



D3.4 Technological Roadmap



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Abstract	This Report - D3.4 Technological Roadmap - will build an all-agreed roadmap defining activities and milestones across the period 2022-2050 to resolve critical bottlenecks in value chains and reach the overall vision of SUNER-C. It will build on SUNERGY's existing Strategic Research and Innovation Agenda (SRIA). It will describe the critical paths to impact by specifying what will have to be executed in 2, 5 and 10 years.

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Executive summary

The **SUNER-C Technological Roadmap** outlines a strategic framework for advancing solar fuels and chemicals technologies in alignment with the EU's ambitions for industrial sovereignty and climate goals.

Developed through extensive expert consultation and stakeholder collaboration, the roadmap defines milestone-driven pathways (from now to 2050) across four core technological enabler families: **electrochemical, biochemical, photo(electro)chemical, and sustainable CO₂ capture.**

These domains were evaluated using jointly defined technical and sustainability KPIs, which are visualized to track maturity progression over time.

The roadmap presents technologies based on the projected effort required by 2035, demonstrating that early investments in R&D, skills development, and system integration can significantly reduce future effort.

It highlights the importance of focusing on the development of complete, fully integrated technology packages at scale, capable of supplying products at commercial specifications to the market by 2035. By doing so, the transition can be eased and industrial readiness significantly enhanced by 2050—thanks to a higher quality of industrial return on experience.

SUNER-C's approach emphasizes **inclusion, co-creation, and continuous iteration.** By providing clear guidance, it empowers policymakers, industry leaders, and researchers to make informed, forward-looking decisions. The roadmap is not static—it is a **living strategy** designed to accelerate Europe's transition toward a **climate-neutral, competitive, and technologically sovereign** energy and chemical economy.

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List of abbreviations

Abbreviations used:	
BoP	Balance-of-plant
CSA	Coordination and Support Action
C&D	Communication and Dissemination
D	Deliverable
H2020	Horizon 2020
IAB	International Advisory Board
IEA	International Energy Agency
KPIs	Key Performance Indicators
LSRI	Large-Scale Research and Innovation Initiative
MI	Mission Innovation
NGOs	Non-profit Organizations
RTOs	Research and Technology Organizations
R&D	Research and Development
R&I	Research and Innovation
SMEs	Small and Medium-Sized Enterprises
SRIA	Strategic Research and Innovation Agenda
WP	Work Package

1 Introduction

The European Union is steadily shifting away from fossil fuels. Due to the past depletion of its own fossil resources, 58% of its overall energy was imported in 2023. These imports are critical for maintaining a competitive industry and living standards but endanger the sovereignty of the member states, as dependence can be used as political leverage.

At the same time, the European Union needs to de-fossilize its industries to mitigate the adverse effects of climate change. This presents an opportunity for the EU to achieve a worldwide absolute advantage in solar-to-carbon-neutral fuel and base chemical industries by using renewables and abundant molecules (CO₂, water, nitrogen), along with its competencies. To match its ambition, the EU has strengthened the regulatory framework with the European Green Deal, Clean Industrial Deal, FuelEU Maritime Regulation, and ReFuelEU Aviation Regulation, supported by funding from the Innovation Fund and Horizon Europe. The remaining step is to translate these regulations and ambitions into investment, technology, and business model implementation.

Since 2020, the Sunergy initiative has gathered European research institutions, industries, and policymakers to provide guidance and facilitate the implementation of solar-to-fuel and chemical conversion technologies. This initiative aims to achieve EU ambitions with a credible and consensual roadmap, featuring clear timelines and milestones.

This report follows the International Energy Agency's¹ recommendations and will cover the reasons motivating this exercise, present the scope, outline the methodology framework, showcase the actual activities implemented to achieve results, and highlight the results and discussions.

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.

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

2.1. 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.²

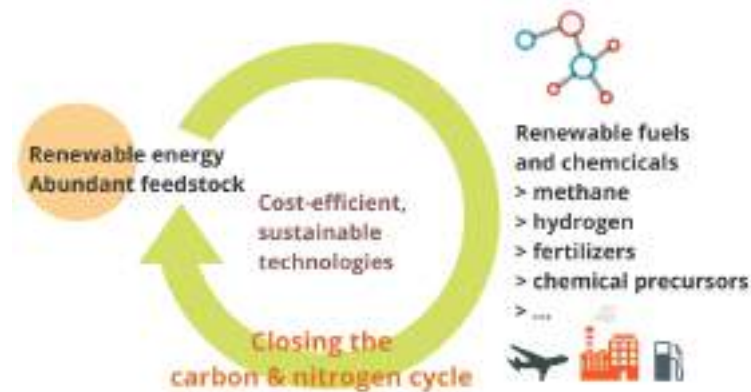


² University of Cambridge, Roadmapping for strategy and innovation;

2.2. Why a technological roadmap?

2.2.1. 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 CO₂

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.**



2.2.2. 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,³ such as SUNERGY, and this aspect has to be taken carefully into consideration when developing the scope and purpose of the roadmap.

2.3. Deduced goal and added value



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

³ 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.

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.
- Convivial conferences are of utmost importance to get to know each other and to exchange openly.⁴ 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.

⁴ 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.

3 Roadmap Scope

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

3.1. 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.

3.2. What is the timeframe for the road mapping 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.

3.3. Which energy sources and end-users sector 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. CO₂), 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** that 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 CO₂) and where electrification or substitution by H₂ 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.

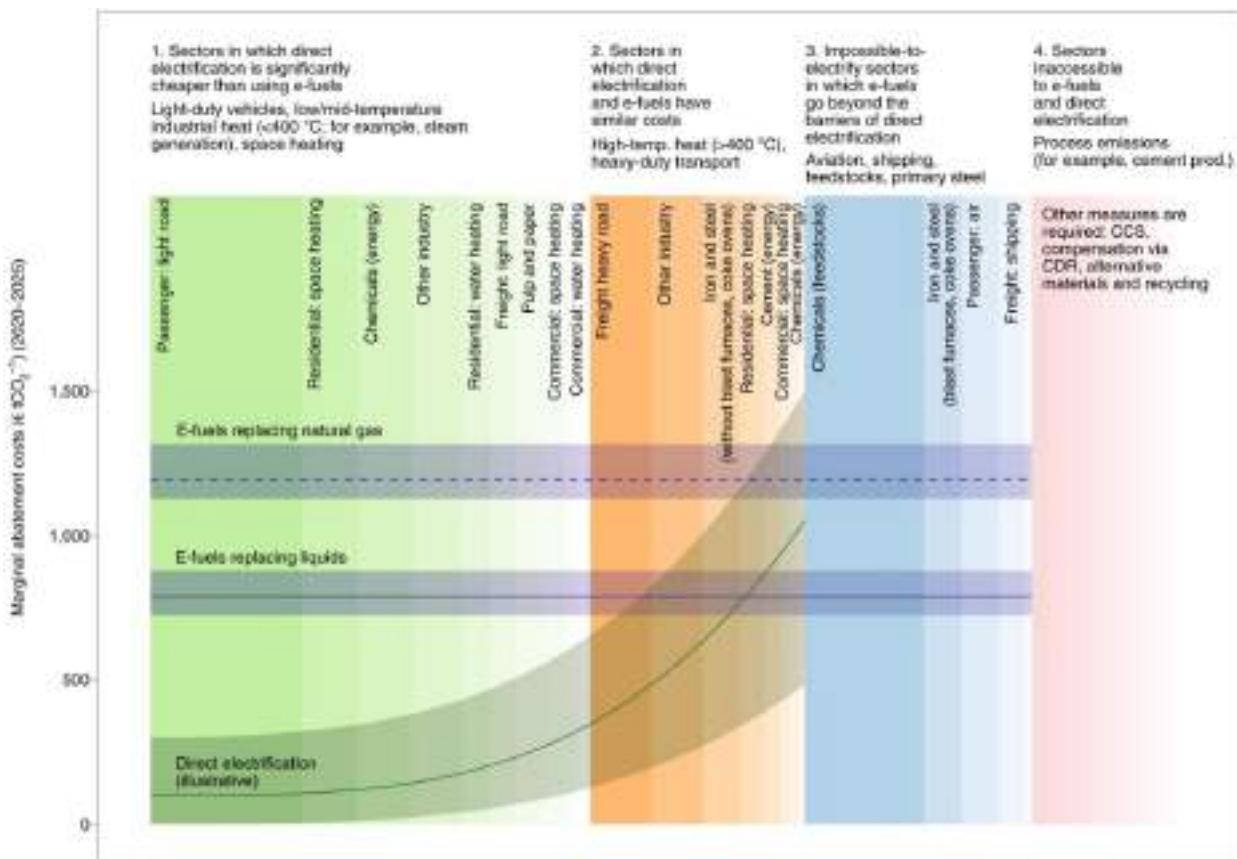


Figure: Costs of directly electrifying different energy end uses (sorting on y-axis from low to high costs of direct electrification), resulting into four categories: 1) Direct electrification is cheaper, 2) Direct electrification and efuels show similar costs, 3) Impossible-to-electrify sectors and 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>

3.4. Which technology areas or classes will the roadmap consider?

3.4.1. Two main technological approaches: one is matured, centralized, but need continuous improvement while the other is emerging, bio-inspired, intensified and decentralized

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 CO₂ 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.

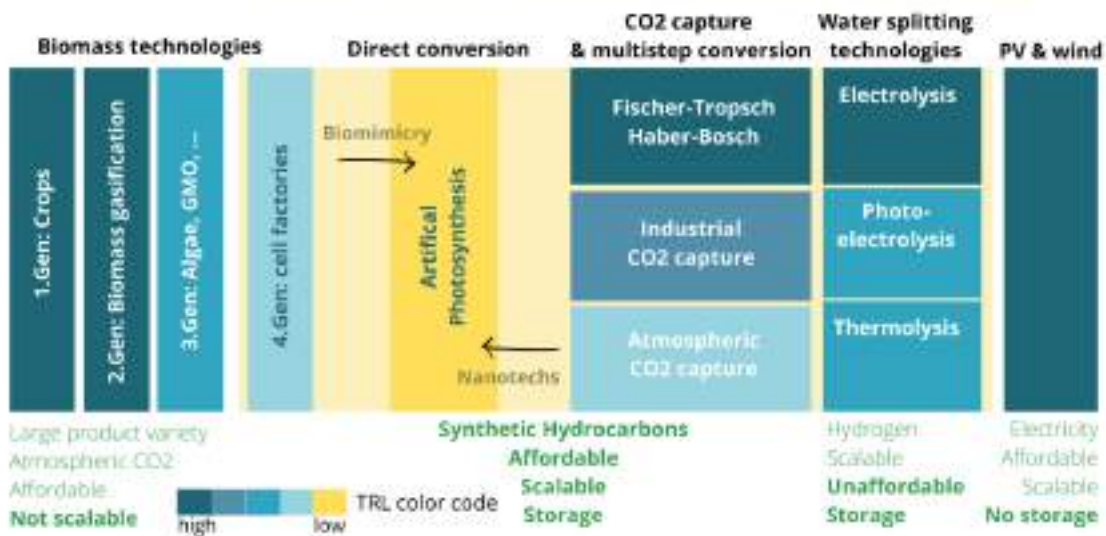
The second approach takes **inspiration from nature**, where - through the process of **artificial photosynthesis** - solar energy, water and carbon dioxide are directly transformed into chemical energy in the form of carbon-based compounds. This is a promising approach for a future decentralized energy 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.

3.4.2. 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,⁵ 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. 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.

The energy conundrum

SUNERGY's overall vision is an affordable, sustainable and scalable technology.

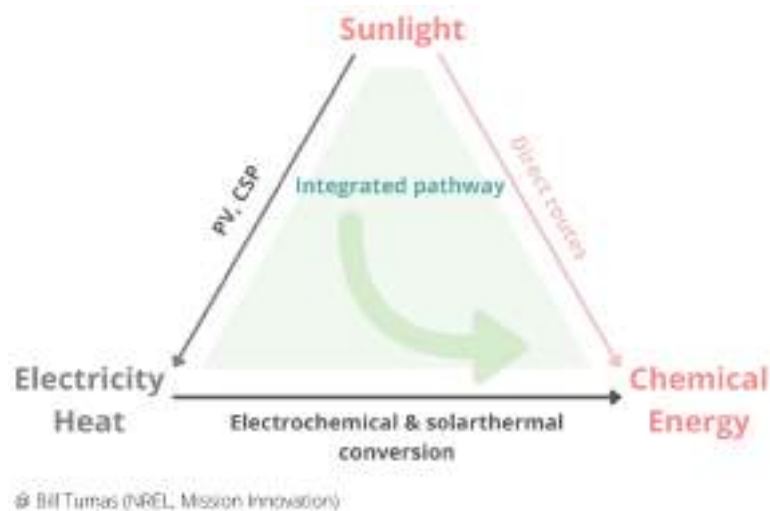


⁵ adapted from G.J. Kramer, Utrecht University;

3.4.3. 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.

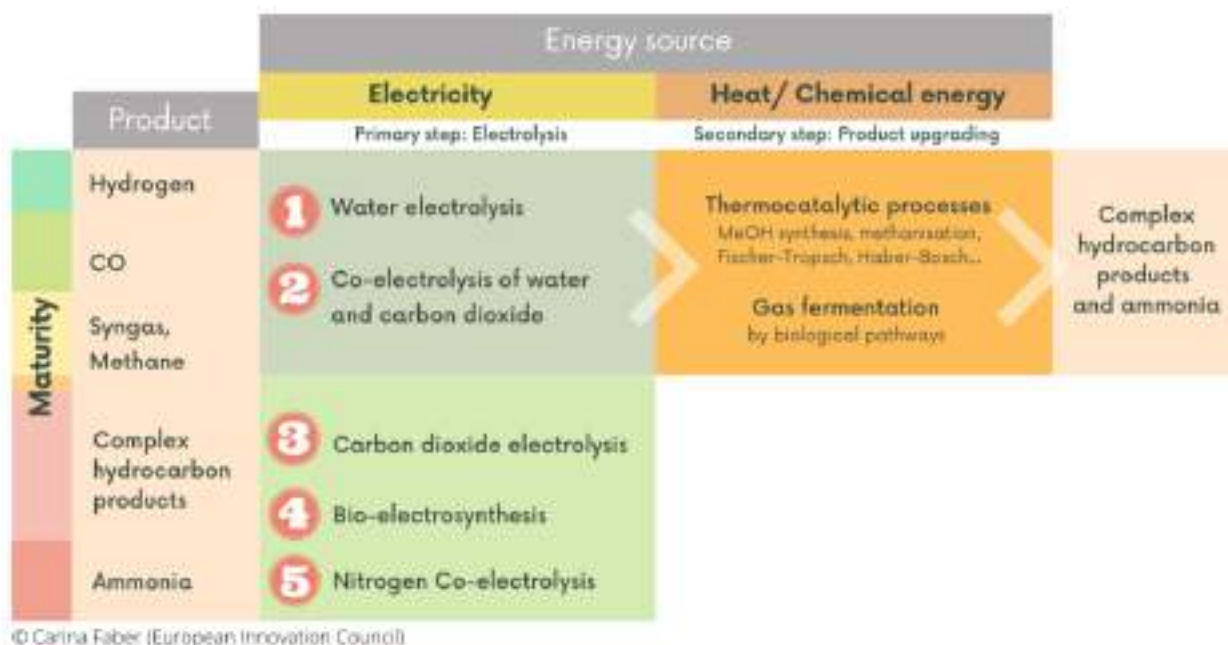
The approach taken here is based on the declared overarching goal: to store solar energy directly in the form of chemical bonds - at scale, on a time horizon from now to 2050. This automatically includes all direct conversion approaches (purple pathway in the below figure). Moreover, mature multi-step 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.



3.4.4. 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 utilization 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 processes⁶, or directly through electrochemical CO₂ reduction. In the latter case, technologies are usually less mature.



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.

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.

⁶ Gas fermentation is a process in which microorganisms can fix CO₂ if sources of reducing power and metabolic energy are available. Hydrogen or CO are energy-rich electron carriers that can drive CO₂ 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 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.

3.4.5. 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 CO₂ into **hydrogen and syngas** in specific materials (so-called RedOx materials). Solar-driven thermochemical water- or CO₂-splitting cycles can produce H₂ or carbon monoxide with very low greenhouse gas emissions.⁷ 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 CO₂ 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 (CO₂, N₂, H-source (CH₄, H₂)) 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 CO₂ conversion, different molecules (syngas, NH₃, C1-C5, oxygenates) can be produced, but research is still needed to increase the selectivity, energy efficiency⁸ and conversion.

3.4.6. 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

⁷ [Converting-Sunlight-into-Solar-Fuels-and-Chemicals-MI-Challenge5-Roadmap](#)

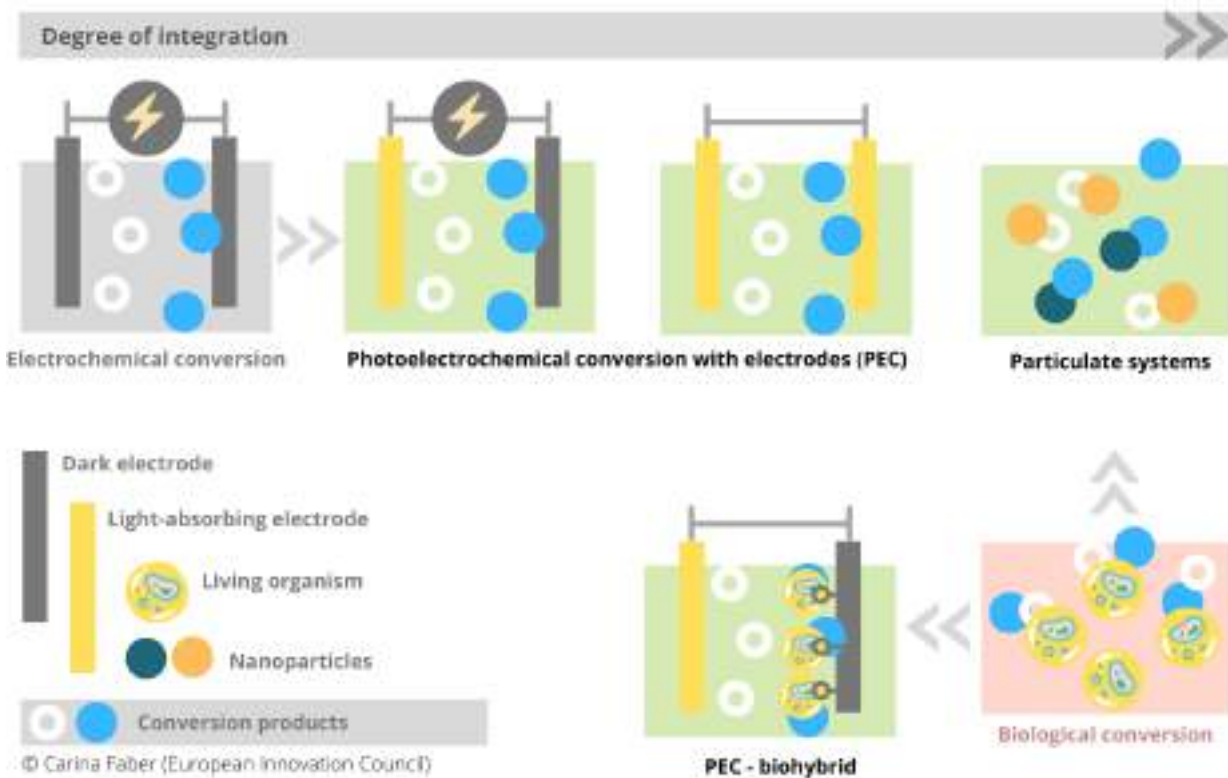
⁸ This requires introducing a definition of the energy efficiency which allows a direct comparison to Solar-to-X technologies.

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.⁹

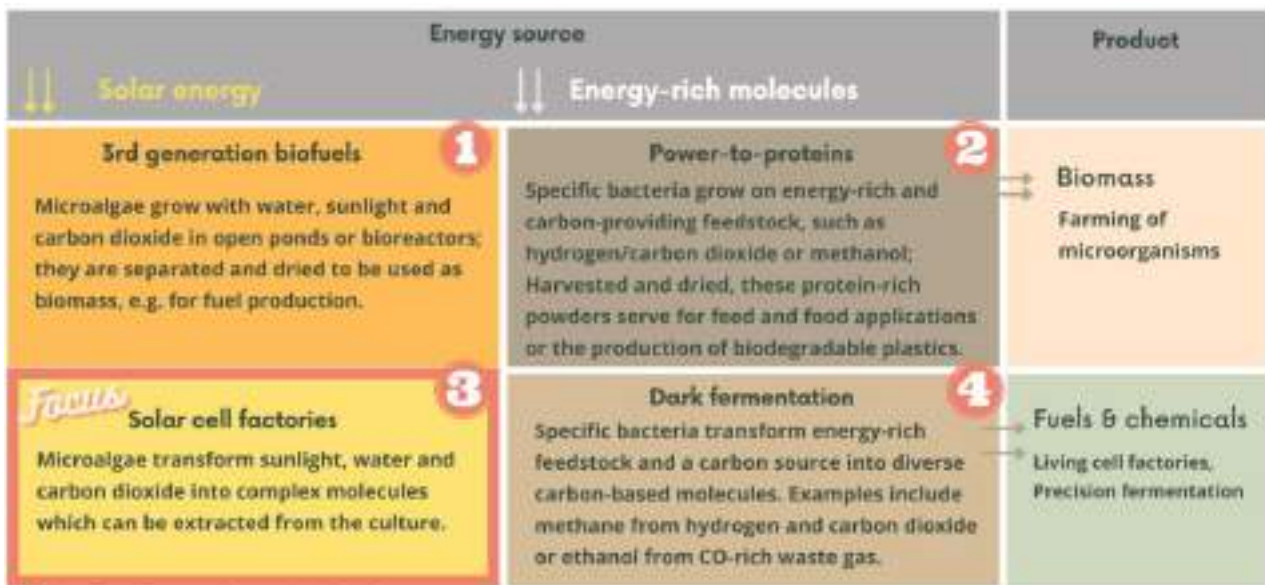
A fundamental distinction exists between photocatalysis and photo(electro)chemical conversion: photoelectrochemical conversion uses solar energy to drive energetically uphill reactions, while photocatalysis speeds up downhill processes. This means that photo(electro)chemistry is an important approach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

⁹ Achieving desired KPIs of Solar-to-X conversion likely will require step-changes in light-absorption efficiencies and ensuing photocatalytic conversion. This stresses the need to support fundamental (low-TRL) research in addition to advancing and scaling up currently known processes and technologies. Following areas of fundamental research appears to be most promising: (i) new/emerging aspects of light-matter interaction ("photon management"), and (ii) light-driven charge separation ("charge management"). Addressing these aspects will require investigating and utilizing phenomena such as plasmonics, polaritons, polarons, photon up- and down-conversion, (nano)structuring of photoelectrode surfaces and photocatalytic interfaces, photophysics and photochemistry of molecular catalysts encompassing earth-abundant metals, acceleration of photoinduced charge separation, as well as developing new materials and molecular systems that can effectively implement them. Most promising light absorbing/converting mechanisms and materials likely still await discovery.



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:



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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 H₂ 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 (CO₂ or organic carbon compounds) and synthesize 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 H₂ (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.¹⁰

3.4.7. Sustainable CO₂ 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 CO₂ from flue gasses. CO₂ capture technology based on chemical absorption (TRL 7-9, depending on the CO₂ concentration) is today the most mature process yet still could benefit from further improvements such as energy consumption per tonne of CO₂ captured, stability of the amine solvents used and efficient solvent regeneration.¹¹ However, alternative technologies, e.g. physical adsorption (TRL 7-9, depending on the CO₂ concentration), membrane separation (TRL 4-9, depending on the CO₂ concentration), calcium looping (TRL 7) and cryogenic separation (TRL 5-9, depending on the CO₂ 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: CO₂ extraction from seawater is based on seawater acidification followed by CO₂ stripping. Acidification is typically achieved thanks to an electrochemical

¹⁰ [IEA]: <https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane>

¹¹ An example is the use of monoethanolamine to capture CO₂ at a scale of 60 kton/year from the waste to energy flue gas at AVR (Duiven, the Netherlands).

process. Two main technologies have been tested so far: bipolar membrane electro dialysis and ion-exchange membranes. Current TRL is 4.¹²

Direct capture and conversion is a not mature, but highly promising pathway to integrate CO₂ 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 CO₂ solution. Such an approach can also be applied to capturing atmospheric CO₂ and directly converting it, the main issue being the presence of O₂ present in the air and remaining trapped at significant concentration in the captured CO₂ solution.

Pre-combustion capture refers to the separation of CO₂ from hydrogen, before its combustion or utilization. An example is the production of blue hydrogen via steam methane reforming.

Next to these main CO₂ removal processes, other possibilities can occur depending on the specific industrial process. Examples are **indirect calcination** during the production of cement (Calix's technology¹³) or the **oxyfuel¹⁴ combustion process** (TRL 6-7, depending on the fuel feedstock) using pure oxygen instead of air.

Certain CO₂ capture technologies are already quite mature and their further development and optimization is driven by industry. Since CO₂ is a crucial feedstock molecule in SUNERGY, there is a strong need to align CO₂ capture and CO₂ conversion technology roadmaps. **The scales and localization of CO₂ provision have to be matched with CO₂ 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 CO₂.¹⁵ 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

¹² 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/>).

¹³ Development for cement industry: indirect heating of the limestone in the calciner in an enveloping vessel, allowing pure CO₂ release from the limestone calcination.

¹⁴ *i.e.* combustion with pure oxygen or oxygen-enriched air; The separation of the produced CO₂/steam mixture can be done by cooling. Oxyfuel capture is shifting the energy-intensive stage from CO₂ separation to oxygen separation; opportunities may arise when O₂ is available as a by-product from water electrolysis.

¹⁵ Drechsler C. and D.W. Agar, 2020. Intensified integrated direct air capture -power-to-gas process based on H₂O and CO₂ from ambient air. *Applied Energy*, 273, 1150763;

4 Methodology: how the roadmap was created?

4.1. 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).¹⁷

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.



¹⁷ 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 groups (Electrochemical conversion, thermochemical conversion, photosynthetic devices, biological conversion and CO₂ capture), social acceptability and the importance of future business models have been discussed.

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**.



4.2. Definition of KPIs by involvement of key technological experts

To develop a roadmap, SUNERGY needed to establish a common language among research institutions, academics, industry professionals, and policymakers, as they have different perspectives and jargon. Moreover, creating a roadmap involves technology benchmarks, which can be tricky due to varying levels of maturity. Technological improvements can be beneficial at early stages, so it is crucial for the community to assess potential challenges and benefits as soon as possible.

A purely analytical assessment, typically involving life cycle cost analysis and life cycle analysis, is complex because it requires extensive experimental data, which is sometimes unavailable, and consistent boundary limits that are not defined at early stages. **Therefore, the road mapping process relies on the expertise of leaders in the field, engaging experts equally**



from academia, industry, and policy. The end goal is to achieve a semi-qualitative quantification of the order of magnitude for each key parameter indicator.

The key performance indicators (KPIs) should be specific, measurable, achievable, relevant, and time-bound. Additionally, due to differences in maturity, **boundary limits should be clearly defined**. A generally advocated boundary is the exemption of carbon capture and conditioning, electricity production (black box approach), and the inclusion of product separation and upgrading to reach final products at commercial specifications defined by end users, such as grade AA for maritime applications (no black box approach).

Within the SUNERGY community, we differentiate between two categories of KPIs. On one hand, there are "**technical KPIs**" measured in the lab, and on the other hand, there are "**sustainability KPIs**" relevant for industrial deployment and upscaling, considering the overall sustainability of the developed technologies¹⁸.

In other words, "**technical KPIs**" refer to the **design values** of a unit—such as surface area, power consumption, selectivity, or conversion rate. These are typically defined by technology licensors and academics, and can vary significantly between different technology families.

On the other hand, "**sustainability KPIs**" are also defined by technology licensors but are intended for policy makers and industrial project developers to support large-scale, real-world implementation. These KPIs mainly reflect the challenges of integrating new technologies into existing production systems, as well as compliance with environmental regulations, and EU sovereignty. We have decided to cover this KPIs:

1. **Water sourcing** should ensure that the technology minimizes the use of high-quality (pure) water, which may conflict with primary uses such as drinking water supply and agriculture. The greater the use of secondary or lower-quality water sources—such as treated wastewater or seawater—the better. This approach supports compliance with Directive 2000/60/EC, the EU Circular Economy Action Plan, Directive (EU) 2020/741, and the Environmental Impact Assessment Directive 2011/92/EU (as amended by 2014/52/EU).
2. **Integration** is key to ensuring that the balance of plant (steam, cooling, electricity for rotary machines, etc.) is minimized and primarily electrified to avoid reliance on fossil fuels. The smaller the balance of plant, the easier it is to integrate into existing production systems and to implement in new builds, facilitating investment decision for industrial

¹⁸ Technology developers use technical KPIs related to physical parameters they can measure on their lab bench, pilot, or demonstration unit. Meanwhile, industrial and policy stakeholders use KPIs related to mass and energy balance, which they integrate into techno-economic analysis and life cycle analysis to inform their investment decisions or strategies.



3. **Chemicals** Understanding the chemicals used in the technology—such as solvents, electrolytes, or nutrients—and whether they depend on fossil fuel production is essential. The fewer chemicals used, the better.
4. **Critical Raw Materials (CRM)** are essential for de-fossilization and are currently being addressed through the European Union’s Critical Raw Materials Act. This policy aims to reduce dependency on third countries (such as China and Russia), strengthen the European value chain, promote a circular economy, and ensure strategic autonomy. These efforts support the EU's Green Deal, the goal of climate neutrality by 2050, the digital transition, and resilience against geopolitical shocks.



Strategic critical raw material are indicated in yellow¹⁹

The less technology use critical raw material via design, recycling the better the technology could achieve de-fossilization and sovereignty target.

5. **Platinum Group Metals (PGMs)**, including platinum, palladium, iridium, ruthenium, and rhodium, are critical raw materials that are generally irreplaceable in catalytic converters for vehicles, renewable hydrogen production, electronics, and the chemical industry. PGMs are included in several European frameworks, such as the Critical Raw Materials Act. In general, the less a technology relies on PGMs, the better, due to their scarcity and high cost.
6. **Per- and polyfluoroalkyl substances (PFAS)**, commonly known as 'forever chemicals,' can accumulate in ecosystems and pose potential risks to human health. Their use is addressed under the REACH Restriction Proposal (2023). Some de-fossilization technologies should aim to limit or avoid the use of PFAS in their sub-components

¹⁹ <https://www.consilium.europa.eu/en/infographics/critical-raw-materials/#0>



These **technical KPIs** should be evaluated on a scale from 1 (low performing) to 5 (high performing). More specifically, a score of 0-2 indicates that basic research is still needed to advance the technology, and the fundamental mechanisms to operate the technology are not yet fully understood. A score of 3 means that the technology works at lab scale, the basic mechanisms are understood and integrated into modelling, but continuous improvement and scaling up are required. Scores of 4-5 indicate that the technology is ready for industrial demonstration and deployment with industry-relevant performance.

These **technical KPIs should be evaluated on the same scale scoring as technical between 1 to 5**. The scoring is more related to improve the sustainability and the supply chain resilience of the technologies, with an emphasis on European sovereignty not at risks . In details the scoring is explained further for each sustainable KPIs:

1. **Water sourcing:** Technology uses pure water **1**, Technology uses wastewater **5**
2. **Integration:** Technology uses only electricity **1**, Technology uses steam, electricity, cooling **5**
3. **Chemicals:** Technology uses fossil based solvent, nutrient **1**, Technology uses no chemical **5**
4. **Critical raw materials (CRM):** Technology uses CRM ($\sim 100 \text{ mg/m}^2$) **1**, Technology uses no CRM **5**
5. **Platinum group metals** Technology uses PGM ($\sim 100 \text{ mg/m}^2$) **1**, Technology uses no PGM **5**
6. **Per- and polyfluoroalkyl substances (PFAS)** Technology uses no PFAS **5**, Technology PFAS ($\sim 100 \text{ mg/m}^2$) **1**

These KPIs were initially defined through specific interviews with key experts for each technology. They were then reviewed by the community through email exchanges and workshops within technological communities. Finally, the consensus KPIs list was validated and checked during the last workshop held on March 26-27, 2025, at IEC SUNERGY.

4.3. State of the art for each technology to have the present pictures by consultation with key technological experts

With the KPIs list defined, a common language has been established between industry, academia, research institutions, and policymakers within the SUNERGY communities. We are therefore ready to define the starting point for each technology, in other words, their state-of-the-art. The state-of-the-art refers to the highest level of development currently achieved for a technology.

It was defined by key experts for each technology via interviews and email exchanges. The definitions were then reviewed by the community through email exchanges and workshops within technological communities. Finally, the state-of-the-art was verified during the CCU/Solar-to-X event in Energy Ville in May 2024.





The state of art for each technology was consigned in the following documents.

- Appendix 1 – Worksheet: Electrochemical conversion
- Appendix 2 – Worksheet: Sustainable CO₂ capture
- Appendix 3 – Worksheet: Photosynthetic devices
- Appendix 4 – Worksheet: Biological conversion

For more details refer to appendix 5 – Workshop May 2024 picture

It was critical to define the stepping stone before the final workshop, which aims to outline the future and expected progress.

4.4. Technological future growth and potential appraised through communities workshop

With the KPIs and state-of-the-art knowledge already established, the SUNERGY roadmap required a forward-looking perspective on the anticipated progress and future development of each technological domain. As this is a prospective and strategic foresight exercise, it was recognized that consensus among experts would provide the most realistic and credible outlook on what might happen within each technological pathway. To gather this collective intelligence, dedicated workshops were organized during the SUNERGY IEC event held on March 26–27, 2025.

These sessions were designed to explore the future outlook of key technologies, aligned with the broader decarbonization targets of the European Union. The selected time horizons for the roadmap were 2025 (current status), 2035 (medium-term outlook), and 2050 (long-term outlook), consistent with the EU's commitment to climate neutrality and sector-specific carbon reduction trajectories.

The workshop was divided into four parallel sessions, each focusing on a major technological family: Electrochemical (led by IMEC), Sustainable CO₂ Capture (led by Engie), Photochemical (led jointly by IEC and Siemens), and Biochemical (led by University of Warsaw). This structure ensured focused discussion and expert-led facilitation within each domain.

Before the breakout sessions, a plenary session was held to explain the objectives and methodology of the roadmap exercise—the “why” and “how” behind the prospective analysis. During each workshop, participants were provided with a worksheet containing the list of KPIs and a summary of the current state-of-the-art for the technology in question. After a round of introductions, the workshop leader gave a brief overview of the technological status and reviewed the KPIs with the participants to confirm their accuracy and relevance.

Participants were then invited to select a technology aligned with their expertise and to propose three SMART KPIs (Specific, Measurable, Achievable, Relevant, and Time-bound) that would





guide the development of the technology. In addition, they were encouraged to articulate a vision for the technology's future and to describe, as qualitatively as possible, the key steps, enabling conditions, and critical milestones needed to achieve their vision. To support this process, a timeline template was provided, allowing participants to structure their inputs across the three defined timeframes—2025, 2035, and 2050. An example is given hereunder:

Technology: Alkaline electrolysis			Product: Hydrogen		
KPI	NOW	2030	2035	2050 - Vision	Level
PGM	Ir content 5mg/cm ²	Ir content 1mg/cm ²	Ir content 0.5 mg/cm ²	No Ir	What?
	Novel catalyst development, Reducing load	New catalyst formulation achieved at lab scale	New catalyst formulation achieved at pilot scale, optimized electrode design for loading		How?

Each participant had the opportunity to present their proposed KPIs, visions, and the steps needed to achieve them to the rest of the group. This exchange fostered open discussion, encouraged collective understanding, and stimulated brainstorming around both current technological challenges and effective strategies to overcome them. The collaborative nature of the workshop allowed for the identification of common bottlenecks, as well as the exploration of synergies between different technological pathways. This participatory approach ensured that the roadmap would reflect not only individual expert insight but also shared priorities and actionable strategies for advancing towards the 2035 and 2050 targets.

For more details refer to appendix 5 - Workshop March 26-27, 2025 picture

4.5. Data visualization

From the workshop, we gathered feedback and observed the evolution of key performance indicators (KPIs). We used spider charts to visualize the technical and sustainability KPIs outlined in Section 4.2.

As a reminder, these graphs represent semi-qualitative consensus levels for each KPI. Each spider chart shows three areas corresponding to different time horizons: the current state (state of the art), 2035, and 2050 (vision). In other word, area showcase absolute effort at a specific time.

To ensure comparability across technologies—since the number of KPIs may vary—we normalized the area of the chart by the number of KPIs present for each technology.





We then defined and calculated an "effort" metric:

- $Relative\ Effort_{2035} = \frac{(Area_{2035} - Area_{now})}{Number\ of\ KPIs}$
- $Relative\ Effort_{2050} = \frac{(Area_{2050} - Area_{2035})}{Number\ of\ KPIs}$

Effort provides a semi-qualitative way to measure the gap between the state of the art and the different milestones.



5 Results and discussion: what strategic vision and plan emerge?

As a reminder, we present the methodology in Section 4. In this section, we will first present the general outlook of the roadmap and the key strategic insights, including the effort required. Then, we will introduce the spider charts used to build the general roadmap for each technological family: Sustainable CO₂ Capture, Electrochemical CO₂ and Nitrogen Conversion, Biological Conversion and Photo(electro)chemical Conversion (Photosynthetic devices).

5.1. Consolidated Technological Roadmap Workshop Key Message

5.1.1. Trends & Drivers

Carbon Capture and Utilization (CCUS) deployment will be pushed by:

- Willingness to decarbonize: part of the solution towards carbon neutrality
- Its recognition as a renewable carbon feedstock
- Sovereignty

A key driver will be the Business Model for carbon capture: capture cost vs revenues. Revenues can be:

- Carbon Tax
- Willingness to pay from e-fuel producers, it might be higher for high value chemicals such as ethylene
- Carbon Removal Credits

Therefore it is key that the CO₂ market expands beyond the current direct utilization market. Regulatory stands out as a key driver as it will create the market and set the incentives.

5.1.2. Enablers, Resources, and Barriers

At this moment, capturing, transforming CO₂ into value added chemicals or storing it is hampered due to

- The cost and availability of renewable energy/hydrogen
- The cost and availability of Transport & Storage infrastructure

Regarding green hydrogen and e-molecules:

- Rapid deployment of renewable energy is currently happening, fostered by technological cost reduction and ambitious goals (REPowerEU). This important renewable energy deployment will call for a stronger role for e-molecule as an efficient option for long-term storage and long-distance transport of renewable energy.



- Main challenge for green hydrogen and derivatives today is the market maturity where green e-molecules have to compete with cheap fossil counterparts. Market penetration will be supported by policy and stakeholders willingness to reach carbon neutrality targets. It is expected that synthetic fuels and chemicals will play a key role starting from 2030-2035, e.g. REFuel EU Aviation Regulation plans a steady increase of synthetic Aviation Fuels complementing biofuels from 2030 and reaching 30% of fuel share by 2050, Maritime is starting to invest in new shipping containers able to operate on e-methanol, e-ammonia, or e-methane...

As far as CO₂ infrastructures are concerned:

- It is expected by 2035 that the deployment of main CO₂ backbones is achieved
- By 2045, it is expected that secondary backbones are developed to connect small scale emitters
- Theoretical storage capacity is 14.000 Gt CO₂ (GCCSI), so theoretically large enough to store all emissions. However only a small fraction is developed commercially today. Potential to develop decentralized storage, via permanent storage in materials such as mineralization, has been mentioned as a way to reduce CCS cost for small scale emitters.

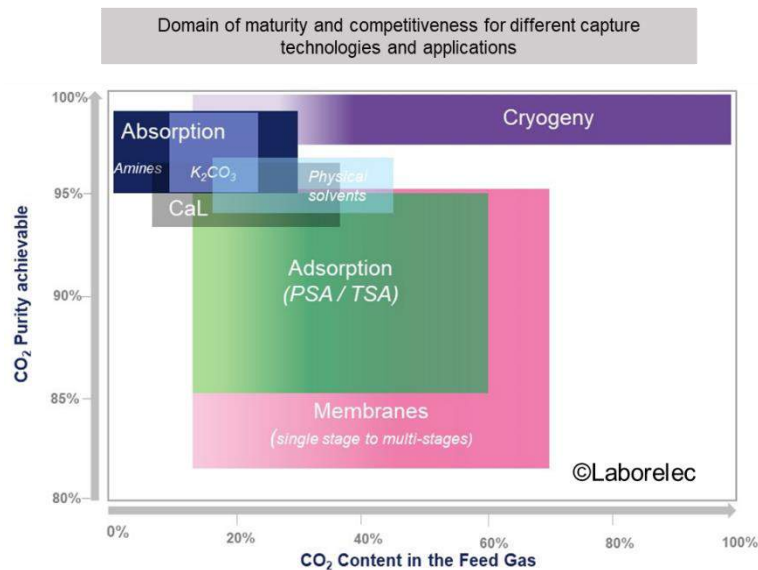
Therefore, it is expected CCU and CCS to reach First-of-a-Kind projects by 2030 and to deploy commercially starting from 2030-2035. However, an attention point is manufacturing capacity which can be an enable but also a barrier.

Finally, societal acceptance can be a barrier as well as policy. It is key to communicate with all stakeholders, to explain what CCU and CCS technologies are about and avoid risk perception.

5.1.3. Sustainable Carbon Capture

Today, post-combustion carbon capture (PCCC) for point source is mature and the dominant technology will depend on the application (type of flue gas and target CO₂ purity) as shown on the figure hereunder. It is expected that those technologies for those domains of applications will be dominant for the next decade. But starting from 2035, we may see the commercialization of disruptive technologies:





- Oxy-combustion carbon capture. Especially, as this capture technology can leverage on the sourcing of fatal oxygen from e-fuel production to reduce capture cost and energy penalty.
- Technologies so far applicable for more concentrated sources such as cryogenic, membrane capture or adsorption are being developed for lower range concentration as they offer different value proposals: modular, no steam required, better HSE properties...

We may see by 2040, a shift of the figure hereunder where the dominant technology can change driven by industrial application preferences: e.g. 15 years ago, carbon capture in Europe was driven by Power Plant Application, this has led to the dominance of amine capture as the preferred solution for large scale application and CO₂ concentration in the flue gas < 15%, especially since steam is readily available in such application. This led to a rapid increase in maturity and optimization of amine capture, which became a reference technology. However, since 2020, carbon capture deployment in Europe is driven by industrial application such as cement industry, this application has enabled other technologies such as adsorption combined with cryogenic capture or oxy-combustion to develop as suddenly, steam supply became a challenge and alternative technologies only relying on electricity were preferred.

Direct Air and Direct Ocean Capture are emerging today and will deploy their First-of-a-Kind projects by 2030 for DAC and 2035 for DOC. They will play a major role starting from 2035-2040 as the demand for biogenic and renewable carbon will increase. Different studies ([Global Availability of Biogenic CO₂ and Implications for Maritime Decarbonization | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping](#), [Assessment of European biogenic CO₂ balance for SAF production](#)) have shown that current and future sources of biogenic CO₂ will not be enough to feed synthetic fuels target, DAC and DOC can be a complementary source of sustainable CO₂.

5.1.4. Carbon Dioxide and Nitrogen Electrochemical Conversion



The carbon dioxide and nitrogen electrochemical conversion community faces significant challenges related to experimental data quality, standardization, modeling, materials, and industrial scalability.

The carbon dioxide and nitrogen electrochemical community is limited by the lack of a shared, large-scale, and reliable material selection for catalysts and cell components. Additionally, scalability issues and high variability in experimental performance measurements make it difficult to achieve consistent results and benchmark different design choices.

To address these issues, the community has advocated for the establishment of dedicated, EU-wide standardized and automated testing facilities—similar to technology centre Mongstad (TCM) for carbon capture. These facilities would enable stakeholders to align around a common agenda and build a shared material performance database using harmonized and standardized testing protocols for electrochemical cells.

Such a harmonized database could also support modeling efforts. While microkinetic models are well-defined, there are significant gaps in mechanical, engineering, and system-level modeling, as well as in the development of digital twins. Moreover, bridges between different modeling scales are currently lacking.

From a sustainability perspective, the community has noted that PFAS membranes are technically feasible but suffer from low market readiness. Catalysts involving critical raw materials are still necessary, but their usage could be reduced through smart electrode design. Furthermore, life cycle analysis (LCA) needs to be broadened to cover the full cradle-to-grave spectrum.

Successful commercialization and industrial deployment of carbon dioxide and nitrogen electrochemical processes will require:

- Early-phase resilient design of cells and catalysts (meaning performance stable over time)
- Involvement of industrial manufacturing partners to provide scalable pathways, as seen in the battery and electronics sectors
- Early-stage business model development targeting high-value molecules, where the market is willing to pay a premium for renewable e-molecules, supported by existing industrial offtakers

5.1.5. Carbon Dioxide Photo(electro)chemical Conversion

The carbon dioxide photo(electro)chemical conversion community has identified several key challenges:





Inconsistency in technology maturity: The wide diversity of technological approaches makes it difficult to define the state of the art and to establish clear performance and sustainability KPIs.

Lack of standardized measurement protocols: The absence of independent and certified testing procedures is a major barrier to objectively evaluating and comparing photoelectrochemical (PEC) systems. Without standardized data reporting, cross-laboratory reproducibility and benchmarking are severely limited—particularly for the following key performance indicators (KPIs):

- **Correct area definition:** Whether total, geometric, or aperture-designated illuminated area is used
- **Faradaic efficiency:** Either calculated by dividing the actual moles of product formed by the theoretical moles based on total charge passed, or by comparing experimentally detected product gas with the theoretically expected amount from current density
- **Solar-to-fuel efficiency**

Standardization and harmonization of half-cell testing (cathode or anode) is also needed to ensure consistent and comparable results across different research efforts.

Once these foundational steps are in place, the photo(electro)chemical CO₂ conversion community could benefit—just as the electrochemical CO₂ and N₂ communities have—from the **establishment of dedicated, EU-wide standardized and automated testing facilities.**

Addressing these challenges through harmonized protocols and shared infrastructure will be essential to accelerate innovation and ensure reliable benchmarking. This will lay the groundwork for scaling up and commercializing photo(electro)chemical CO₂ conversion technologies across Europe.

5.1.6. Carbon Dioxide Biological Conversion

The carbon dioxide biological conversion community has identified several key challenges:

Upscaling and optimizing bioreactor design remains a major bottleneck. Efforts are needed to improve light utilization efficiency, minimize fouling, and significantly reduce the costs of feedstocks for microbial cultivation (e.g., green hydrogen, CO₂, and green methane), as well as water and nutrient usage.

Integration with the balance of plant (BoP) is currently insufficient, particularly with renewable hydrogen electrolyzers, other bioreactors, and product separation systems. Developing pilot projects and robust mechanical designs could help reduce the overall cost of this technology family.





Market strategies should initially focus on high-value, complex products, such as those for the pharmaceutical and cosmetics sectors, where premium pricing can offset high production costs—especially those related to electricity and the current lack of affordable green hydrogen and methane feedstocks.

A circular economy framework is essential to reduce BoP costs through waste stream utilization and to enhance system synergies. This approach would also improve environmental performance and increase social acceptance.

Supportive policy frameworks and infrastructure are critical to making green hydrogen affordable for microbial and hybrid biological processes. Additionally, efficient and harmonized regulations are needed to guide the commercialization of renewable, fossil-neutral biomolecules, particularly those intended for feed or human consumption.

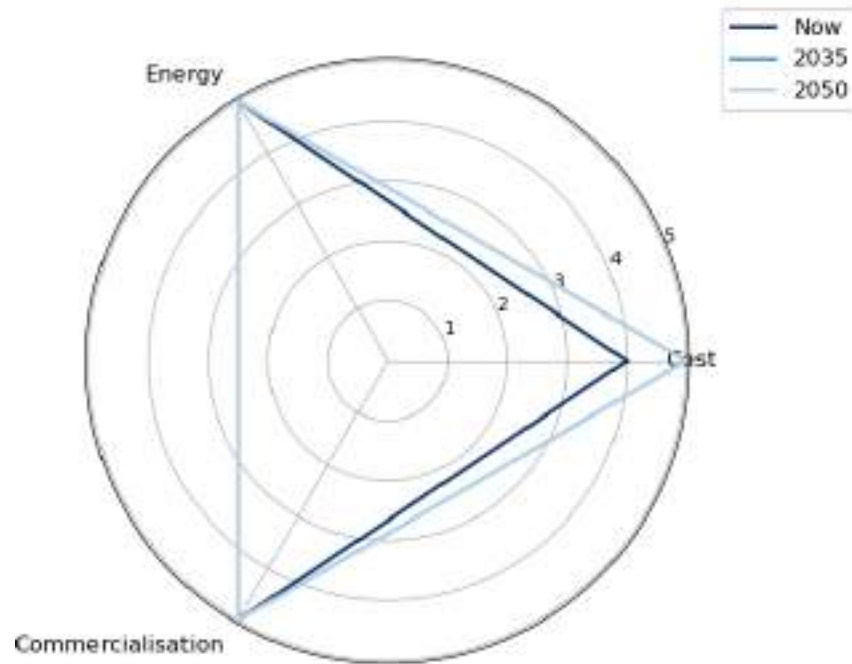
Advancements in synthetic biology toolkits are urgently needed to enable stable metabolic engineering for the production of lipids and other valuable biochemicals. Overcoming these challenges will require coordinated efforts in engineering, policy, and market development. A strategic focus on integration into the full value chains, adhering to circularity for cultivation and product separation, and focusing R&I particularly on high-value products can accelerate the path to commercialization and sustainability.



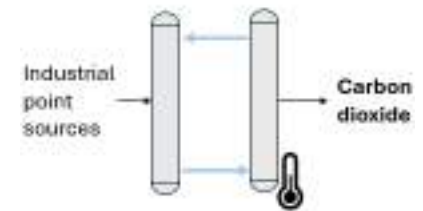
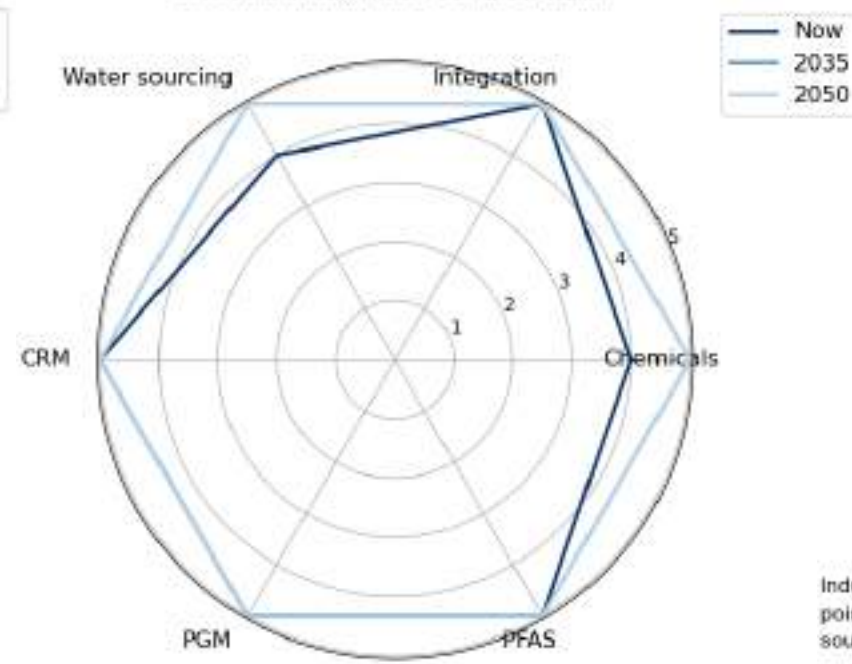
5.2. Sustainable carbon capture in detail

Commercialization refers to the stage at which a technology licensor is capable of deploying its solution at an industrial scale. This indicates that the market is mature, the technology is proven, and the supporting supply chain is resilient. Furthermore, it implies that the commercial offer is sufficiently competitive to support a positive Final Investment Decision (FID).

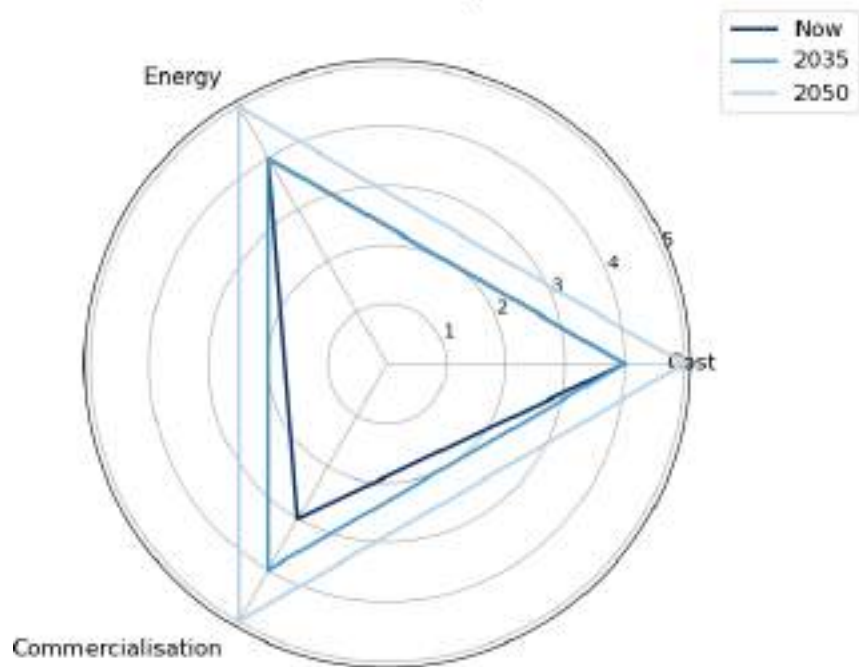
Performance KPIs for Absorption



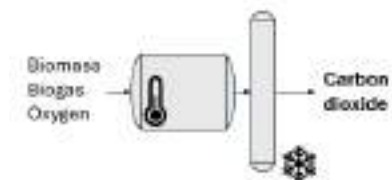
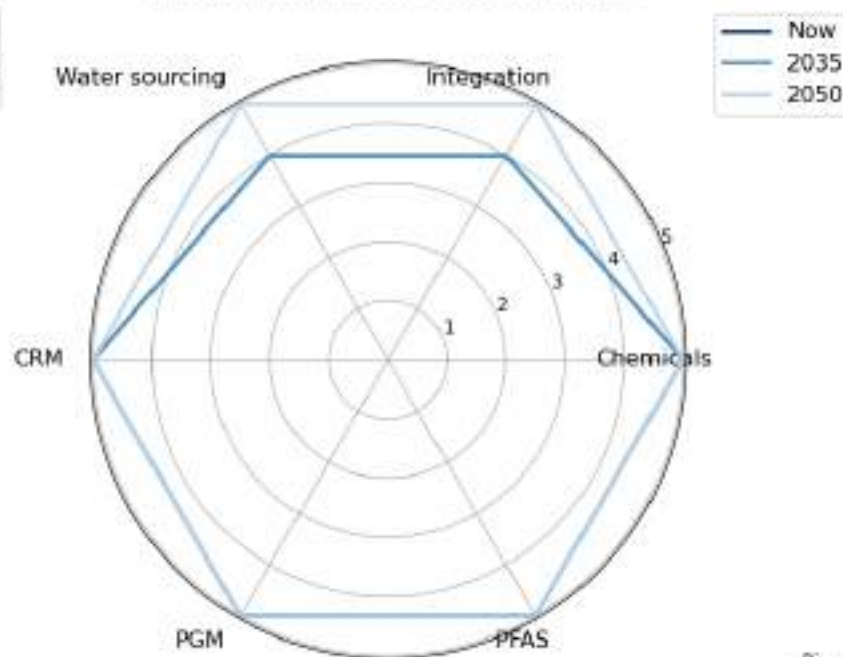
Sustainability KPIs for Absorption



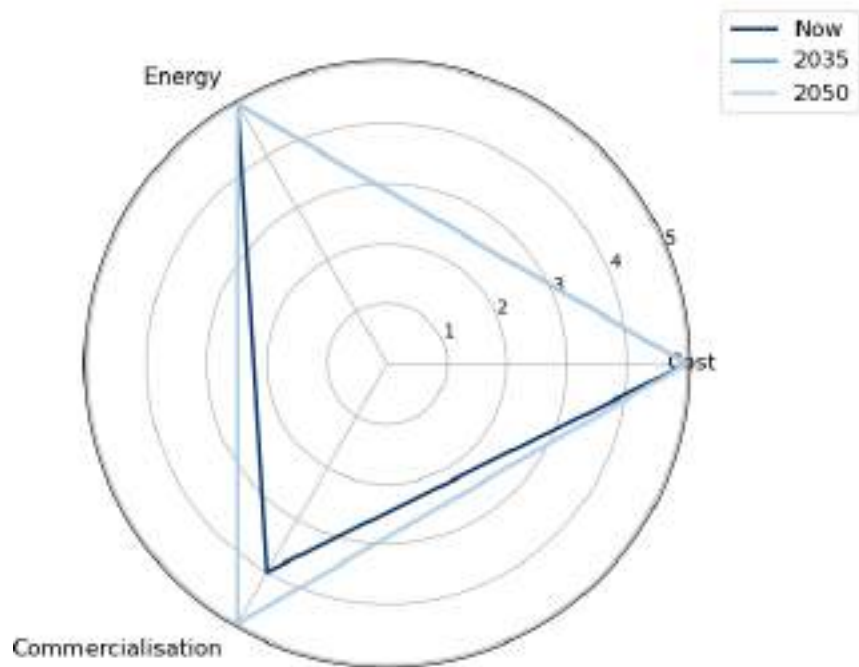
Performance KPIs for Oxycombustion



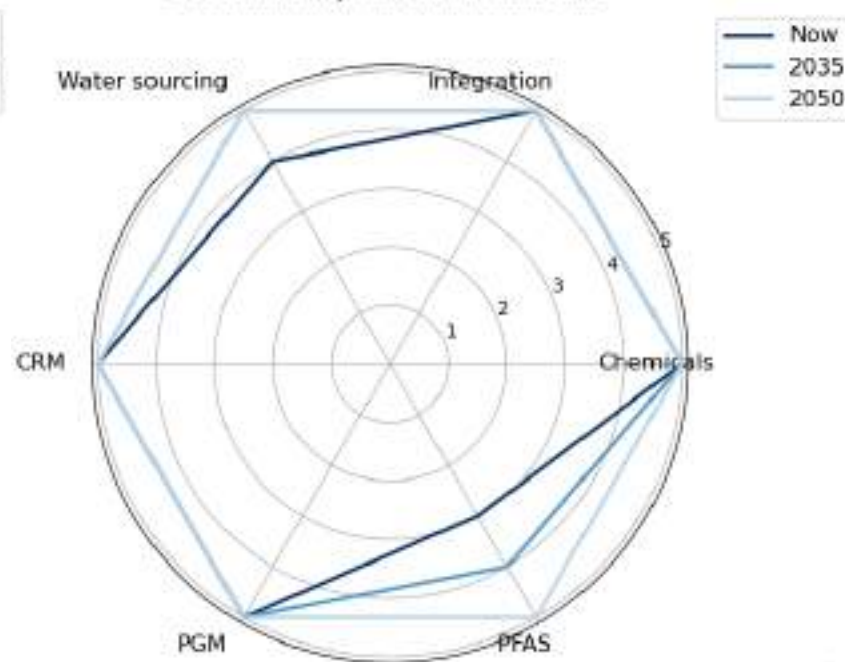
Sustainability KPIs for Oxycombustion



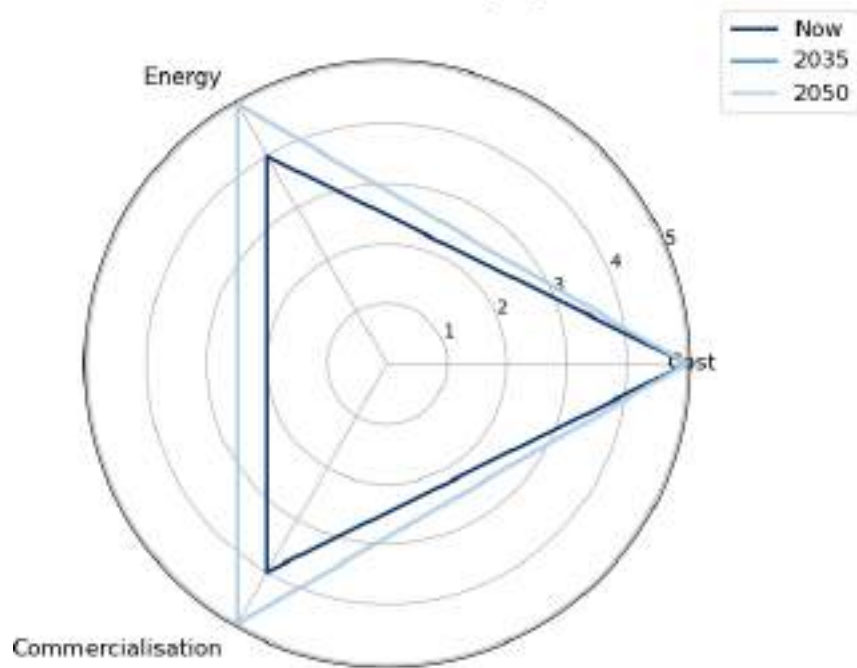
Performance KPIs for Membrane



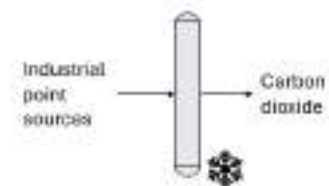
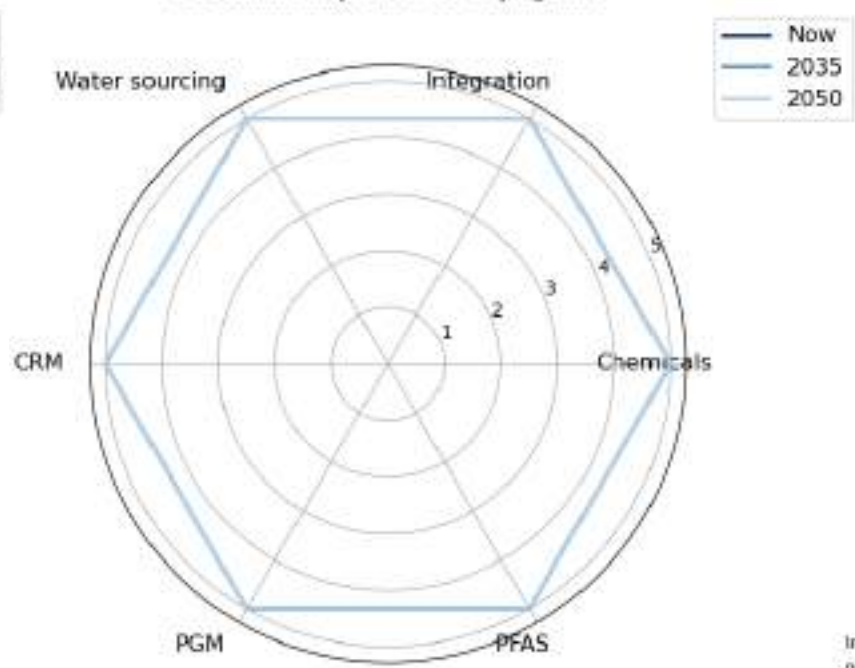
Sustainability KPIs for Membrane



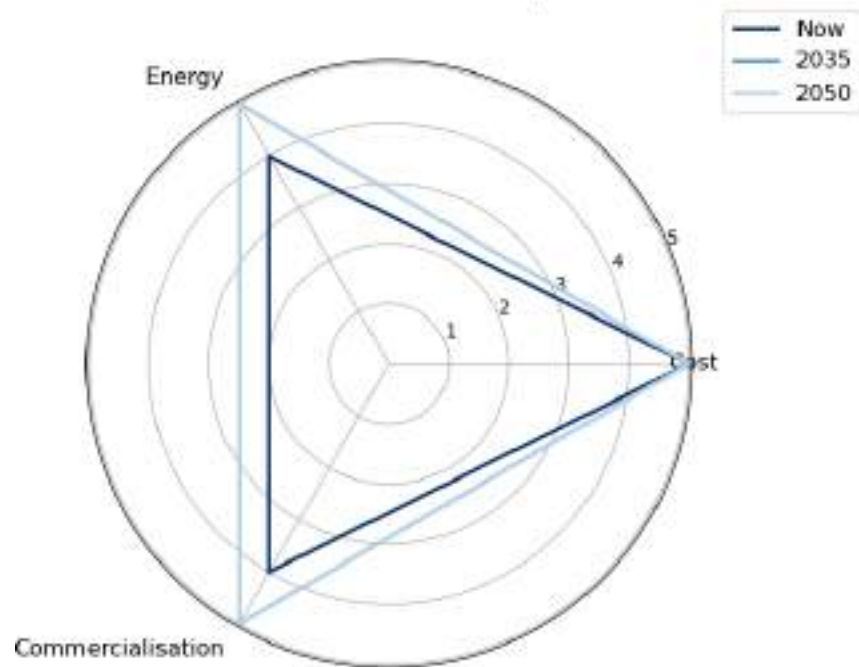
Performance KPIs for Cryogenic



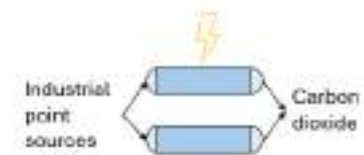
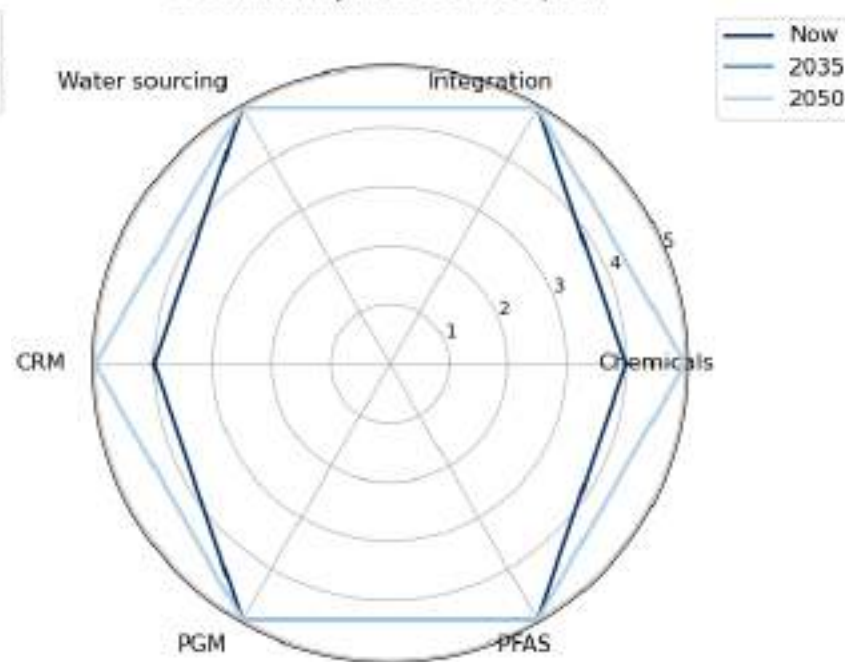
Sustainability KPIs for Cryogenic



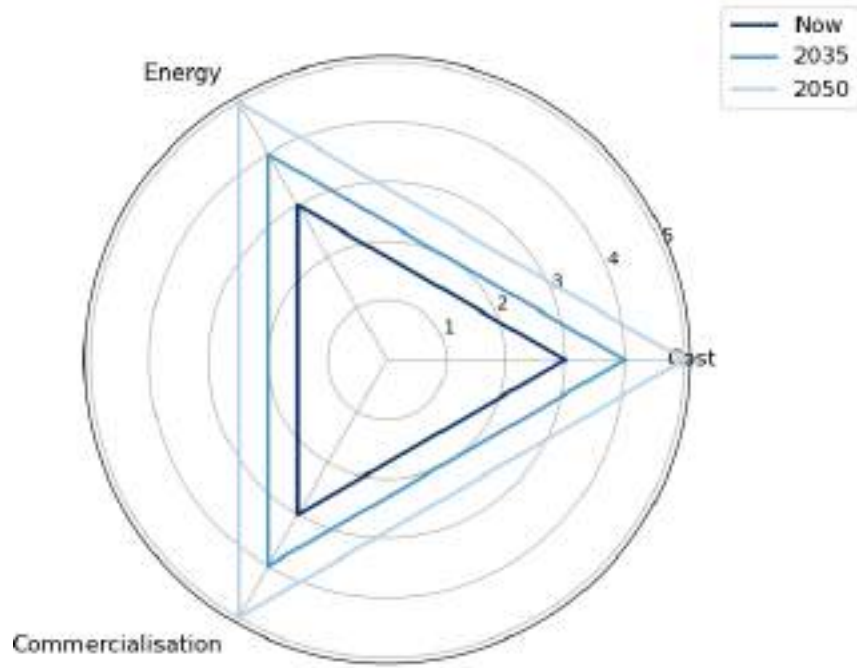
Performance KPIs for Adsorption



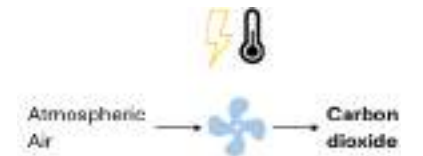
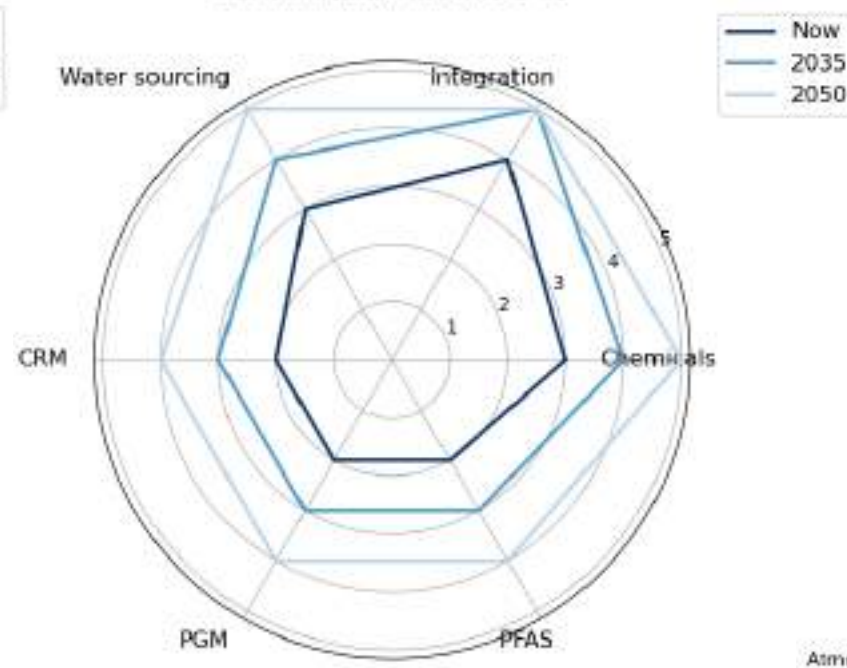
Sustainability KPIs for Adsorption



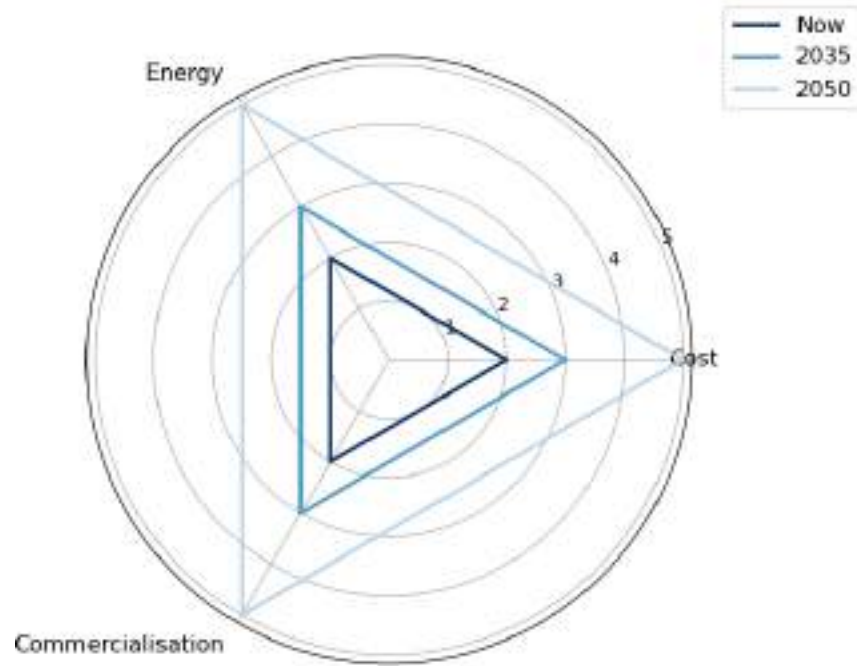
Performance KPIs for DAC



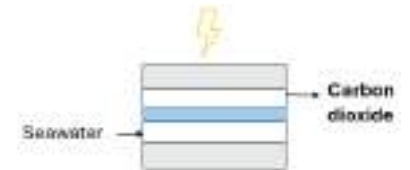
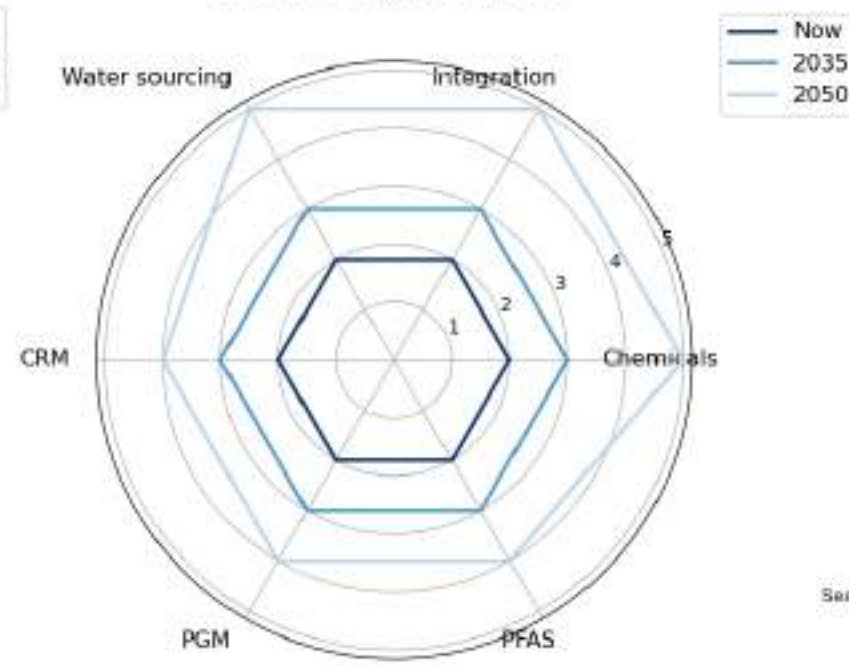
Sustainability KPIs for DAC



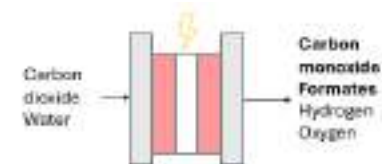
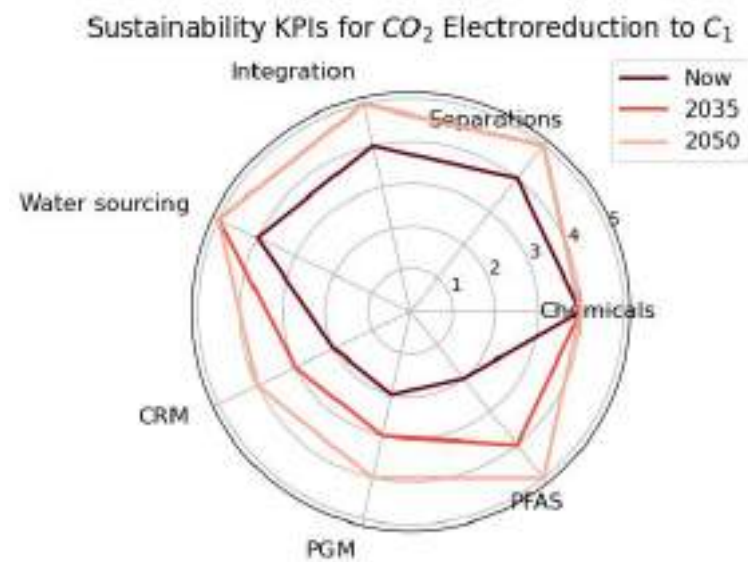
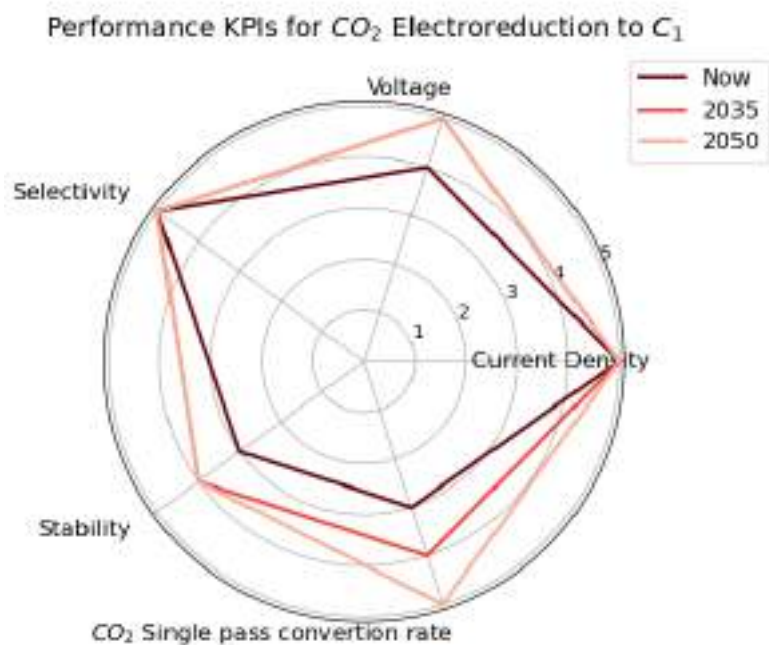
Performance KPIs for DOC



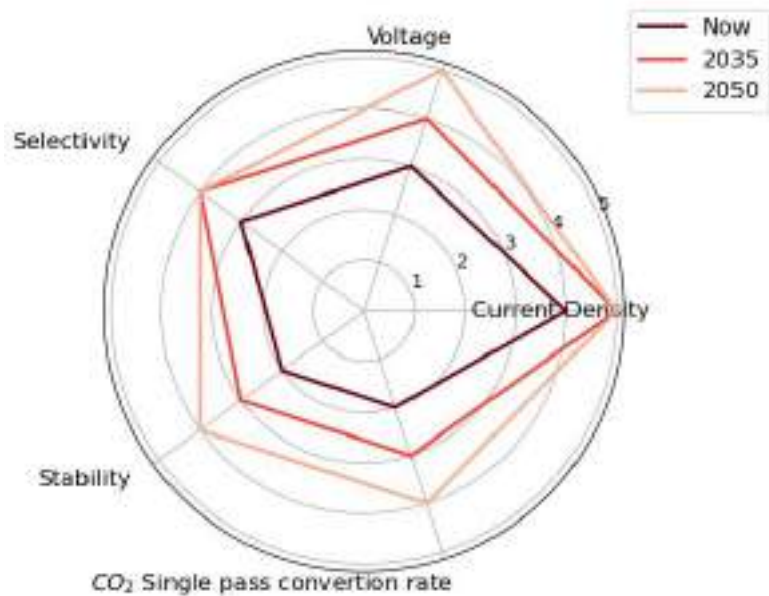
Sustainability KPIs for DOC



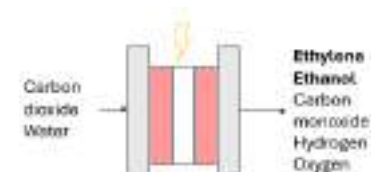
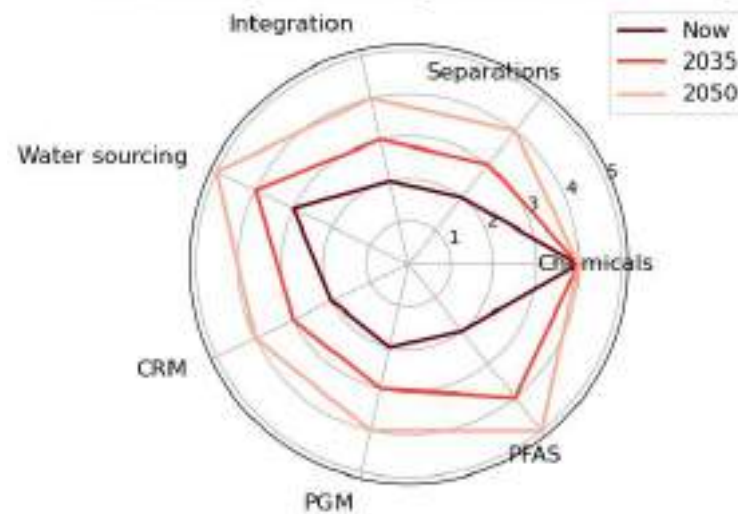
5.3. Carbon Dioxide and Nitrogen Electrochemical Conversion in detail



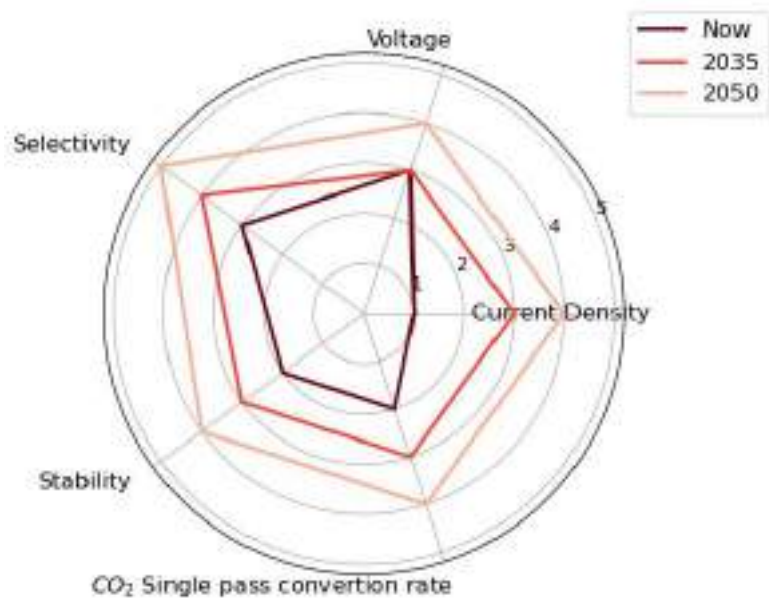
Performance KPIs for CO₂ Electroreduction to C₂



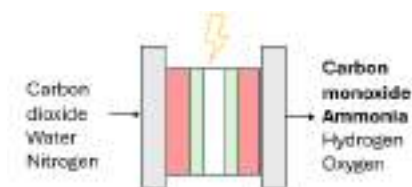
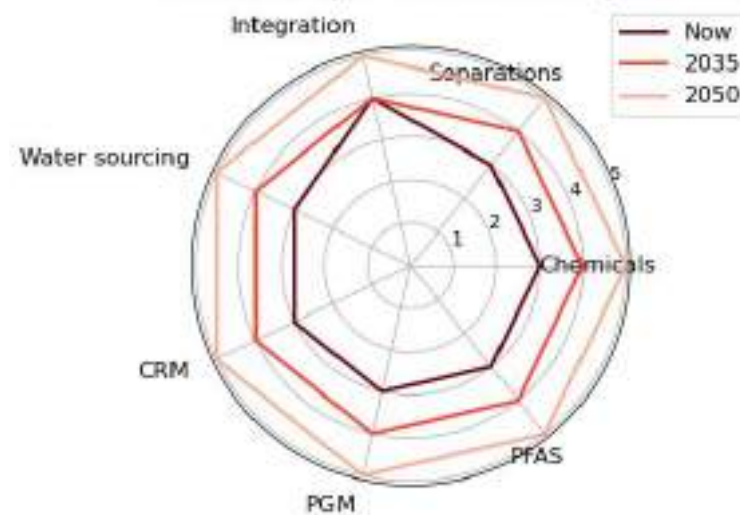
Sustainability KPIs for CO₂ Electroreduction to C₂



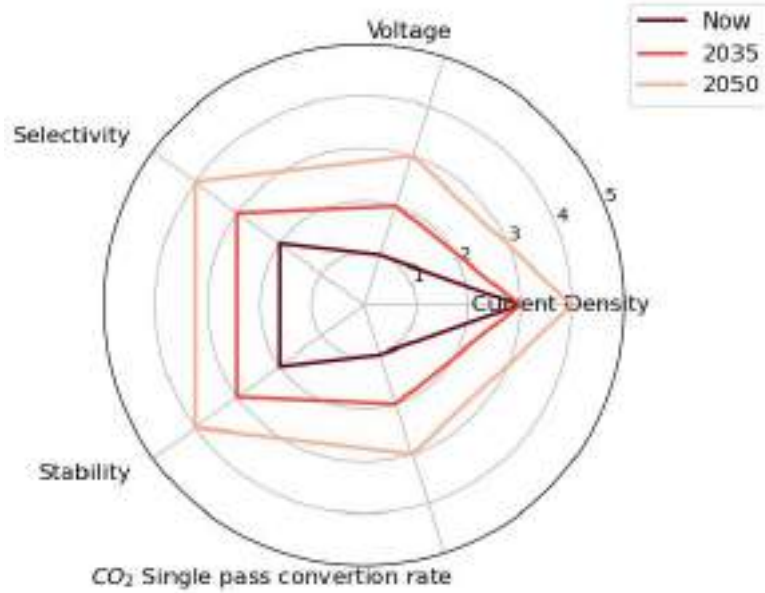
Performance KPIs for Bioelectrolysis



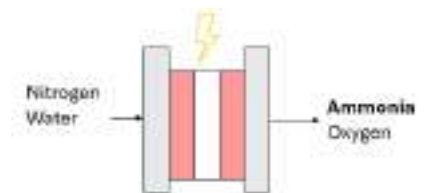
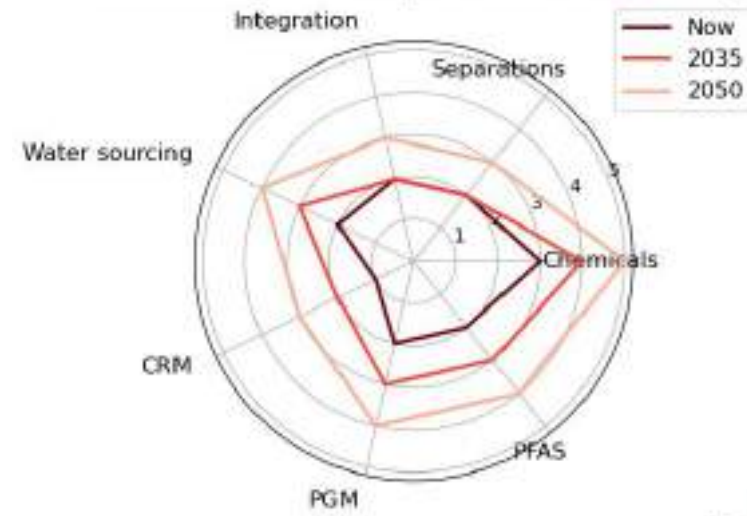
Sustainability KPIs for Bioelectrolysis



Performance KPIs for N_2 Electroreduction to NH_3



Sustainability KPIs for N_2 Electroreduction to NH_3



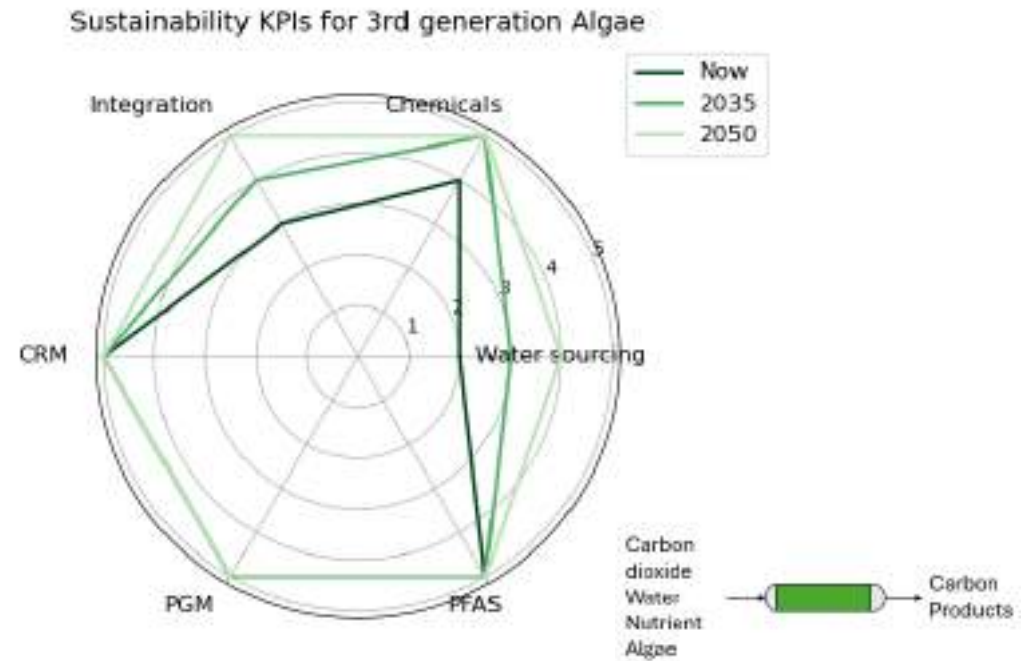
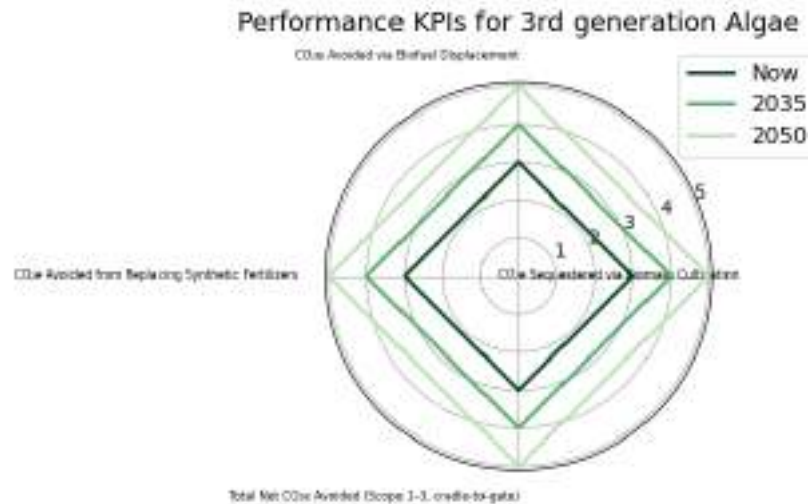


5.4. Direct Photo(electro)chemical Conversion in detail

Due to the current lack of comprehensive data on PEC cells, no radar chart could be developed at this stage. Nevertheless, progress has been made in defining relevant technical key performance indicators (KPIs). The next steps will focus on establishing the current state of the art, setting targets for 2035, and formulating a long-term vision for 2050 to complete the roadmap.



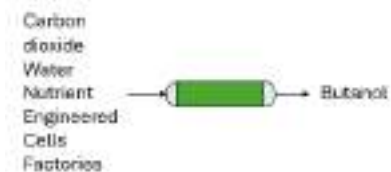
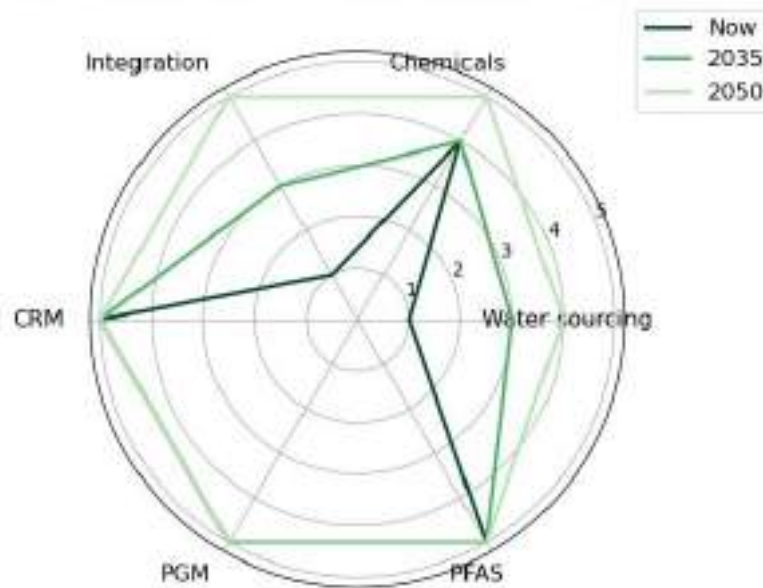
5.5. Biological Conversion in detail



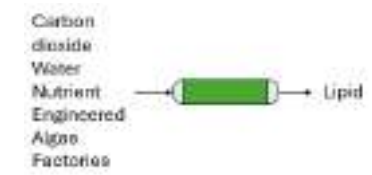
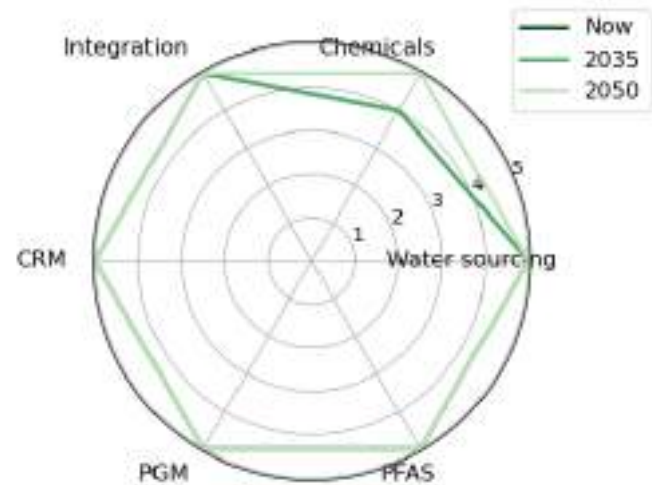
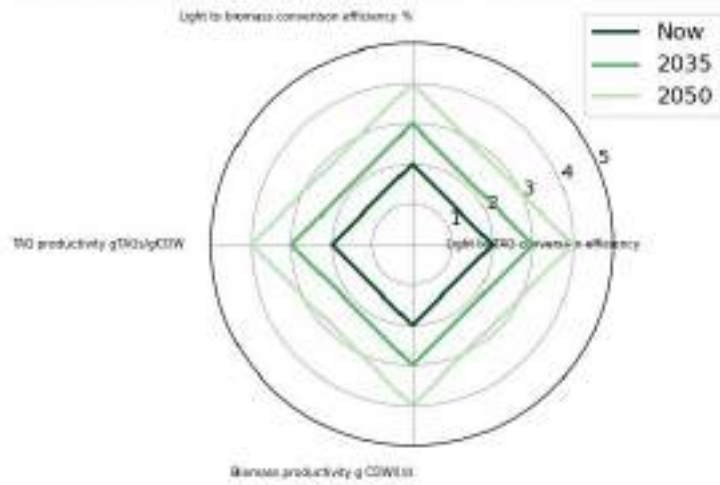
Performance KPIs for Solar to butanol by engineered cell



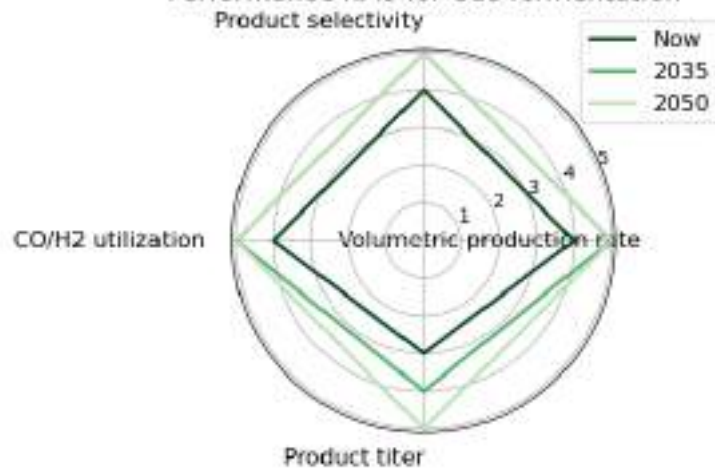
Sustainability KPIs for Solar to butanol by engineered cell



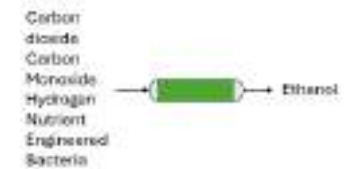
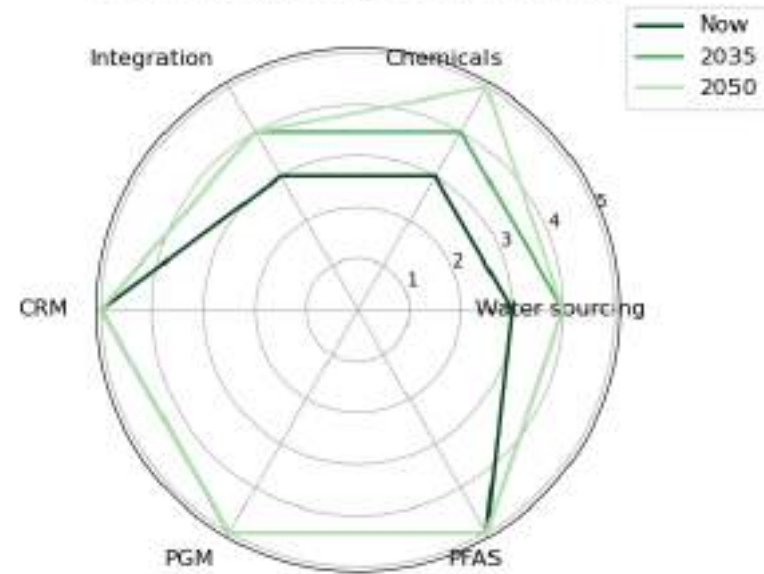
Performance KPIs for Solar to lipid fuel by engineered algal Sustainability KPIs for Solar to lipid fuel by engineered algal



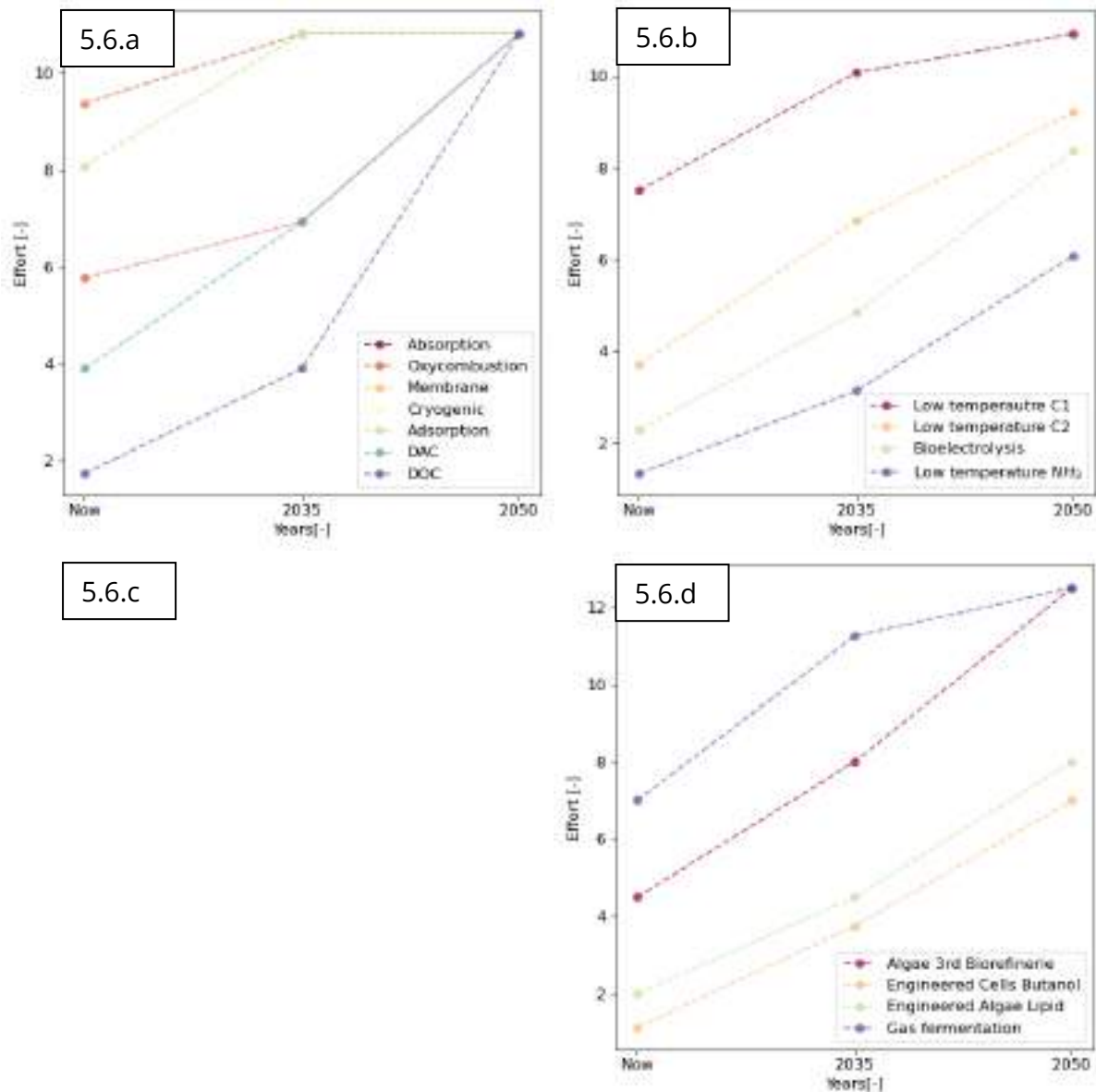
Performance KPIs for Gas fermentation



Sustainability KPIs for Gas fermentation



5.6. Technical Roadmap and Strategic Insight



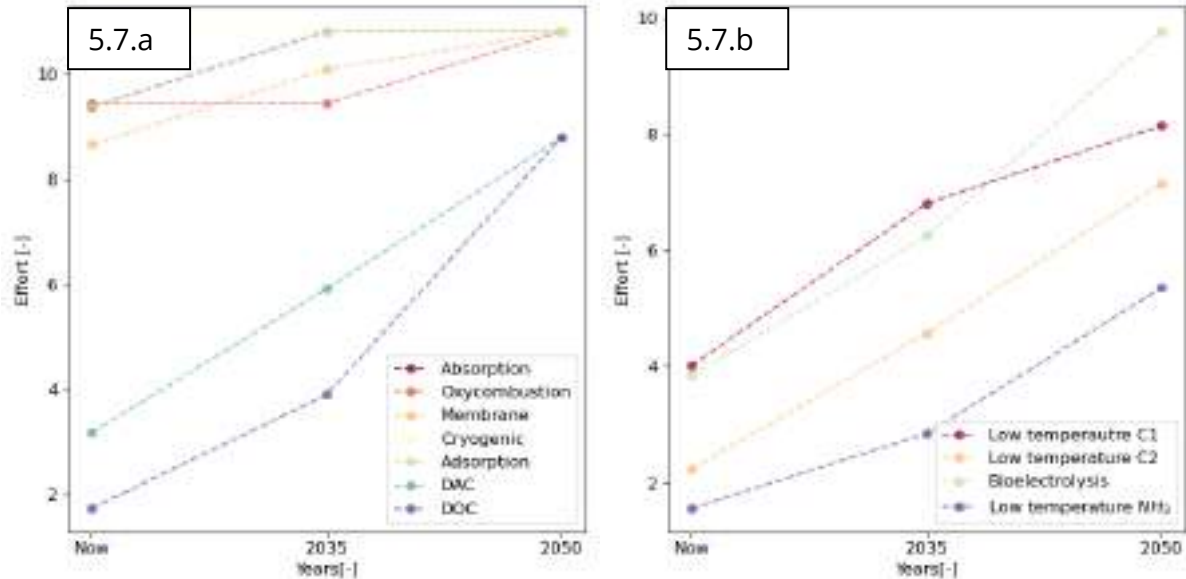
Technical KPIs Roadmap, with absolute effort already made and their evolution through milestones of EU de-fossilization.

- Figure 5.6.a** Sustainable carbon dioxide capture technologies have already achieved significant absolute technical effort, particularly in absorption, adsorption, membrane, and cryogenic systems. These technologies are considered technologically ready within their respective application domains, although they still require further progress in terms of market readiness. Meanwhile, oxy-combustion, direct air capture (DAC), and direct ocean capture (DOC) are currently initiating their development and R&D efforts. However, they have the potential to catch up with the more mature technologies and become competitive by 2050.
- Figure 5.6.b** Electrochemical technologies are still in the R&D technical effort. By 2035, the first industrial, first-of-a-kind implementations for C1 carbon molecules (such as CO and formates) could be anticipated, and industrial demonstrators for C2 carbon molecules (such as ethylene and ethanol) may be completed. Both are expected to be

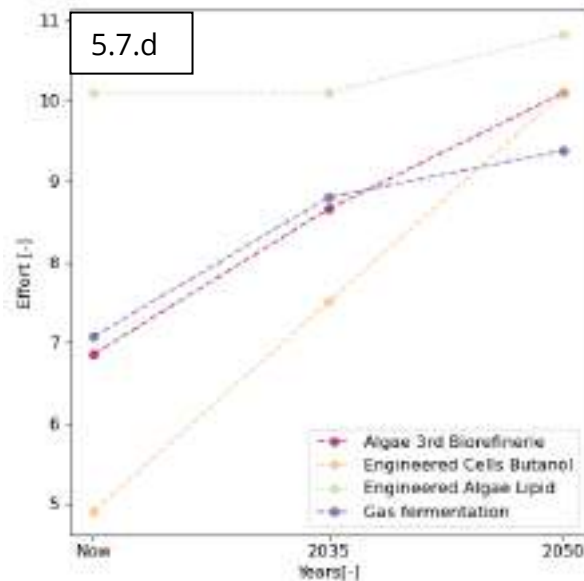
industrially technically relevant by 2050. Meanwhile, bio-electrolysis and low-temperature ammonia conversion will still require R&D technical efforts to be ready for the piloting phase after 2035.

- **Figure 5.6.c** The photo(electro)chemical domain remains under development due to the relative immaturity of the field. While notable progress has been made in defining technical key performance indicators (KPIs), the roadmapping process is still ongoing. The next steps will focus on establishing the current state of the art and defining clear targets for 2035, along with a long-term vision for 2050, to complete the strategic framework.
- **Figure 5.6.d** Biological conversion technologies have already seen significant technical effort, particularly in gas fermentation and third-generation algae biorefineries. By 2035, gas fermentation is expected to advance further toward commercialization and could reach maturity by 2050, supported by continuous technical improvements through industrial implementation. Algae-based third-generation biorefineries are following a similar path toward industrialization. Engineered microorganisms, however, will require additional R&D efforts to prepare for industrial piloting after 2035.

5.7. Sustainable Roadmap and Strategic Insight



5.7.c



Sustainable KPIs Roadmap with absolute effort already made and their evolution through milestones of EU de-fossilization.

- **Figure 5.7.a** Sustainable carbon dioxide capture. Most carbon capture technologies are already considered sustainable. Technologies such as absorption, oxy-combustion, membrane, and cryogenic systems are expected to benefit from continuous industrial improvements, leading to a further reduction in their sustainability impact from now through 2050. Direct Air Capture (DAC) and Direct Ocean Capture (DOC), however, still require additional R&D efforts focused on sustainability—particularly in understanding life cycle impacts related to contactor materials. These technologies are expected to achieve sustainability after 2035.
- **Figure 5.7.b** Currently, sustainable R&D efforts should focus on PFAS-free membranes and electrode designs that minimize the use of critical raw materials (CRMs) and platinum group metals (PGMs). By 2035, these R&D efforts are expected to transition into industrial efforts aimed at improving sustainability during the scale-up phase through efficient manufacturing processes. By 2050, technologies for C1 and C2 molecule conversion, as well as bio-electrolysis, are expected to achieve sustainability.
- **Figure 5.7.c** The photo(electro)chemical domain remains under development due to the relative immaturity of the field. While notable progress has been made in defining sustainable key performance indicators (KPIs), the roadmapping process is still ongoing. The next steps will focus on establishing the current state of the art and defining clear targets for 2035, along with a long-term vision for 2050, to complete the strategic framework.
- **Figure 5.7.d** Biological conversion technologies currently require the highest level of effort to ensure sustainability. However, additional industrial efforts are still needed—particularly in areas such as water usage and sourcing of non-fossil nutrients. As these technologies scale up, continuous improvement efforts from industry—through circular

economy practices and system integration—can help reduce their environmental impact. This will be especially important for the less mature technologies, which are expected to reach sustainability by 2050.

5.8. Translation of the roadmap into relative effort to be made by the field between milestones

From the evolution, and applying the methodology in 4.4, we obtained the following graph that summarize effort to be made:

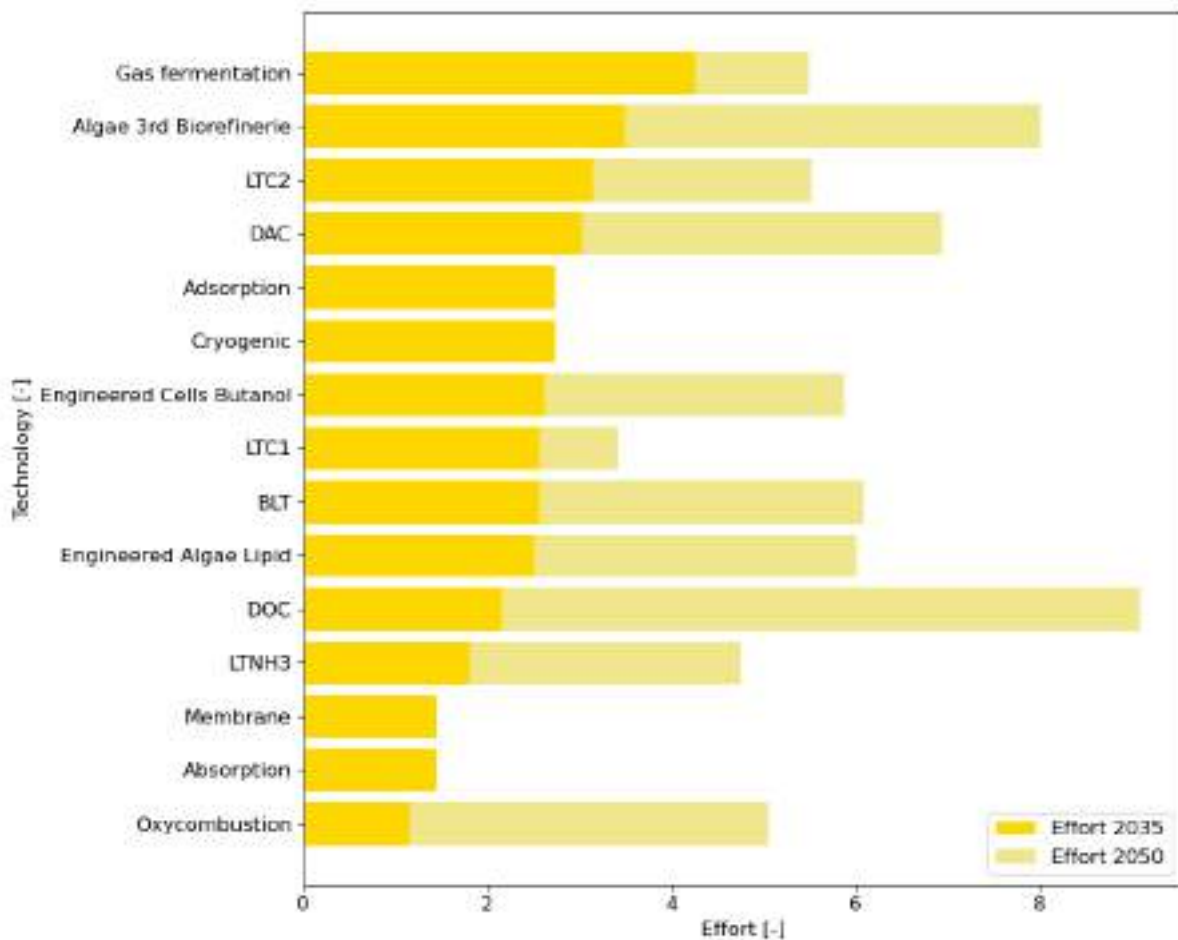


Figure 5.8.1 Performance KPIs Roadmap

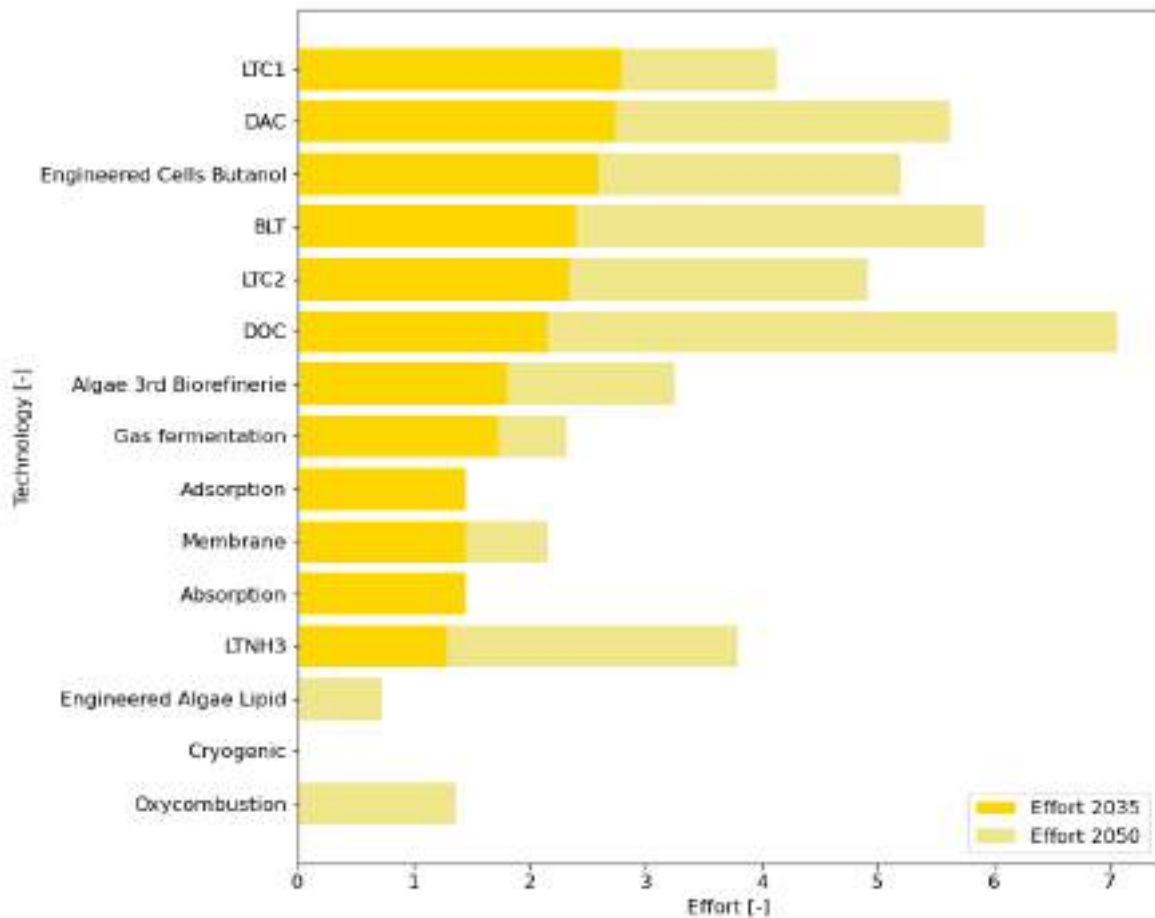


Figure 5.8.2 Sustainable KPIs Roadmap

The sorting was based on the projected effort required by 2035. This effort reflects the relative intensity needed to achieve ideal performance and sustainability for each technology by 2035 and 2050. It includes investment, research activities, skills development, modeling, life cycle analysis, and business model innovation to support the growth of each technology between these milestones. The effort increases exponentially—meaning that early stages of technology development require less effort than later stages.

In both Figure 5.3.1 and Figure 5.3.2, which focus on performance and sustainability, we observe that certain efforts made by 2035 can reduce the effort required by 2050. This indicates that such technologies are more likely to be suitable for industrial implementation.

It is essential that effort is directed toward integrated technological packages—from CO₂ capture at relevant point sources to the production of e-molecules that meet commercial specifications and societal expectations. A complete technological package ensures that the different process blocks—CO₂ capture, utilization, and separation—are well integrated, and that their respective industrial-scale deployments are aligned, all while meeting sustainability criteria.



The industrial deployment of renewables, CO₂ capture systems, and supporting infrastructure must be in place by 2035. Once feedstocks are secured, each CCUS (Carbon Capture, Utilization, and Storage) technology can become competitive within its specific application domain and molecular market niche. Early candidates—such as electrochemical conversion to C1 carbon molecules (e.g., formate, carbon monoxide), gas fermentation, and third-generation biorefineries using algae—could provide valuable operational experience. This experience can accelerate the deployment of more advanced but less mature technologies.

A diversified yet focused portfolio of integrated technologies could help the EU and industry stakeholders build an efficient supply chain for renewable fuels, chemicals, and plastics.





| 6 Conclusion

The SUNERGY/SUNER-C roadmap identifies both the technological potential and the areas where focused effort is needed across the CO₂ capture and utilization value chain.

Early-stage technologies—such as biohybrid devices and direct photo(electro)chemical conversion—will require increasing effort over time. In contrast, more mature approaches like electrochemical synthesis of C1 molecules and gas fermentation offer immediate industrial feasibility.

Prioritizing industrial implementation can enhance the return of experience and create feedback loops that accelerate the development of other less mature emerging technologies.

The roadmap concludes that targeted efforts by 2035—particularly in integration, scale-up, and system-level sustainability optimization—could significantly reduce the transition burden by 2050 and unlock the industrial readiness of renewable fuels, chemicals, and plastics.

Looking ahead, the roadmap emphasizes the importance of cohesive technological packages, where CO₂ capture, conversion, and product separation are fully integrated, standardized, and aligned with sustainability criteria. To develop these packages, the SUNERGY/SUNER-C network bringing together academia, industry, and policymakers—is essential.

The roadmapping exercise led by SUNERGY/SUNER-C should be regularly updated to reflect changes in geopolitics, technological advancements, and evolving EU regulations to remain relevant.

Building such a portfolio requires early operational experience, coordinated infrastructure deployment, and agile innovation strategies. A supportive policy framework will be a cornerstone for establishing a de-fossilized fuel, chemical, and plastics industry in the EU.





Appendix 1:

Sustainable carbon capture



Working_Sheet_Sustai
nable_CO2_capture.doc





Appendix 2:

Carbon dioxide and nitrogen electrochemical conversion



Worksheet_Electrochemical_conversion_Me





Appendix 3: Direct photo(electro)chemical conversion



Worksheet_Direct_Conversion_Photosynthesis





Appendix 4:

Biological conversion



WorkingSheet_Biological_conversion_March



Appendix 5: Workshops

Workshop 14-15 June 2022: Shaping the future, renewable fuels and chemicals from a solar energy for a climate neutral Europe



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. H  l  ne 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-Fillol)



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

Workshop 4-5 June 2024: Harnessing renewables for a sustainable future: Exploring CCU, power to X and solar to X innovations in Energy Ville Genk Belgium





Reminder of SUNERGY/SUNER-C goals



Reminder of SUNERGY vision

This workshop was aimed to have a preliminary definition of the state of art for each technology.

Workshop 26-27 March 2025: Sustainability meets scalability, Joint EIC – SUNERGY Roadmapping event on renewable hydrogen, fuel, and chemicals.

This workshop was aimed to unite academia, industry, and policy to forge a critical milestones for EU's sustainable Energy and Chemical Innovations.



Reality check: Pivotal Role of Molecules in Energy industry: Dr. Carina Faber (EIC) sets the scene for the roadmapping exercises, reminding the audience of the methodology, the time horizon, state of art, and vision for years 2035 and 2050.



Reality check: Pivotal Role of Molecules in Energy industry: Dr. Jan Mertens (ENGIE) sets the industrial perspective and the challenges with hydrogen economies and emerging e-fuel, e-chemicals.



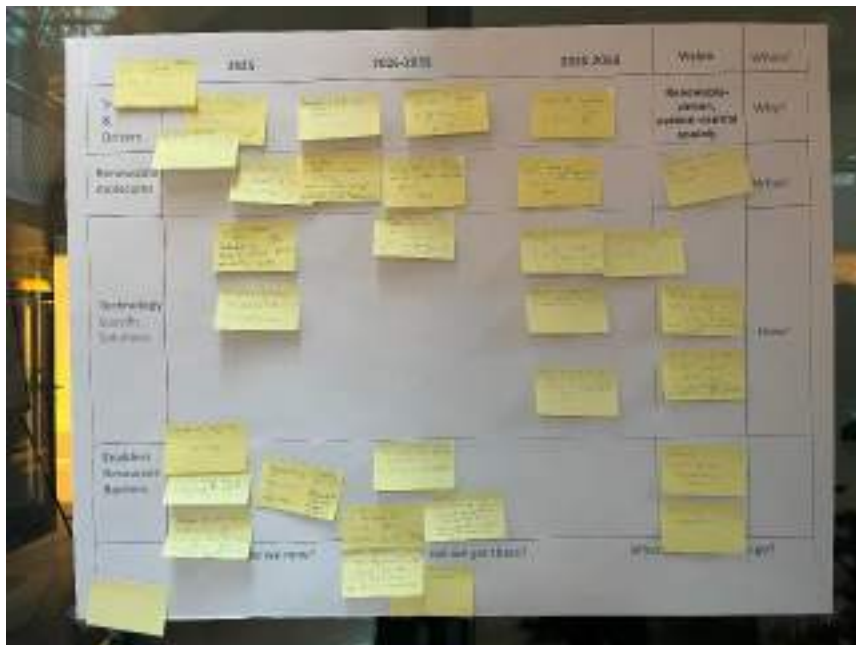
Societal needs: Frame setting and policy support, Martin Lange (European Commission, directorate-general GROW), Fabien Ramos (European Commission, Directorate General CLIMA), Eva Nuss Mueller (European Commission, Directorate General REGIO), Pedro Francisco (European Commission, Directorate General MOVE)



Prof. Joanna Kargul (University of Warsaw) and Prof. Yagut Allahverdiyeva-Rinne (University of Turku) are facilitating the roadmap breakout session on carbon dioxide biochemical conversion.



Han Hunyh (ENGIE) is guiding the roadmap breakout session on sustainable carbon dioxide capture.



Participants of the roadmapping breakout sessions fill the board with their quantitative KPIs and judgments related to the state of the art (2025), as well as progress and vision for years 2035 and 2050, initiating brainstorming.

Appendix 6:

SWOT Analysis

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.

<p>STRENGTHS</p> <ul style="list-style-type: none"> ● 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; 	<p>WEAKNESSES</p> <ul style="list-style-type: none"> ● SUNER-C funding limited in time, SUNERGY cannot 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;
<p>OPPORTUNITIES</p> <ul style="list-style-type: none"> ● 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; 	<p>THREATS</p> <ul style="list-style-type: none"> ● Roadmap will not be implemented; ● <u>Miss the right timing</u>: 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 state clearly the goals, risks, helping and hindering mechanisms of such an endeavor and to deduce a related overall strategy.

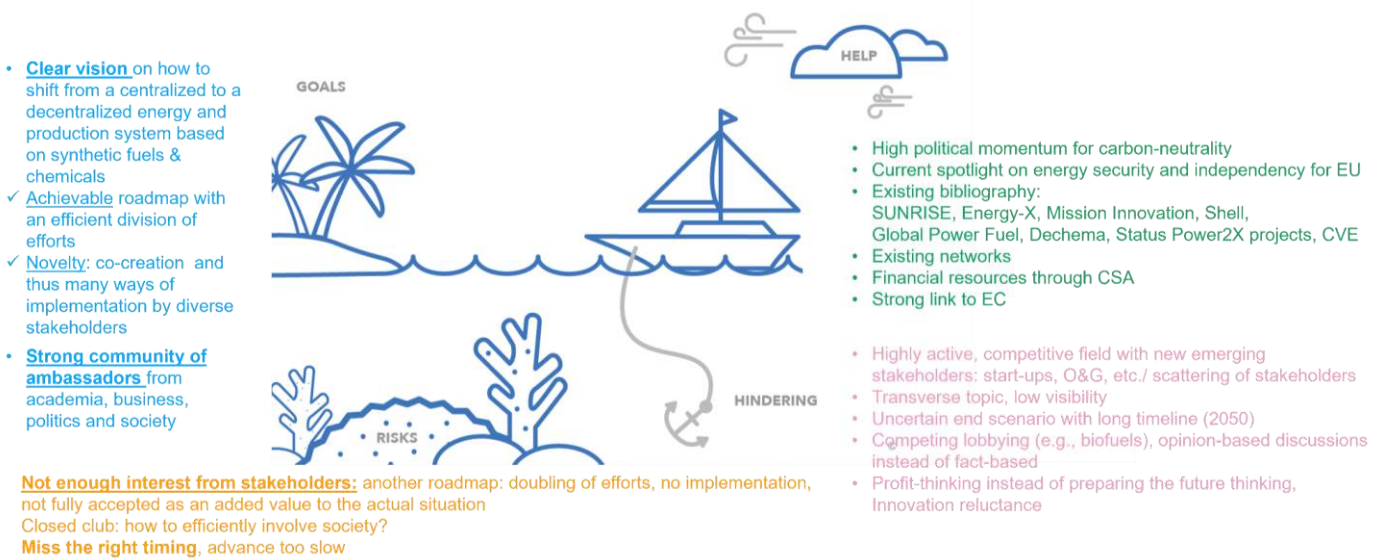
Deduced strategy for the SUNERGY Roadmapping process:

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.





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