO), …	
Photosynthetic Devices	Dr. Ann Magnuson (UUppsala)	Prof. Julio Lloret (ICIQ)
	Dr. Carina Faber (European Innovation Council), Prof. Joanna Kargul (UWarsaw), Prof. Huub De Groot (ULeiden), Dr. Vincent Artero (CEA), Prof. Jose Ramon Galan-Mascaros (ICIQ), Prof. Siglinda Perathoner (UMesina, ERIC), Philippe Schild (DG RTD), Dr. Indraneel Sen (UUppsala), Dr. William Tumas (NREL), Dr. Roel van de Krol (Helmholtz-Zentrum Berlin für Materialien und Energie), Dr. Murielle Chavarot-Kerlidou (CNRS), Dr. Salvador Eslava (Imperial College London), Dr. Philipp Gotico (CEA), Dr Georgios Katsoukis (UTwente), Dr. Haifeng Yuan (KU Leuven), Prof. James Durrant (Imperial College London), Dr. Carles Ros (ICFO), Dr. Nathalie Herlin (CEA), Dr. Winfried Leibl (CEA), Dr. Mauricio Schieda (Helmholtz-Zentrum Berlin HERISON), Dr. Negar Naghavi (CNRI-IPVF), Dr. Adeline Miquelot (ENGIE), Prof. Sylvestre Bonnet (ULeiden), Victor de la Pena O'Shea (IMDEA), …	
Biological Conversion	Prof. Joanna Kargul (UWarsaw)	Prof. Yagut Allahverdiyeva-Rinne (UTurku)
	Dr. Carina Faber (ENGIE), Dr. Gaspard Bouteau (ENGIE), Prof. Tekla Tammelin (VTT), Dr. Aniek van der Woude (Photanol BV), Dr. Kristof Verbeeck (ArcelorMittal Belgium, Steelanol), Dr. Vera Grimm (BMBF), Prof. Lars Lauterbach (Aachen University), Peter Lindblad (UUppsala), Patrik Jones (Imperial College) ...	
Solar-thermal Conversion	Dr. Martin Roeb (DLR)	Dr. Stefan Baumann (FZ Jülich)
	Nathalie Dupassieux (CEA), Delphine Bourdon (CEA), Alicia Buceta (CENER), Manuel Romero (IMDEA), …	
Sustainable CO_2 Capture	Alexander van der Made (Shell), Carbyon	Han Huynh (ENGIE)

	Dr. Jan Mertens (ENGIE), Dr. Hervé Bercegol (CEA), Wim Verstappen (Carbyon), Prof. Patricia Luis (UCLouvain), Jakob Kuhs (Ughent), Nicolas Nouvel (Nouvel Consulting), Ivan Souček (Association of the Chemical Industry of the Czech republic), Vasilic Parvulesco (University of Bucharest), …	
Computational Materials Science	Prof. Gian-Marco Riganese (UCLouvain)	Dr. Simon M.-M. Dubois (UCLouvain)

Informed public

Group that consists of the SUNERGY community which is **not actively participating** in drafting the roadmap, but informed about the results. The SUNERGY community already counts more than 300 supporters from policy, research and industry, but the intention is to make the community grow around a common goal (importance of dissemination and stakeholder engagement activities).

Appendix

SWOT analysis of the SUNERGY Roadmapping Process

The below analysis of the strengths, weaknesses, opportunities and threats is one of the tools used by the SUNERGY Strategic R&I agenda lead team to determine the added value of the SUNERGY Roadmapping process compared to the current landscape. Moreover, it helped to identify bottlenecks and to design the roadmapping process and working philosophy accordingly. The above presented scope, purpose and scope is a direct result of such an analysis.

STRENGTHS	WEAKNESSES
● Motivated, existing community; ● Previous roadmapping experience; ● SUNER-C funding for roadmapping; ● Strong link with possible implementers: EC, industrial players from energy and hard-to-abate sectors, tech developers, chemistry; ● Great know-how on disruptive technologies of direct conversion (front runners); ● Coordinated policy advocacy team for selected topics on MS and EU level;	● SUNER-C funding limited in time, SUNERGY can not be the implementer of the roadmap; ● The authors of the roadmap have to rely on ambassadors for implementation; ● Diverse stakeholders: pay attention to conflicting bubbles; ● Some leaders in the field not already actively involved; ● Unclear timelines for emerging technologies; Lack of awareness by decision makers of potential impact of solar fuel technologies;
OPPORTUNITIES	THREATS
● Align a diverse community around common goals; ● Bring Direct Conversion Technologies on the table of decision makers; ● Create a clear vision on how to shift from a centralized to a decentralized energy & production system; ● Prepare political, industrial and societal stakeholders to this drastic change: a concrete way to reach out to society; ● Involve new experts/stakeholders not yet approached; ● Conceive an achievable roadmap with high chances to be implemented by individuals; ● Scale-up to meet industrial needs; ● Built a strong community of ambassadors around the topic;	● Roadmap will not be implemented; ● Miss the right timing: giving answers too late; ● Direct conversion technologies are seen as unrealistic, not worth investing; ● SUNERGY is perceived as inefficient and useless for decision makers; ● Not enough input or not enough expertise in all areas; ● Lack of social awareness and acceptance of the technologies; ● Duplication: many other roadmapping exercises; ● Lack of coordination at current stakeholders level; ● Highly competing field: reluctance to disclose technological breakthrough results; ● Lack of transparency and inclusiveness;

Speedboat analysis

In addition to the SWOT analysis, a so-called speedboat analysis has been carried out to help identify the best possible purpose and scope of the SUNERGY Roadmap. The goal was to clearly state the goals, risks, helping and hindering mechanisms of such an endeavor and to deduce a related overall strategy.

Deduced strategy for the SUNERGY Roadmapping process:

Co-creation of a strategic roadmap on solar fuels

How is it helping the community? Foresight + Collaboration + Dissemination

→ Get a clear view on future milestones in an emerging domain by collective wisdom,
→ Enable stakeholders to build their own internal strategies and ensure implementation,
→ stakeholders gain high external visibility as drivers for the energy transition.

Overarching goal: Create credible and influential ambassadors helping internal decision-makers understanding the new roles of companies/politics and possible new ways of investing, working and delivering for solving major societal issues.

- **Clear vision** on how to shift from a centralized to a decentralized energy and production system based on synthetic fuels & chemicals
- ✓ Achievable roadmap with an efficient division of efforts
- ✓ Novelty: co-creation and thus many ways of implementation by diverse stakeholders
- **Strong community of ambassadors** from academia, business, politics and society

- High political momentum for carbon-neutrality
- Current spotlight on energy security and independency for EU
- Existing bibliography:
  SUNRISE, Energy-X, Mission Innovation, Shell,
  Global Power Fuel, Dechema, Status Power2X projects, CVE
- Existing networks
- Financial resources through CSA
- Strong link to EC

- Highly active, competitive field with new emerging stakeholders: start-ups, O&G, etc./ scattering of stakeholders
- Transverse topic, low visibility
- Uncertain end scenario with long timeline (2050)
- Competing lobbying (e.g., biofuels), opinion-based discussions instead of fact-based
- Profit-thinking instead of preparing the future thinking, Innovation reluctance

Not enough interest from stakeholders: another roadmap: doubling of efforts, no implementation, not fully accepted as an added value to the actual situation
Closed club: how to efficiently involve society?
Miss the right timing, advance too slow

Résumé of SUNERGY's First Roadmapping workshop

Shaping the future: renewable fuels and chemicals from solar energy for a climate-neutral Europe

Joint roadmapping workshop on future milestones by SUNERGY, EIC and DG RTD

What? A strategic roadmapping workshop on the future of solar fuels and chemicals, jointly organized by SUNERGY (within the framework of the EU SUNER-C CSA), EIC and DG RTD.

When? 14/15 June 2022

Where? Academy of Science, Brussels.

Concept in a nutshell:

- **Meet and discuss with the principal stakeholders along the whole solar fuels value chain**
- **Bring together diverse realities**: make scientists understand today's industrial reality - and industrials the breakthrough innovations of tomorrow and their impact on future business models;
- 2-day workshop in Brussels to elaborate an all-agreed roadmap;
- Mix of high-level overview presentations by leaders in the respective field and roadmapping exercises in the specific working groups.

*SUNERGY: large-scale EU initiative on the production of renewable fuels and chemicals. The considered technologies range from mature, electricity driven technologies (e-fuels) to technologies directly converting sunlight into chemical compounds (solar fuels). SUNERGY has obtained a 3-year European funding (4 Mio.) for the creation of a solar fuels community.

Short workshop summary

- One of the main goals of the workshop was to reunite the community after three years of limited contact; as a result, a very open and sharing atmosphere can be noted

  → **excellent opportunity for networking with key stakeholders from the whole innovation value chain;**

- The focus of the workshop was to bridge industry and academia, and also EU policy makers; thanks to intensive efforts during the workshop preparation (individual interviews with key stakeholders, personal invitations for key roles at the workshop), there was a **highly diverse mix of industrial players, high-level academic researchers and a strong involvement from the European Commission side**.
- 140 participants in total
- Funded by: SUNER-C EU project (project start: 1st of June, 4 Mio. for 3 years)
- Next to **six technical working groups** (Electrochemical conversion into hydrogen; Electrochemical conversion into carbon-based fuels; Photosynthetic devices; Biological conversion; CO_2 capture; Solar thermal conversion), a **Think Tank on Future Business Models** has been introduced to directly address questions coming from business (What are the products to target for a market entry? What are the related production scales on a timeframe? etc.); **Social acceptability** has been addressed in a dedicated Think Tank led by the Danish Board of Technology and the Licrox EU project.
- The **key outcome** of the workshop is the consolidation of the scope of proposed technological solutions and the creation of a (diverse and open minded!) network which serves as a basis to develop the roadmap.
  - The SUNERGY Roadmapping leaders had prepared working sheet documents for each working group including extensive background information based on literature review (state of the art for validation during workshop, Day 1), and concrete roadmapping exercises to determine future milestones for e-fuels and solar fuel technologies (Day 2);
  - Based on the preparation material and and the received expert input at the workshop, the elaboration of a technological roadmap structure has been started;
  - The latter will address questions such as technological maturity and adaptability, sustainability, or the products to be addressed.
  - Document structure: living document
  - Work structure : dedicated working group meetings for the following three years.

Workshop impressions

Policy meets leading solar fuel researchers. (Prof. Marco Pantaleo, Dr. Siglinda Perathon, Prof. Gabriele Centi, Dr. Andrea Napolitano, Dr. Francesco Matteucci)

A strong industrial participation can be noted, as here from a team of ENGIE researchers. (Dr. Hélène Lepaumier, Gaspard Bouteau, Dr. Adeline Miquelot, Han Huynh)

Presentation of the Strategic Research and Innovation Agenda and the workshop structure. (Dr. Carina Faber, Prof. Joanna Kargul)

Computational material science as one of the key enabling technologies, with a dedicated ”ask- me anything“ session. (Dr. Simon M.-M. Dubois, Prof. Gian-Marco Rignanese)

Working Group on Photosynthetic Devices. (Led by Dr. Ann Magnuson and Prof. Julio Lloret)

Working Group on Electrochemical Conversion. (Led by Prof. Maximilian Fleischer and Prof. F. Pelayo Garcia de Arquer)