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SUNER-C

Deliverable 3.2: Blueprint

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Reviewers	Project Coordination Team (UU, CEA, CVE & ICIQ) & SUNER-C Quality and Impact Assurance (Q&IA) Board
Abstract	This deliverable presents a blueprint on how to implement, with targeted EU calls, the SUNERGY research and innovation structure to advance emerging technologies and processes to couple solar to chemistry and direct air capture. It is based on the roadmap (D3.1) and includes results from three blueprint working sessions with the SUNER-C partners. It focuses on proposing funding instruments (IA, RIA, IEC Pathfinder, Demo), the companies involved, and the targets (KPIs with values) for the priority research directions (PRDs) and sub-PRDs identified in the roadmap.

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Beneficiaries:

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4. UNIVERSITEIT GENT (UGent)
5. UNIVERSITEIT LEIDEN (LU)
6. UNIWERSYTET WARSZAWSKI (UW)
7. FUNDACIO PRIVADA INSTITUT CATALA D'INVESTIGACIO QUIMICA (ICIQ)
8. SIEMENS ENERGY GLOBAL GMBH & CO. KG (SE)
9. DECHEMA GESELLSCHAFT FUR CHEMISCHETECHNIK UND BIOTECHNOLOGIE (DECH)
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11. CARBYON BV (CAR)
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13. USTAV FYZIKALNI CHEMIE J. HEYROVSKEHO AV CR, v. v. i. (HIPC)
14. UPPSALA UNIVERSITET (UppU)
15. COVESTRO DEUTSCHLAND AG (COV)
16. CO2 VALUE EUROPE AISBL (CVE)
17. FUNDACION IMDEA ENERGIA (IME)
18. ALMA DIGIT SRL (AD)
19. INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM (IMEC)
20. AVANTIUM CHEMICALS BV (AVT)
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22. ALLIANCE EUROPEENNE DE RECHERCHE DANS LE DOMAINE DE L'ENERGIE (EERA)
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28. ENGIE (ENGIE) – **Affiliate Entity**
29. RHODIA OPERATIONS (SOLVAY) – *until 30/06/2023*
30. BOND BETER LEEFMILIEU VLAANDEREN (BBL)
31. TOTALENERGIES ONE TECH BELGIUM (TEOTB) -- **Associated Partner**
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Executive Summary

This document, D3.2 – blueprint, is a deliverable of the SUNER-C project, which is funded by the European Union's Horizon Europe under Grant Agreement No 101058481.

The objective of the SUNER-C blueprint is to map out strategies for the implementation of the SUNERGY research and innovation structure to advance emerging technologies and processes for coupling solar energy conversion to chemistry and DAC. This has been done by determining action points with timescales for implementation of the roadmap, resolving the financial instruments and identifying relevant stakeholders. The blueprint focuses on the concrete steps required to ensure that critical hurdles on the way to coupling solar to chemistry and DAC are successfully addressed. The technological roadmap D3.1 presents the identified priority research directions (PRDs) for further research and innovation. What are the research and innovation pipelines to provide a framework to these PRDs? What are the calls to be proposed to the EU? How to make it open and inclusive? What criteria are necessary for this? What is the critical path to bring us to the future? These are questions the blueprint aims to provide answers to.

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List of Abbreviations

List of abbreviations	
AP	Artificial Photosynthesis
CCU	Carbon Capture and Utilization
CSA	Coordination and Support Action
D	Deliverable
DAC	Direct Air Capture
EC	Electrochemical
EIC	European Innovation Council
EQE	External Quantum Efficiency
EROI	Energy Return on Investment
IA	Innovation Action
LERU	The League of European Research Universities
LSRI	Large-Scale Research and Innovation Initiative
O&M	Operations and Maintenance
PEC	Photoelectrochemistry
PEM	Proton Exchange Membrane
PRD	Priority Research Direction
PV	Photovoltaic
RIA	Research and Innovation Action
R&D	Research and Development
R&I	Research and Innovation
SOEC	Solid Oxide Electrolyzer Cell

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SOFC	Solid Oxide Fuel Cell
STF	Solar-to-Fuel
STP	Standard Temperature and Pressure
STY	Space-Time Yield
TRL	Technology Readiness Level
WP	Work Package

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1 Introduction

1.1 SUNER-C

The overarching objective of the SUNER-C project is to create an inclusive innovation community and ecosystem that builds on the current SUNERGY network and includes new stakeholders across Europe. Once the SUNER-C vision (D1.1) of coupling solar energy conversion to chemistry and direct air capture (DAC) is realized, cleaning up the atmosphere can become reality. Bringing together fundamental and applied knowledge from various sectors of society can lead to an enhanced community. This can then turn into a partnership or another instrument to be discussed and agreed upon with the Commission and the Member States and Associated Countries. On the way to this long-term goal, this blueprint provides a pragmatic approach to overcoming scientific, technological, organizational, and socio-economic challenges, accelerate innovation in solar fuels and chemicals, and enable the transition of existing and future technologies from laboratory and demonstrator levels to large-scale industrial and broad societal applications.

Through its holistic approach, SUNER-C will contribute to bottom-up design of the energy society of the future and a circular economy, aiming for displacing fossil-derived fuels and chemicals with renewables and carbon recycling in a scalable socio-economic framework, as a key element toward the EU net-zero emissions target by 2050. SUNER-C builds upon the work of SUNERGY, a pan-European initiative on fossil-free fuels and chemicals from renewable power and solar energy, with currently over 300 supporting organizations across and beyond Europe.

In *Figure 1* an overview is presented of the work package structure of SUNER-C with its eight work packages (WPs). The deliverable 'D3.2 – Blueprint' is a deliverable of 'WP3 – Long-term technological roadmap'.

Please see here: https://sunergy-initiative.eu/suner-c/ for more information.

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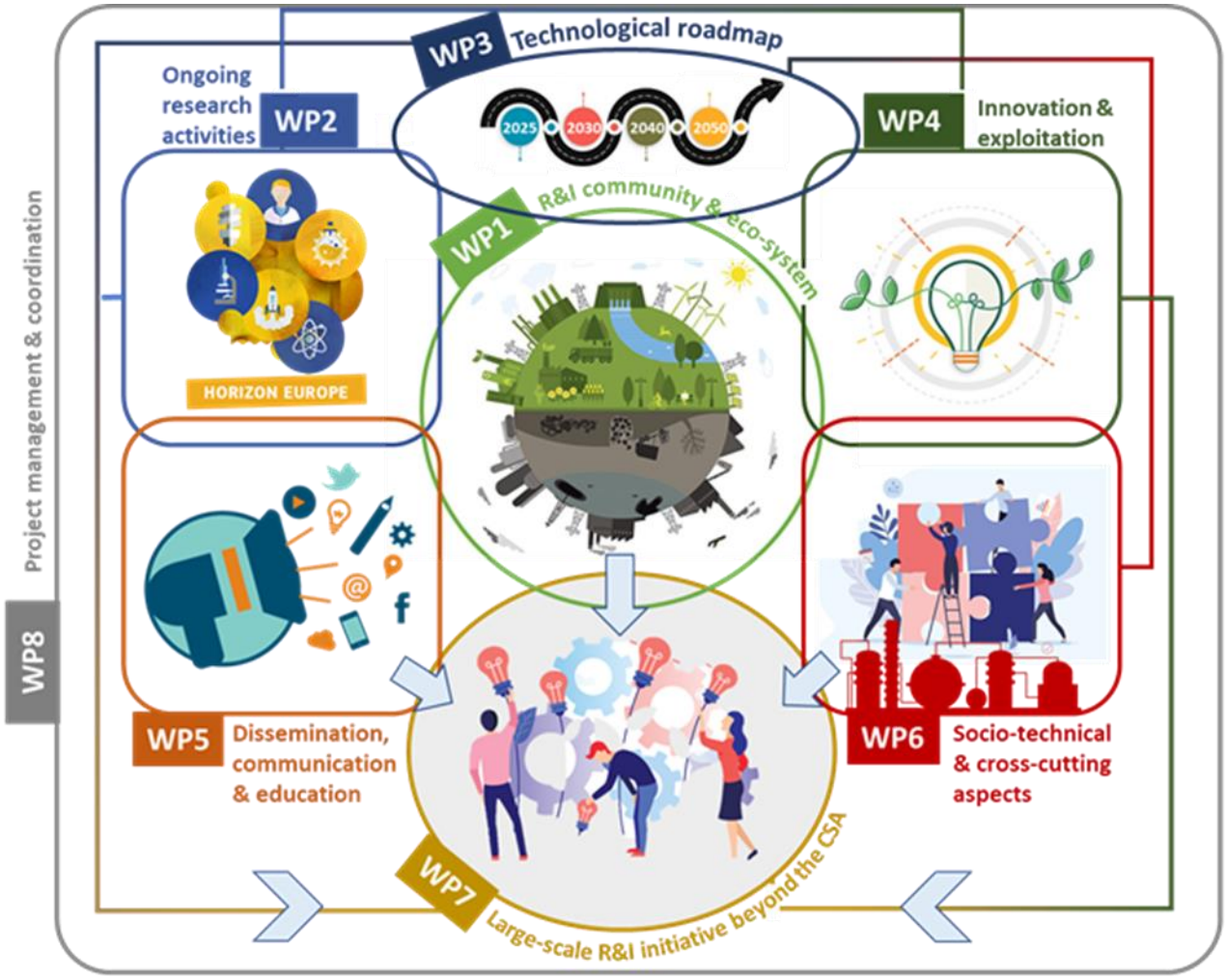

Figure 1: SUNER-C CSA project and its eight work packages. The deliverable 'D3.2 – Blueprint' is a deliverable of 'WP3 – Long-term technological roadmap'.

1.2 Purpose of the deliverable

D3.2 presents a blueprint on how to pursue, with targeted EU calls, the SUNERGY research and innovation structure to advance emerging technologies and processes for coupling solar energy conversion to chemistry and DAC. It is based on the roadmap (D3.1) and the contributions from SUNER-C partners for identifying priority research directions (PRDs). D3.2 is a document projecting into the future the four SUNERGY research and innovation pipelines (A, B, C, and D, in *Figure 2*) with their key performance indicators (KPIs, D2.2), pointing relevant stakeholders and realistic funding instruments towards these targets. In the past, this approach has proven successful, both in terms of advancing R&I and in terms of growing the community that is open to all interested technology stakeholders. *Table A1* in the appendix shows that previous calls falling under the SUNERGY scope have provided over € 250 M for the portfolio of projects indicated with their acronyms in *Figure 2*. Next to the actively involved beneficiaries, there is also a large number of contributors who prepared proposals that were not funded. Our

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analysis (back of the envelope calculation) indicates an average of *ca* 10 beneficiaries per funded project (cf. *Table A1*) and with a success rate of *ca* 8%, this leads to an open innovation community of *ca* 7000 organizations and counting. Evidently the open character makes determining an exact number difficult and care has to be taken here. For instance, there are organizations participating in many projects, such as ICIQ, CEA, IMDEA, Fraunhofer, Uppsala University, and Universities within the League of European Research Universities (LERU). Nevertheless, there is a sizable community of actors in the field of SUNER-C, which forms the base for coordinated funding. This could be in the form of a partnership, or alternatively it is still possible to bring solid funding instruments for technologies within the SUNER-C scope. Moving beyond the SUNER-C CSA, with this blueprint we are presenting a plan now which is adding up to another total investment of about € 450 M - € 500 M for the coming 5-10 years.

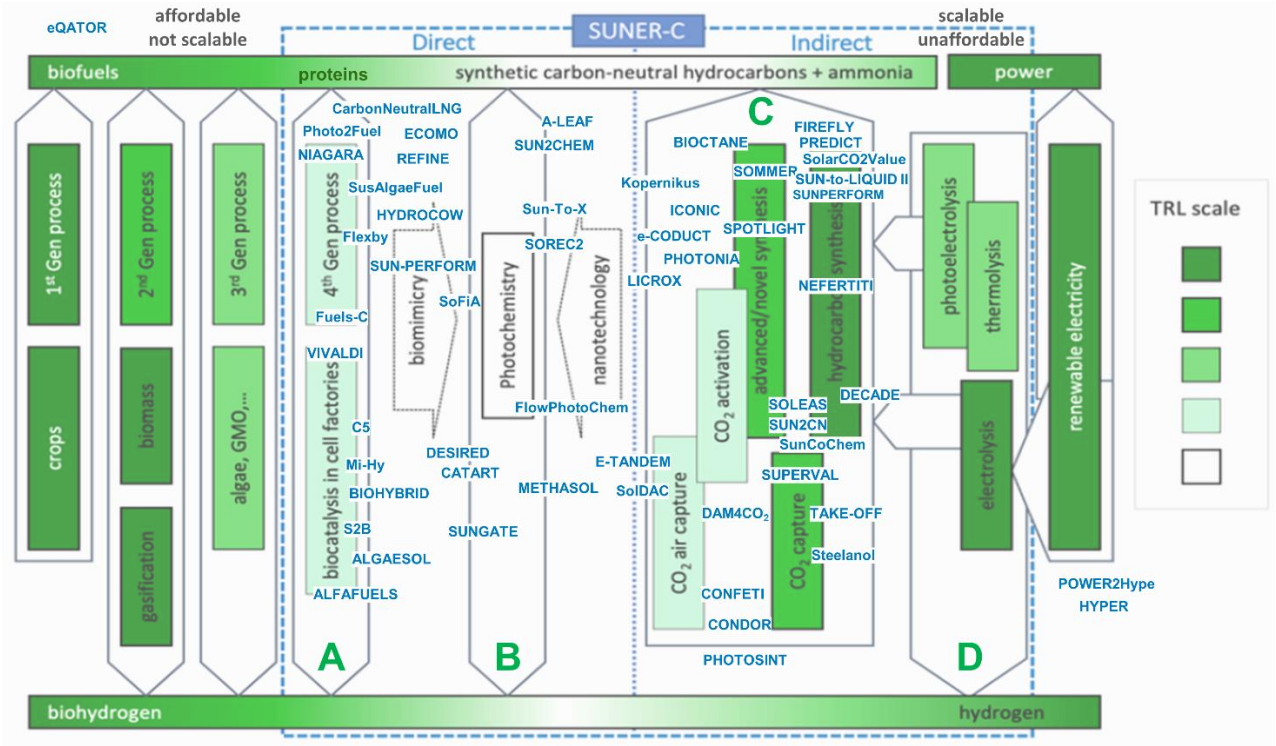

Figure 2: The broad field of communities working on technologies from biofuel to renewable power, and their technology readiness levels (TRLs), (schematic). The target area of the SUNER-C consortium is indicated with a dashed contour. On the research and innovation pipelines A, B, C, and D, are 55 EU-funded projects focusing on the technologies on which their acronyms are placed (see *Table A1)*. The EU-funded projects have been selected based on the 'List of Projects in the Portfolio at Mid-term' (D2.1) and the updated portfolio in the 'KPIs and Action to Foster Project Synergies' (D2.2) SUNER-C deliverables and are complemented with the outcomes of recent calls. *Figure is adapted from ref no:1*.

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1.3 From the SUNER-C beneficiaries to a community at large

SUNER-C is a highly motivated consortium with a confirmed interest in the topic that is regularly coming together to work on our joint endeavor. Next to our consortium members, including many industrial partners (*Figure 3*), its parent, the SUNERGY initiative, has initially built a guiding coalition. *Table A3* in the appendix presents a list of organizations in the 'SUNERGY community mapping tool', that are actively involved in guiding the scientific community into coupling solar to chemistry and DAC (D1.2). Many of these early adapters are also partners of the projects shown in *Figure 2*.

A longer list of organizations that at an early stage expressed their interest in the SUNERGY community can be found under the 'SUNERGY community' webpage. The community webpage also contains a list of 'supporters from previous initiatives'.

Further details about the SUNERGY community can be found in the 'Updated Community Mapping & Structured Innovation Ecosystem' deliverable (D1.3).

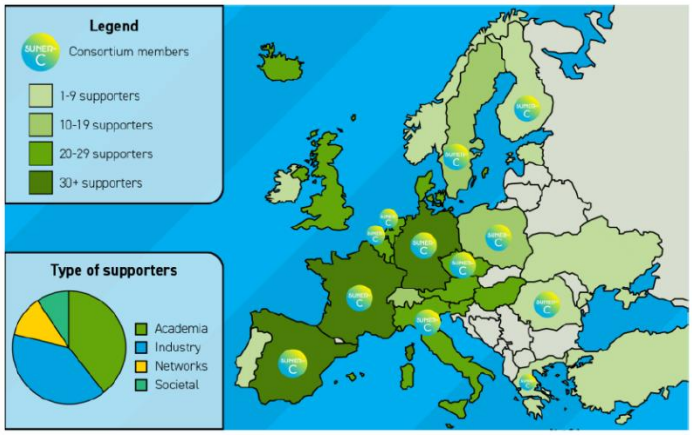

Figure 3: SUNER-C consortium: distribution by type of beneficiaries/partners; geographical coverage as compared to the existing SUNERGY community; organizations involved with their sector of activity. SUNER-C Project - SUNERGY.

1.4 Communities within the SUNER-C target area

In *Figure 2* is the SUNER-C target area indicated with a dashed contour in relation to other sustainable fuel and chemical production routes. There are essentially three elements of core information in *Figure 2:* the technologies, the outputs, and the communities of these technologies. The SUNER-C target area covers a broad range of technologies for direct and indirect conversion routes. On the right side in *Figure 2* are the indirect, multistage conversion routes where the renewable electricity from solar panels and wind turbines is coupled with electrochemical conversion. Alternatively, the concentrated heat from the sunlight can be used for thermochemical reactions. These are the technological routes under the research and innovation pipeline labeled with the letter *D*. On pipeline *C,* are various carbon capture technologies and direct air capture, which are then combined with electrochemical or

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thermochemical conversion routes for indirect conversion of solar energy into carbon-based fuels and chemicals. On pipeline *C,* there are also novel synthesis technologies that cover indirect ammonia production. The indirect conversion technologies are scalable; however, the scalability of these routes is hindered by the high capex for the installations and electrolyzers.

On the left side of *Figure 2* are biological conversion routes starting with first-generation biofuels, where crops are directly used for fuel production. The second-generation processes use waste material, biomass, for biofuel production and the third-generation processes focus on natural algae production; large-scale cultivation of algal biomass which is then followed by extraction via biorefinery. While biomass can provide conversion at an affordable rate, it faces scalability hurdles. On pipeline *A*, is the direct conversion with fourth-generation processes, where engineered cells, modified algae are used to produce and secrete targeted molecules, this is called biocatalysis in cell factories. The last research and innovation pipeline is *B,* representing photochemistry. It is important to be able to improve energy conversion efficiency beyond the current practices of advanced electrolysis methods where renewable electricity is combined with electrolysis, and CO_2 capture. This can be done by eliminating or integrating the conversion steps and optimizing interfaces by mimicking the biological conversion with nonadiabatic nanotechnology. [2] This perspective can then bring us away from indirect technologies towards a sweet spot of direct photochemical conversion (artificial photosynthesis). This low TRL pipeline (*B*) enables direct and decentralized production of solar fuels and chemicals, and offers the possibility of conversion of solar energy into fuels and chemicals at minimized thermodynamic losses, awaiting further exploration and progress.

On the research and innovation pipelines in *Figure 2*, are also the acronyms of various EU-funded projects focusing on the technologies on which they are placed. These projects have been identified in the 'List of Projects in the Portfolio at Mid-term' deliverable (D2.1) and the updated portfolio in the 'KPIs and Action to Foster Project Synergies' deliverable (D2.2). *Figure 2* also presents the SUNER-C methodology for the structuring of the relevant communities for direct and indirect conversion for solar to fuel and chemicals R&D. What is crucial here is that these communities can interact. It is important to identify the interfaces between the communities as the interfaces are generally the spots where genuine innovation takes place. For example, the EU-funded REFINE project involves a combination of semiconductors and biocultures for selective production of isopropanol and butanol through water photoelectrolysis, and CO_2 capture and conversion. This could happen thanks to the efforts of the SUNERGY initiative, which has been triggering many calls.

1.5 Interconnection with other activities in the project

Deliverable 3.2 is a blueprint for the implementation of the roadmap (D3.1). D3.2 will consider the members of the SUNERGY community documented by D1.2 and D1.3, the current capabilities and actions, and the perspective on what actions are necessary for turning the roadmap into a blueprint. D3.2 will use the portfolio of projects from documents D2.1 and D2.2 where the selected projects within the scope of SUNERGY have been identified. The blueprint

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also covers thoughts generated during the 'SUNER-C Workshop Towards an Innovation Ecosystem for Solar Fuels and Chemicals in Europe' that took place in July 2024 in Ghent. During this workshop, industrial players have been actively involved in making future projections for technological advances, financial de-risking, and development of possible business models, which is presented in detail in D1.3.

1.6 Future usage of this document

The multiannual plan presented in this blueprint will first cover the fundamental and applied research needs for coupling solar to chemistry and DAC through the calls, which will be proposed in this document in *Table 1* under *Chapter 4 Investment Scenarios*. Second, it serves to facilitate the further development and implementation of a European initiative as a main driver to identify and tackle long-term research and innovation challenges to de-fossilize society with solar fuels and chemicals; prepare the foundations for a strategy plan, ready to be launched as soon as possible, through an instrument to be agreed upon with the European Commission and the Member States.

2 The Need for a Multiannual Plan

A smooth energy transition and climate-neutrality for Europe require significant investments in renewable and clean energy resources and conversion technologies. The sun offers its abundant energy, and this energy can be used for manufacturing sustainable fuels and chemicals from abundant atmospheric molecular sources such as water and carbon dioxide. The products include renewably produced hydrogen, ethanol, methane, ethylene, formate, and carbon monoxide, which are molecules with high energy densities that can be used as fuels, or molecules that can be used as feedstock in the chemical industry (*Figure 2*). Bringing a specific technology to an industrial level at competitive cost is a multidimensional process that needs a sound innovation plan. Therefore, an elaborate analysis and comparison are necessary for the identification of priority research directions for future investments in this field, and also for the assessment of the dependencies on other advancements in a societal context, as discussed in the SUNER-C 'Identification of Important Socio-Technical Cross-Cutting Challenges and Relevant Stakeholders' deliverable (D6.1).

It is also necessary to determine a viable strategy that is both economically and societally acceptable. So far, we have collected many pieces of information and now we are putting these pieces into a coherent plan. The industrial players have been involved in preparing the plan and defining the targets and hurdles to be tackled early on.

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3 | Technologies within the SUNER-C Scope – PRDs and Sub-PRDs

The SUNERGY 'Technological Roadmap' deliverable (D3.1) has identified the PRDs and sub-PRDs, which came out of the community contributions to the roadmap D3.1/D3.4, for the sustainable production of three types of products (hydrogen, ammonia, and carbon-based fuels and chemicals) and the sustainable CO_2 sourcing to feed the production of sustainable carbon-based fuels and chemicals. In *Figure 2*, we have presented the four research and innovation pipelines (A, B, C, and D) that fall under the SUNER-C scope. *Figure 2* is based on the classification of the technologies and the relevant communities (advanced electrochemical conversion: *D + C*, photochemistry: *B*, and biological conversion: *A*). Pipeline *C* also covers communities focusing on sustainable CO_2 capture that feeds advanced electrochemical conversion, photochemistry, and biological conversion for carbon-based products. This can also be summarized as follows:

- Advanced Electrochemical Conversion (*pipelines D and C*)
  - Carbon Capture (*pipeline C*)
- Photosynthetic Devices / Photochemistry (*pipeline B*)
  - Carbon Capture (*pipeline C*)
- Biological Conversion (*pipeline A*)
  - Carbon Capture (*pipeline C*)

Indirect conversion

Direct conversion

Here, the PRDs and sub-PRDs from the roadmap have been merged with the four research and innovation pipelines (A, B, C, and D) for a full overview of the SUNER-C scope, as shown in *Figure 4* on the following page. For each type of product (hydrogen, ammonia, and carbon-based fuels and chemicals), conversion can be done through two main routes, *indirect* or *direct* conversion. Indirect conversion routes combine renewable electricity or heat with further processes for the purpose of production of solar fuels and chemicals. This predominantly happens in a centralized manner at large facilities. Direct conversion routes on the other hand provide the potential for reduced conversion losses. This type of conversion predominantly takes place in a decentralized manner where the target products are generated directly at places where they are needed the most, and ideally next to the resources that that they need as input. Direct conversion PRDs not only offer the possibility of increased energy conversion efficiency but also reduced transport costs for the inputs and the products. What is more, these PRDs and sub-PRDs also provide a solution to the limitations with the electricity grid and help with resolving the potential net congestion issues due to the increased usage of renewable electricity. Ultimately, the direct conversion PRDs could be employed either on an individual basis or through energy communities within neighborhoods, leading to prosumers of solar fuels and chemicals where ownership by the citizens becomes central, enhancing citizen autonomy, democracy and securing human dignity.

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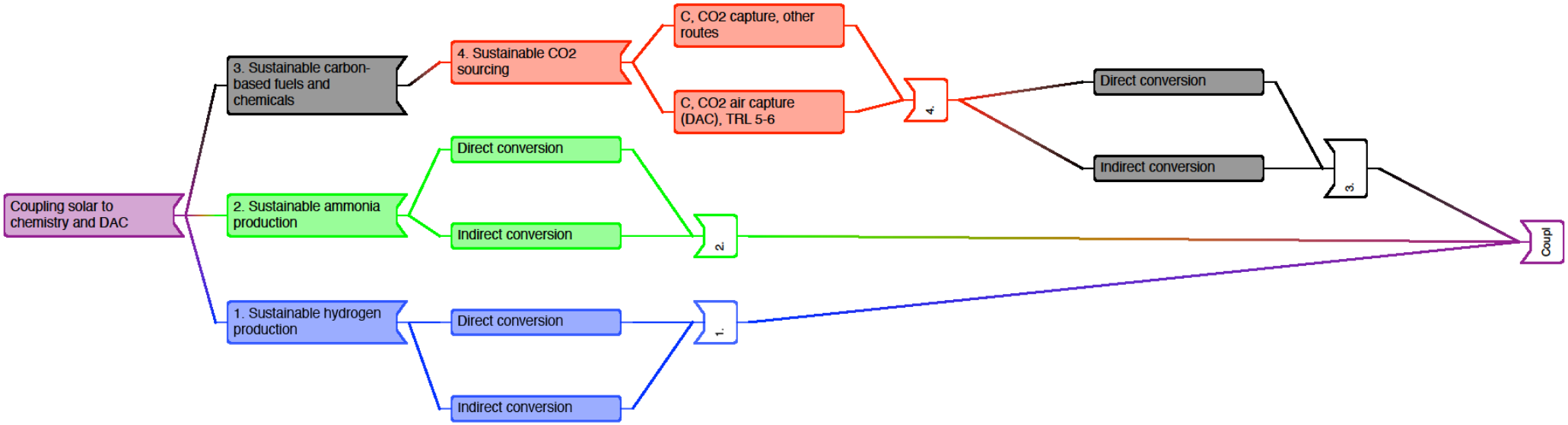

Figure 4: Broad overview of the three types of products, hydrogen (blue), ammonia (green), and carbon-based fuels and chemicals (black), and the sustainable CO_2 source (red) split into the two main conversion routes direct and indirect.

Under direct and indirect conversion routes shown in *Figure 5* on the next page, various PRDs from the roadmap D3.1/D3.4 are distributed based on which research and innovation pipeline they belong to (A, B, C, or D as labeled in *Figure 2*). More elaborate investigations of these technological routes are presented later in this document from *Figure 6* till *Figure 9*.

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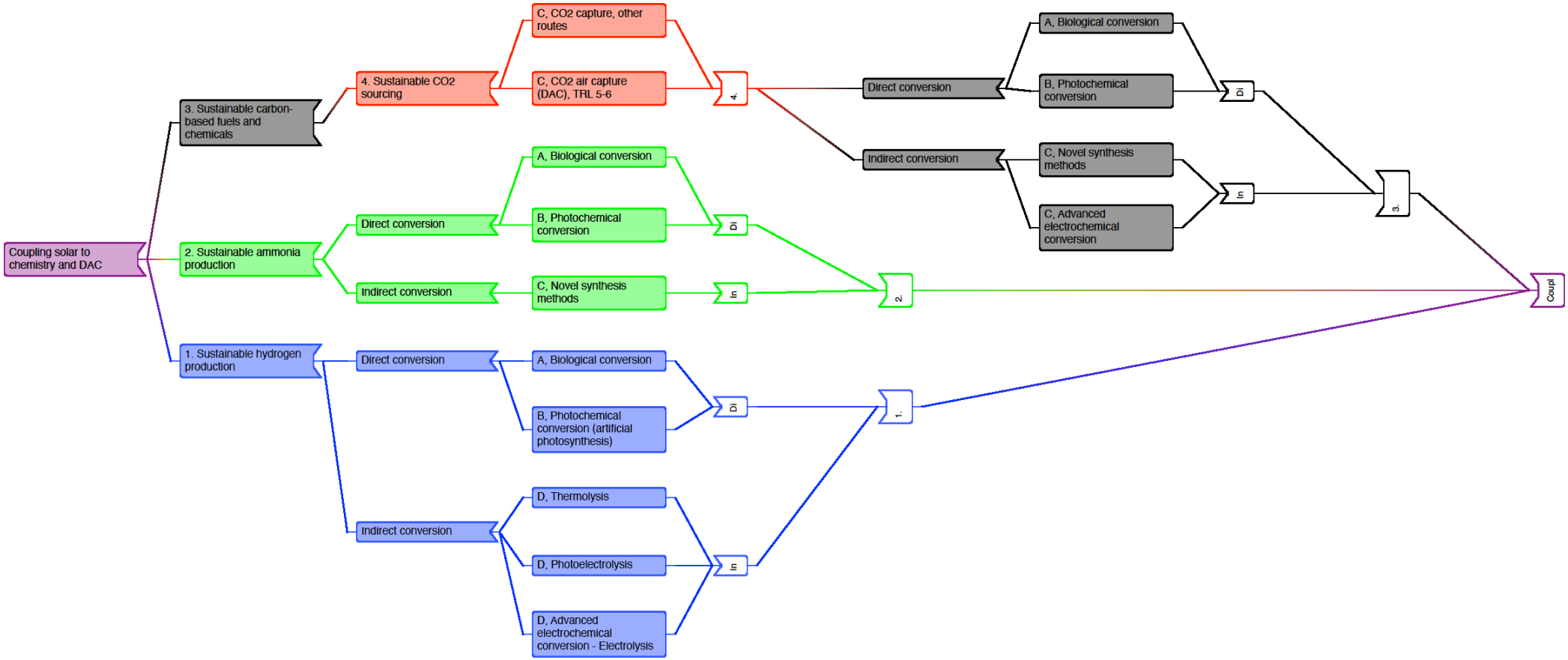

Figure 5: Overview of the PRDs towards the target products, hydrogen (blue), ammonia (green), and carbon-based fuels and chemicals (black), distributed over the four research and innovation pipelines (A, B, C, and D as labeled in *Figure 2*).

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3.1 Sustainable hydrogen production

Renewable hydrogen production has already been established, and mature technologies exist on the indirect conversion route. The communities focusing on sustainable hydrogen production are already members of the Clean Hydrogen Partnership focusing on advanced electrochemical conversion for hydrogen production, and SUNER-C have connections with this partnership through various partners. SUNER-C is also supporting developments initiated by Hydrogen Europe.

Below are the highlights of technologies for indirect and direct production of sustainable hydrogen, with the network diagram shown in *Figure 6.* At the end of each sub-PRD are also the KPI targets for ~2030. The complete list of KPIs can be found in *Table 1*.

a. Indirect conversion
- Advanced electrochemical conversion: Electrolysis
- Photoelectrochemical conversion
- Solar-thermochemical conversion

b. Direct conversion
- Photochemical conversion
- Biological conversion
    - Biohybrid devices
    - Solar microbial cell factories

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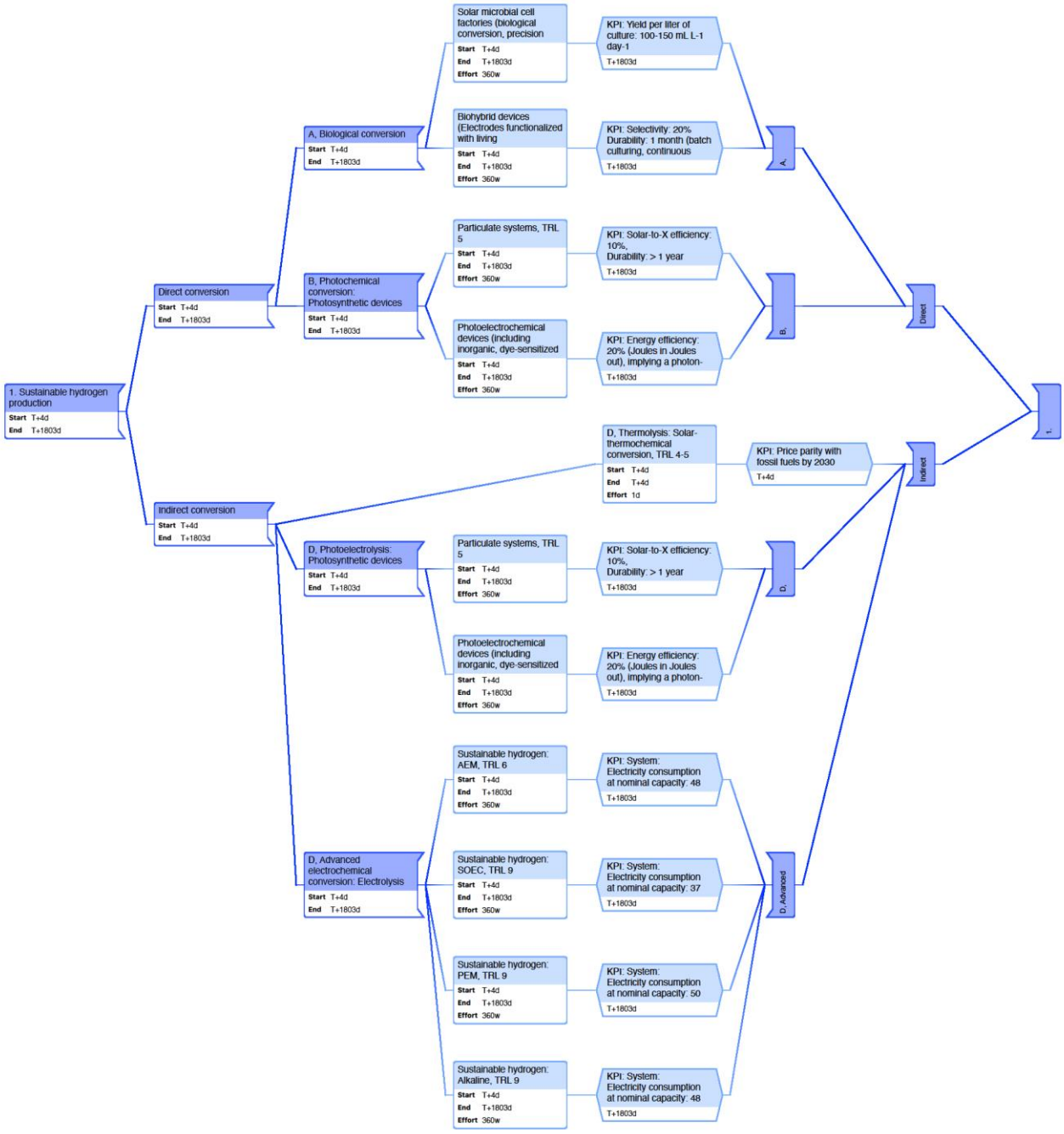

Figure 6: The PRDs (blue boxes) and sub-PRDs (light blue boxes) for sustainable hydrogen production distributed over the three research and innovation pipelines (A, B, and D as labeled in *Figure 2*). At the end of the sub-PRDs are the KPI targets for ~2030. Full KPIs listed in *Table 1.*

Indirect conversion for hydrogen production takes place at high TRL (8-9) through electrolysis powered by renewable electricity. This could be through various technologies including alkaline electrolysis, proton exchange membrane (PEM) electrolyzers, solid oxide electrolyzer cells (SOEC) or anion exchange membrane electrolysis. Indirect conversion can also take place

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through photoelectrochemical cells that combine light absorbing layers and catalysts for the hydrogen and the oxygen evolution reactions, in a single device. What is crucial here is that this can be a route towards the decentralized production of renewable hydrogen if all the components are integrated within a single device. However, these devices should be distinguished from photochemical technologies that fall under the direct conversion routes. This is because in genuine direct conversion, correlated electrons are used for the conversion of H_2O into H_2 and O_2 before they get mixed in an electron sea in a valence band of a metal electrode or wire and become uncorrelated. With correlated electrons high selectivity can become reality, through deterministic quantum driven conversion of source molecules into products. Another major advantage of the integration of all the elements in a single device is lowering the total system costs. The photoelectrochemical hydrogen production devices are still at low TRLs and either at the laboratory stage or at the stage of initial prototypes for decentralized units.[3] *Table A2* in the appendix presents a list of recent H_2 production photovoltaic (PV) + electrochemical (EC) conversion devices, including monolithic device configurations. Solar-to-hydrogen conversion efficiencies at the laboratory scale reach beyond 20%. A last category for indirect hydrogen production takes place through solar-thermochemical conversion, where solar power can be concentrated through parabolic dishes or heliostats towards the reactor for thermochemical splitting of water.[4]

Direct conversion for hydrogen production primarily takes place through photochemical conversion by molecular or organic systems, or through biological conversion. Biological conversion covers solar microbial fuel cell factories with engineered organisms for precision fermentation with high selectivity. Likewise, biohybrid devices with electrodes functionalized with microorganisms target optimized hydrogen production. Direct conversion systems are currently at low TRL levels (1-2 for photochemical conversion and 2-4 for biological conversion). Multiple configurations of PEC and photocatalytic systems are available (see roadmap D3.4 for overview of state-of-the-art), but at present they suffer from poor solar-to-fuel efficiency and lack of standardized protocols for reliable performance evaluation (see Technical Annex 4 of the roadmap, D3.4). However, they hold the great potential of being scalable with low capex, which makes them crucial technologies for decentralized production of hydrogen.

3.2 Sustainable ammonia production

A topic of rapid technological growth is nitrogen conversion, which potentially provides another energy vector and a sustainable solution for fertilizers. By closing cycles at a small scale, the disadvantages of ammonia (such as a strong smell) can be partially alleviated.

Below are indirect and direct routes for sustainable ammonia production, based on the PRDs and sub-PRDs presented in the roadmap D3.1/D3.4, with the network diagram shown in *Figure 7.* Since interest in ammonia is emerging, we have grouped these PRDs into one timeline that can be further developed in the coming years. At the end of each sub-PRD are also the KPI targets for ~2030. The complete list of KPIs can be found in *Table 1*.

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a. Indirect conversion

- Novel synthesis methods
    - Low-emission Haber-Bosch
    - (Photo)electrochemical conversion
    - Plasma-assisted ammonia synthesis
    - Solar-thermochemical conversion

b. Direct conversion

- Photochemical conversion
- Biological conversion
    - Biohybrid devices
    - Solar microbial cell factories

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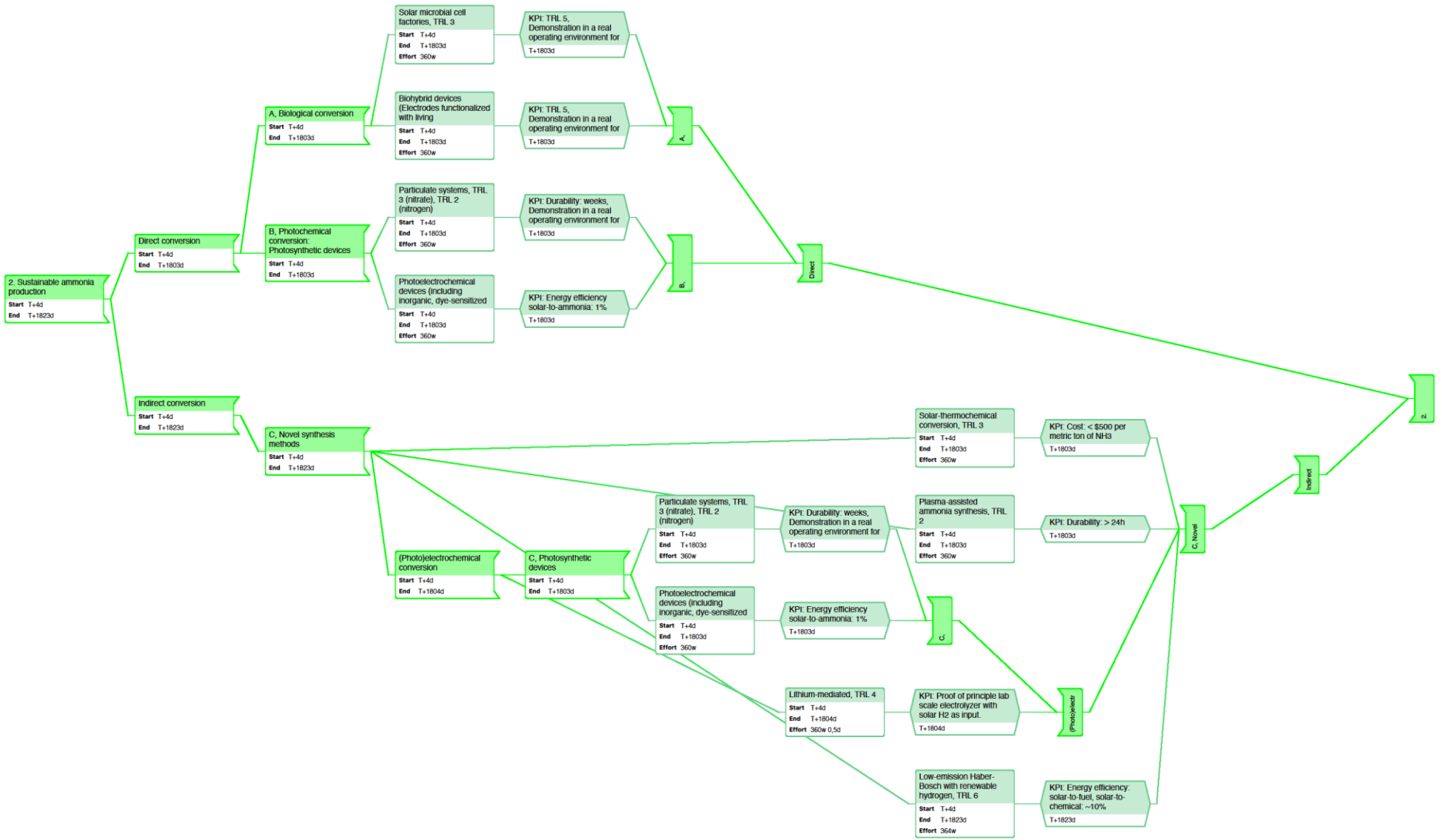

Figure 7: The PRDs (green boxes) and sub-PRDs (light green boxes) for sustainable ammonia production distributed over the three research and innovation pipelines (A, B, and C as labeled in *Figure 2*). At the end of the sub-PRDs are the KPI targets for ~2030. Full KPIs listed in *Table 1*.

Various novel synthesis methods are employed for indirect conversion of atmospheric nitrogen (N_2) into ammonia (NH_3). These technologies include low-emission Haber-Bosch (Green H_2 production directly integrated with Haber-Bosch thermochemical conversion for large-scale production) with a TRL of 6. Alternatively, lithium-mediated electrochemical conversion with a TRL of 4, eliminates the requirement for hydrogen production. Photoelectrochemical ammonia production routes are currently at their initial stages with a TRL of 2-3. Likewise, particulate systems are at TRL 3 when the starting material is nitrate, and 2 when it is N_2. Non-thermal plasma-assisted synthesis uses electricity as an alternative for chemical conversions, but it is still at its very infancy. Solar-thermochemical conversion for ammonia production uses concentrated sunlight and hydrogen, and targets a rate of < $500 per metric ton of NH_3.[5]

Similar to direct solar hydrogen production, direct production of ammonia can take place through photochemical conversion or biological conversion. These technologies are currently in their laboratory stages with TRL1-3.

3.3 Sustainable carbon-based fuels and chemicals

Sustainable carbon-based fuels and chemicals is the target type of product where we observe a large interest within the SUNERGY community. This is also naturally in good alignment with the SUNERGY vision of solar conversion closely coupled to chemistry and DAC. This product pipeline covers many technologies with indirect routes having higher TRLs thanks to the lessons learned from hydrogen technologies. However, continuous advancements are taking place for the direct conversion routes due to the urgent need for carbon circularity, leading to focused research on CO_2 conversion into carbon-based fuels and chemicals both through biological routes and direct photochemical technologies.

Below are indirect and direct routes for the manufacturing of sustainable carbon-based fuels and chemicals, based on the PRDs and sub-PRDs presented in the roadmap, with the network diagram shown in *Figure 8.* The sub-PRDs for the manufacturing of carbon-mased products are fed with the sustainable CO_2 sources. At the end of each sub-PRD are also the KPI targets for ~2030. The complete list of KPIs can be found in *Table 1*.

a. Indirect conversion

- Advanced electrochemical conversion: Hydrocarbon synthesis
- Novel synthesis methods
    - (Photo)electrochemical conversion (direct electro-reduction of CO_2 in a single device)
    - Direct solar-thermochemical conversion of water and CO_2

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b. Direct conversion

- Photochemical conversion
- Biological conversion
    - Bioelectrosynthesis
    - Biohybrid devices
    - Indirect biohybrid synthesis (PV with PEM electrolyzer integrated in the fermenter)
    - Solar microbial cell factories

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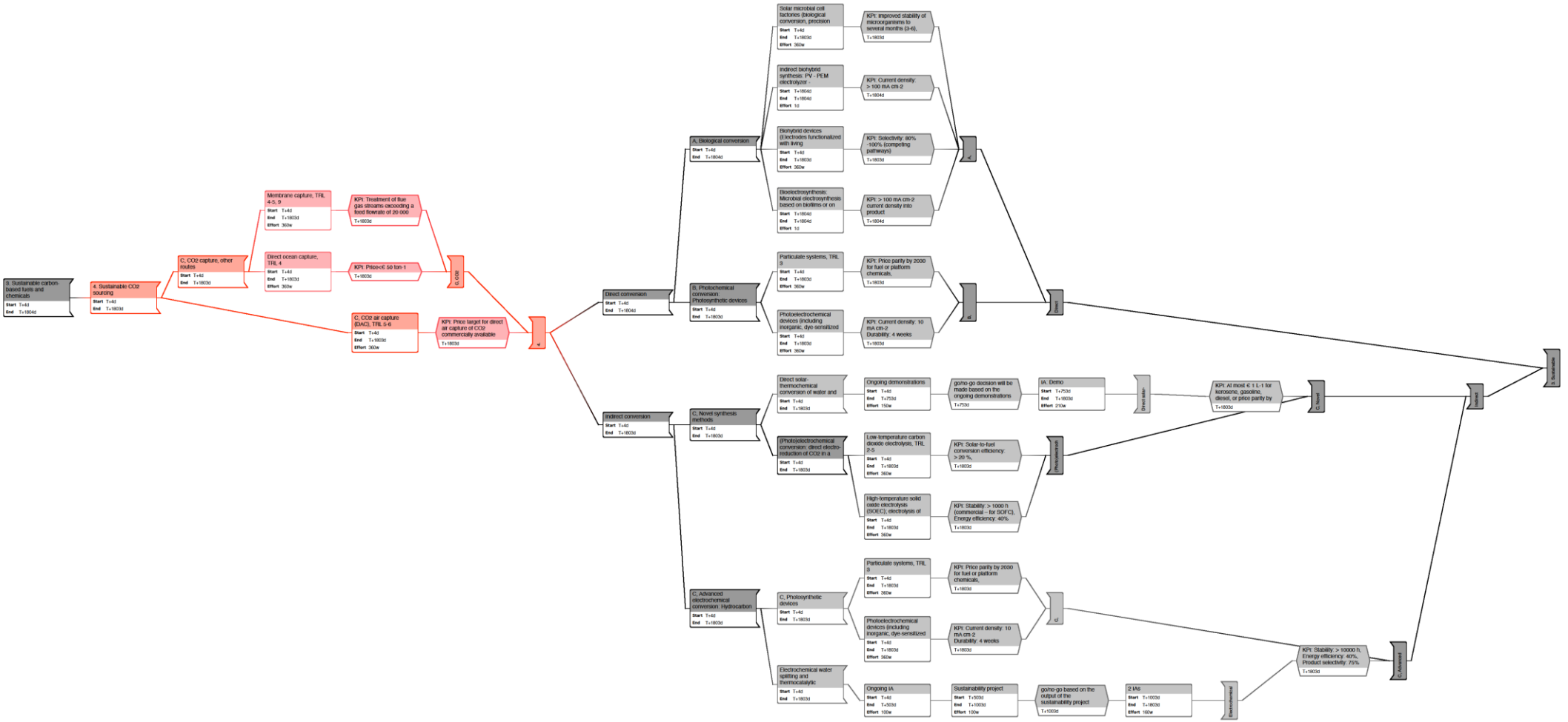

Figure 8: The PRDs (black boxes) and sub-PRDs (gray boxes) for sustainable carbon-based fuels and chemicals production, distributed over the three research and innovation pipelines (A, B, and C as labeled in *Figure 2*). These technologies are fed with sustainable CO_2 sources either through DAC or other (advanced) carbon capture technologies shown as CO_2 capture PRDs (red boxes) and sub-PRDs (pink boxes). At the end of the sub-PRDs are the KPI targets for ~2030. Full KPIs listed in *Table 1*.

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Carbon-based fuels and chemicals can be indirectly produced with the aid of advanced electrochemical conversion combined with sustainable CO_2 sourcing. Such hydrocarbon synthesis technologies include electrochemical CO_2 reduction and thermocatalytic conversion of CO_2 (multi-stage process, Power-to-X, CCU) at TRL 6-7. Under the novel synthesis methods, low temperature CO_2 electrolysis is currently at a TRL of 2-5. (Photo)electrochemical cells for CO_2 valorization into carbon monoxide (CO) or syngas are currently at an improvement stage dependent on the developments on the CO_2 reduction catalysts that can be combined with light-absorbing materials. Here, the challenge becomes development of new catalysts based on earth abundant materials and performing stable electrochemical conversion, next to the separation of the target gases from the output mix.[3] Another obstacle in low-temperature CO_2 electrolysis is the formation of carbonate at alkaline conditions which are required for low cell voltages.[6] Current lab-scale PV-EC cell structures can reach above 19% solar-to-CO efficiency.[7] It is again important to note that photoelectrochemical conversion of CO_2 into carbon-based products can take place through single-device structures where all the components are integrated. Similar to the single-device PEC hydrogen production devices, these CO_2 conversion devices also provide decentralization opportunities for the production of carbon-based fuels and chemicals. High-temperature solid oxide electrolysis (SOEC); electrolysis of CO_2 and co-electrolysis of steam and CO_2 is currently at TRL 7. Although the technologies are at an industrially relevant stage already, the stability of the catalysts is poor and needs further improvement against poisoning and increase in stability forwards fluctuating operation conditions.[3] Direct solar-thermochemical conversion of water and CO_2, can again take place with the aid of parabolic dish concentrators or heliostat field concentrator for large scale applications, producing syngas (H_2 + CO) that can then be converted into liquid hydrocarbon fuels. This technology is currently at a TRL of 4-5.[8]

Direct conversion for carbon-based fuel and chemical production can also be through photochemical conversion with the aid of biomimicry or nanotechnology, or through biological conversion. As briefly pointed during the hydrogen production PRDs, it is important to make the distinction between the PEC devices for photochemical conversion and the PEC devices where all components are integrated for a single-device structure. In the latter, the light absorbing layers are combined with electrocatalysts, where the electrochemical reaction runs with uncorrelated electrons received from the light absorbing layers through metal conductors or wires. Therefore, they are considered as *indirect* conversion technologies, thus are placed under the indirect conversion routes in *Figure 8*. However, if the CO_2 reduction takes place through photochemistry in a 'PEC' device where correlated electrons are used, such a molecular device for instance is classified under the *direct* conversion routes in *Figure 8*. The advantage of photochemical conversion is that the electrons in these systems are kept correlated as much as possible, and it then becomes thermodynamically more efficient to make a chemical bond with these electrons since they are still in a concentrated state when they are correlated, similar to the electrons within chemical bonds. Once the electrons are collected on a conductor, such as a metal electrode or a wire, they become a part of an electron sea. They are then uncorrelated and diluted. Therefore, additional concentration losses are introduced when

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these electrons need to be used again to form chemical bonds for the chemical synthesis of desired products.

Biological conversion technologies include bioelectrosynthesis *i.e.* microbial electrosynthesis based on biofilms or on mediators (living electrodes, electrodes functionalized with non-photosynthetic, electrophilic cells) at TRL 2-3, biohybrid devices at TRL 2, indirect biohybrid synthesis (PV - PEM electrolyzer - fermentation to butanol / hexanol) at TRL 5, or solar microbial fuel cell factories at varying TRLs of 1-6 depending on the end product. The solar microbial cell factories aim to domesticate a diverse range of microorganisms that utilize solar energy for sustainable biocatalytic production of various fuels and feedstocks for the chemical industry. Currently, biofuel and biochemical production rely on a biomass supply which is not scalable for producing large quantities of fuels and chemicals in the long term. To address this limitation, we propose a rational redesign of photosynthetic organisms by engineering them to convert atmospheric CO_2 into products with high light-to-product yields closer to theoretical max (which is 13 %). Additionally, we design biohybrid systems that feed renewable electricity, hydrogen, or carbon-based feedstocks into engineered microorganisms for further downstream conversion with high production yields. Initial progress in this field is evident as photosynthetic designer organisms are emerging from scientific laboratories for field testing. However, significant improvements are still required. Synthetic biology necessitates further development, and the cost of bioreactors needs to be reduced while enhancing their performance.[3]

3.4 Sustainable CO_2 sourcing

Sustainable CO_2 sourcing is the bridging step for the production of sustainable carbon-based fuels and chemicals. CO_2 capture from point sources is already a mature technology, however, the atmosphere is also a huge reservoir of CO_2, therefore, it is of great interest and necessity to capture the CO_2 in the atmosphere. On the other hand, due to its low concentration of only about 400 ppm, it is a challenge to capture the CO_2 from the atmosphere effectively at low cost.

Below are various CO_2 capture PRDs and sub-PRDs listed as direct air capture, and other CO_2 capture technologies, also presented in the network diagram shown in *Figure 9.* At the end of the PRD and sub-PRDs are also the KPI targets for ~2030. The complete list of KPIs can be found in *Table 1*.

a. CO_2 air capture (DAC)
b. CO_2 capture
- Direct Ocean capture
- Membrane capture

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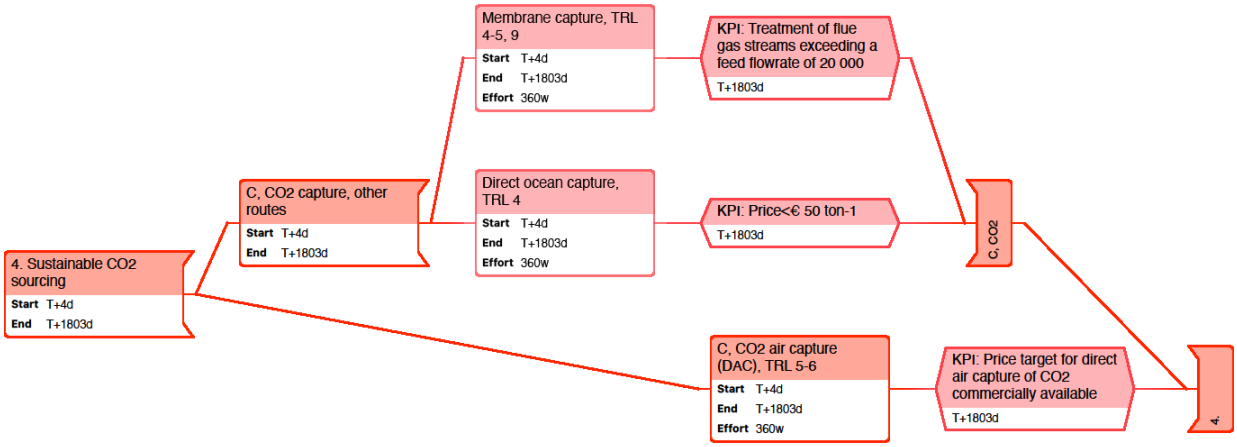

Figure 9: The PRDs (red boxes) and sub-PRDs (pink boxes) for sustainable CO_2 sources, either through DAC or other (advanced) carbon capture technologies. CO_2 captured through these PRDs and sub-PRDs feed the technologies for sustainable carbon-based fuels and chemicals. At the end of the sub-PRDs are the KPI targets for ~2030. Full KPIs listed in *Table 1*.

The SUNER-C vision emphasizes direct air capture, where CO_2 from the atmosphere is either directly utilized by direct conversion routes, or is first captured (TRL 4), and concentrated, followed by an indirect conversion method into carbon-based fuels and chemicals. Among the other CO_2 capture technologies, membrane capture is at TRL 7-9. A developing technology is direct ocean capture for capturing the dissolved CO_2 from the seawater, currently at TRL 4.

4 | Investment Scenarios

4.1 Funding instruments

Table 1 summarizes the implementation of the roadmap with a framework of proposed EU calls (RIA, IA, EIC Pathfinder / Demo), listed in the 'Proposed funding instruments' column. These calls have been proposed for a period of *ca* 5 years, *i.e.* as early as 2030. A total amount of € 450 M - € 500 M has been proposed for the research and innovation pipelines falling under the SUNER-C scope. Among the three types of products, calls with a total amount of ~ € 260 M have been proposed for the PRDs and sub-PRDs focusing on carbon-based fuels and chemicals.

4.2 Identifying relevant stakeholders

For the multiannual plan, important players that will take part in the implementation of the roadmap have been determined through various SUNER-C sources. The SUNERGY community mapping portfolio has been used to assign stakeholders for each PRD and sub-PRD. Next to the mapping portfolio, a list of SUNER-C supporters and suggestions from SUNER-C partners during

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the working sessions have also been considered. The suggested companies have been listed in the 'Relevant stakeholders: Companies involved' column in *Table 1.*

4.3 Targets - KPIs

What can be achieved by ~2030 has been identified based on the deliverables D2.2, D3.1, and through working sessions. The following list of defined KPIs from D2.2 and D3.1/D3.4 have been considered, have been converted into practical, qualitative KPIs on a 5-year timescale during the working sessions with the community. These qualitative KPIs have been listed in the 'KPI targets for ~2030' column in *Table 1*.

Core KPIs for evaluating solar-driven production technologies (as defined in D2.2):

- Solar-to-chemical efficiency
- Cost per unit of product
- CO_2 recycling efficiency
- STY: Space-Time Yield (product yield per unit of space per time) [g L^{-1} day^{-1}].
- Energy efficiency
- Environmental sustainability
- Social acceptance
- Technological flexibility

Technical performance indicators (as considered in the roadmap, D3.1/D3.4):

- Selectivity [%]
- Active electrode area [m^2]
- Applied potential [V]
- Current density [A m^{-2}]
- CO_2 yield [%]
- Operating temperature [°C]
- Electricity-to-fuel efficiency [%]
- Degradation of the cathodes, anodes
- Degradation of the membrane

For advanced electrolysis sub-PRDs towards H_2 production, some further defined KPIs are:[9]

- Electricity consumption: [kWh kg^{-1}]
- Capital cost: [Euro kW^{-1}]
- O&M cost: [Euro kW^{-1} yr^{-1}]
- Degradation: [% $(1000h)^{-1}$]
- Current Density: [A cm^{-2}]
- Use of critical raw material: [mg W^{-1}]

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Table 1: Technologies (PRDs and sub-PRDs) within the SUNER-C scope listed as defined by the roadmap / community. The PRDs and sub-PRDs are also distributed among the research and innovation pipelines (A, B, C, and D) as presented in *Figure 2*. The proposed funding instruments, KPIs, and suggested companies have been listed for each sub-PRD.

Technologies within the SUNER-C scope						
Research and innovation pipeline	**PRDs and Sub-PRDs**	**TRL end 2023***	**TRL target 2030***	**KPI targets for ~2030 *** **	**Relevant stakeholders: Companies involved**	**Proposed funding instruments (RIA € 5M, Demo € 10M, IA € 10-20M)****
	1. Sustainable H_2					
D	1a. Advanced electrolysis[1]					
	i. Alkaline	9	9	System: Electricity consumption at nominal capacity: 48 kWh kg^{-1} Capital cost: € 800 $(kg\ d^{-1})^{-1}$ € 400 kW^{-1} O&M cost: € 21$[(kg\ d^{-1})\ yr^{-1}]^{-1}$ Stack: Degradation: 0.10% $(1{,}000hrs)^{-1}$ Current density: 1.0 A cm^{-2} Use of critical raw materials as catalysts: 0.0 mg W^{-1}	Wärtsilä, MAN B&W.	For Alkaline and PEM: innovation funding for implementation.
	ii. PEM	9		System: Electricity consumption at nominal capacity: 50 kWh kg^{-1} Capital cost: € 1000 $(kg\ d^{-1})^{-1}$ € 500 kW^{-1} O&M cost: € 21 $[(kg\ d^{-1})\ yr^{-1}]^{-1}$ Stack: Degradation: 0.12% (1 000hrs)$^{-1}$ Current density: 3.5 A cm^{-2} Use of critical raw materials as catalysts: 0.3 mg W^{-1}	Siemens Energy, SCHP ČR, SolHyd.	
	iii. SOEC	7-8		System: Electricity consumption at nominal capacity: 37 kWh kg^{-1} Heat demand at nominal Capacity: 8 kWh kg^{-1} Capital cost: € 800 $(kg\ d^{-1})^{-1}$ € 520 kW^{-1} O&M cost: € 45 $[(kg\ d^{-1})\ yr^{-1}]^{-1}$ Stack: Degradation at U_{TN}: 0.5% (1 000hrs)$^{-1}$ Current density: 1.5 A cm^{-2}	Wärtsilä, MAN B&W.	For SOEC and AEM: 2-3 IAs.
	iv. AEM	6, 4		System: Electricity consumption at nominal capacity: 48 kWh kg^{-1} Capital cost: € 900 $(kg\ d^{-1})^{-1}$ € 450 kW^{-1} O&M cost:		

[1] Target KPIs for advanced electrolysis have been taken from the document: 'Hydrogen Europe Strategic Research and Innovation Agenda Final Draft, October 2020', https://acrobat.adobe.com/id/urn:aaid:sc:EU:ce3c80c8-623f-43cc-b8c2-1675e1b521c7

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				€ 21 [(kg d^{-1}) yr^{-1}]$^{-1}$ Stack: Degradation: 0.15% (1,000hrs)$^{-1}$ Current density: 1.5 A cm^{-2} Use of critical raw materials as catalysts: 0.0 mg W^{-1}		
	1b. Photosynthetic devices					
B, D	i. Photoelectrochemical devices (including inorganic, dye-sensitized and biomolecular architectures)	4	7-8	Energy efficiency: 20% (Joules in Joules out), implying a photon-to-product yield of ~50%. (moles in moles out).	ENGIE.	RIA → at least 3 projects funded from 1 RIA call.
	ii. Particulate systems	5	7-8	Solar-to-X efficiency: 10%, Durability: > 1 year	SyNest.	RIA. DEMO/Pathfinder.
A	iii. Biohybrid devices (Electrodes functionalized with microorganisms)	2-3	5	Selectivity: 20% Durability: 1 month (batch culturing, continuous culturing)	-	RIA, IA participation, EIC.
	1c. Solar microbial cell factories (biological conversion, precision fermentation)	4	5	Yield per liter of culture (STY): > 1000 mL H_2 $L_{culture}^{-1}$ d^{-1} Light-to-H_2 conversion efficiency: 5% Stability: several months	Biopetroleo, Total, St1.	At least 2 RIAs.
D	1d. Solar- thermochemical conversion	4-5	7	Price parity with fossil fuels by 2030	Synhelion, Saint Gobain, SyNest.	IA, EIC accelerator.
Research and innovation pipeline	**PRDs and Sub-PRDs**	**TRL end 2023***	**TRL target 2030***	**KPI targets for ~2030*** **	**Relevant stakeholders: Companies involved**	**Proposed funding instruments (RIA € 5M, Demo € 10M, IA € 10-20M) ** **
	2. Sustainable ammonia					
C	2a. Low-emission Haber-Bosch (Green H_2 production directly integrated with Haber-Bosch thermochemical conversion for large-scale production)[2]	6	9	Energy efficiency: solar-to-fuel, solar-to-chemical: ~10%	SCHP ČR.	IA → 1.
	2b. Electrochemical conversion					
	i. Lithium-mediated	4	8	Proof of principle lab scale electrolyzer with solar H_2 as input. Durability: weeks	CEA center for new technologies.	IA → 1.
	2c. Plasma-assisted ammonia synthesis[3]	2	4-5	Durability: > 24h	SCHP ČR.	Demo.
	2d. Solar-thermochemical conversion[4]	3	5	Price: < $500 per metric ton of NH_3	Yara, Thyssenkrupp.	RIA → 1.
	2e. Photosynthetic devices					
B, D	i. Photoelectrochemical devices (including inorganic, dye-sensitized and biomolecular architectures)[5]	2-3	4	Energy efficiency solar-to-ammonia: 1%	-	RIA → 1.
	ii. Particulate systems (particulate → Dispersed)	3 (nitrate)	5	Durability: weeks, Demonstration in a real operating environment for a month.	-	
	iii. Particulate systems	2 (nitrogen)	4		-	RIA →1 or 2 (nitrate, ammonia), nitrogen fixation.
A	iv. Biohybrid devices (electrodes functionalized with photosynthetic or non-photosynthetic - cells)	3	4	TRL 3 → 5, Demonstration in a real operating environment for a month, Selectivity of 100% with increased durability.	Novonesis.	RIA → 2.
	2f. Solar microbial cell factories	3	4	TRL 3 → 5, Demonstration in a real operating environment for a month, 40 mg NH_3 m^{-2} day^{-1}	-	RIA → 2-3.

[2] This could be participation in an existing IA.
[3] This could also be an RIA.
[4] This could be an RIA or an EIC Pathfinder.
[5] This could also be participation in an existing IA.

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Research and innovation pipeline	PRDs and Sub-PRDs	TRL end 2023*	TRL target 2030*	KPI targets for ~2030 ***	Relevant stakeholders: Companies involved	Proposed funding instruments (RIA € 5M, Demo € 10M, IA € 10-20M)**
	3. Sustainable carbon-based fuels and chemicals					
C	3a. Electrochemical water splitting and thermocatalytic conversion of CO_2 (multi-stage process, Power-to-X, CCU)	7, 6-7, 6	9	Stability: > 10000 h, Energy efficiency: 40%, Product selectivity: 75%	Siemens Energy, Covestro, ENGIE, SyNest, Liquid Wind, SCHP ČR, (including their supply chain and the offtakers), eChemicles, ESy-Labs.	IA → 2 (meaning 2 funded projects, not two topics), there is ongoing activity and a demonstration plant being taken into account, Demo. An IA will be followed by a 1–2-year sustainability project, which will determine go/no-go. Based on this, 2 IAs will follow.
	3b. Direct electro-reduction of CO_2 (In a single device)					
	i. High-temperature solid oxide electrolysis (SOEC); electrolysis of CO_2 and co-electrolysis of steam and CO_2[6]	7	8	Stability: > 1000 h (commercial – for SOFC), Energy efficiency: 40% (commercial), Product selectivity: 75% Scale: from 50 kW to above 1 MW	Total.	IA level. Emphasis on durability. Not yet EIC level because of durability, which needs an RIA with at least 2 funded. (RIAs could start immediately)
	ii. Low-temperature carbon dioxide electrolysis	5, 4, 3, 2	7, 6	Solar-to-fuel conversion efficiency: > 20 %, Durability: weeks, Coupling of PEC with direct air capture technologies.	ENGIE, Siemens Energy, Total.	Combination of 2 RIAs and EIC accelerator, at least 10 funded (out of the 10, 2 accelerators).
A	3c. Bioelectrosynthesis					
	i. Microbial electrosynthesis based on biofilms or on mediators (Living electrodes, electrodes functionalized with non-photosynthetic, electrophilic cells)	2-3	5	> 100 mA cm^{-2} current density into product	Evonik, Topsoe.	RIA → at least 3.
	3d. Indirect biohybrid synthesis (Combination of spatially and temporarily separated light absorption, electrochemical and biological conversion)					
	i. PV - PEM electrolyzer - fermentation to butanol / hexanol	5	7	> 100 mA cm^{-2}	LanzaTech, Vattenfall.	Further than RIA: EIC accelerator → at least 3 funded.
C	3e. Direct solar-thermochemical conversion of water and CO_2	4-5	7	At most € 1 L^{-1} for kerosene, gasoline, diesel, or price parity by 2030	SyNest, SCHP ČR, Synhelion, Saint Gobain, Lufthansa, Bauhaus, Total, CAC (Chemieanlagen bau Chemnitz).	IA (2027-2030), EIC accelerator, Demo (1 accelerator and 2 demos-RIA). Preceding steps are ongoing, see *Figure 2*. *Go/no-go* decision will be made based on the ongoing demonstrations. The Demo is the IA
	3f. Photosynthetic devices					
B, D, (C)	i. Photoelectrochemical devices (including inorganic, dye-sensitized and biomolecular architectures)	3	5-6	Current density: 10 mA cm^{-2} Durability: 4 weeks Efficiency: 10-20% of EQE	Sunrgyze, ENGIE, Toyota.	RIA → at least 5 funded.
	ii. Particulate systems	3	5-6	Price parity by 2030 for fuel or platform chemicals, Durability: months, EQE: 5 % by exploring new architectures towards artificial photosynthesis photothermal systems (different call topics)	Toyota, SyNest.	RIA → at least 5 funded.

[6] TRL is said to be high because you can make the devices, but the durability of the electrolyzer material is poor, so more research is needed.

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A	iii. Biohybrid devices (electrodes functionalized with living, photosynthetic cells)	2	3-4	Selectivity: 80% -100% (competing pathways)	-	RIA → at least 5 funded.
	3g. Solar microbial cell factories (biological conversion, precision fermentation)	5-6, 3 2-6	8, 5-6	Improved stability of microorganisms to several months (3-6), Light-to-product conversion efficiency: 5%, Space time yield for butanol 4 g L^{-1} day^{-1}	St1, Total, Swedish Algae Factory, Cyanotech (USA), Simris.	Several (2-3) RIAs and EIC Pathfinders.
Research and innovation pipeline	**PRDs and Sub-PRDs**	**TRL end 2023***	**TRL target 2030***	**KPI targets for ~2030 *** **	**Relevant stakeholders: Companies involved**	**Proposed funding instruments (RIA € 5M, Demo € 10M, IA € 10-20M)****
	4. Sustainable CO_2 sourcing[7,8]					
C	4a. Direct air capture (new technologies: TRL - 2)	5-6 (2 for new technologies)	8-9	Already explored by other communities, we will follow. Price target for direct air capture of CO_2 commercially available for € 150 ton^{-1} by exploring advanced business models. From air directly to carbon-based products with yields from CO_2 to CO: 80% making carbon-carbon bond. Demonstration at 100 000 tCO_2 yr^{-1}	Carbyon, Carbon Recycling International, Siemens Energy, ENGIE, Sumitomo, Technip.	IA will be supported. RIA (into low-TRL research into new catalysts that can directly capture CO_2 from the air and at the same time do the catalysis) → Bring it towards TRL3-4. Joining existing activities.
	4b. Direct Ocean capture	4	5-6	< € 50 ton^{-1} as ocean is a larger source for CO_2	SyNest, Aker Carbon Capture, SkyTree, SeaO2, Brineworks.	At least 2 RIAs, 5 years from now.
	4c. Membrane capture	9, 4-5	9, 6	Treatment of flue gas streams exceeding a feed flowrate of 20 000 $m^{-3}_{(STP)}$ h^{-1}. Production of 50 000 m^2 membrane area per year.	Carbyon, Pentair, Air Liquide, Linde.	Participation in Innovation funds / IA.

* See the Technological Roadmap deliverable (D3.1) for further details about varying TRLs.

** RIAs can potentially be pathfinders.

*** For several sub-PRDs, the current and target KPIs for around 2030 have been retrieved from the Annexes of the SUNRISE Roadmap, SUNRISE Technological Roadmap - SUNERGY.

4.4 Suggestions

With realistic recommendations about RIA, IA and EIC pathfinders, we need to assess how far we are from bridging our ideas into action. Our community is currently at a level, ready for putting its efforts into EIC Pathfinder prototypes. It is seen in the EIC records that there have been 86 proposals submitted for the EIC Challenge "Solar-to-X devices for the decentralized prosumption of renewable fuels, chemicals and materials as climate change mitigation

[7] Relevant companies for concentrated CO_2 sources: Remora (USA), Ecocat (Italy)

[8] Other carbon capture PRDs that have been handled in the roadmap (D3.1/D3.4) are Amine Capture, Oxy-combustion carbon capture, Adsorption (e.g., zeolites, new fundamental research porous materials, etc. reactive capture), Cryogenic capture, and Calcium Looping. Relevant stakeholders for these PRDs include Babcock & Wilcox, Foster + Partners, Buse, and Mitsubishi Heavy Industries.

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pathway" (EIC Pathfinder – 2024 Challenges call closes with high interest - European Commission). Out of these proposals 7 of them have been granted with funding (EU Funding & Tenders Portal). This means only an 8% success rate. This high number of applications shows that there is a need for more funding allocated for the pathfinders in this field.

Second, in *Figure 2* there is a large coverage of the SUNER-C target area by the EU projects. However, the so-called sweet spot of photochemistry (artificial photosynthesis) mentioned earlier, currently needs more research projects, as also explained before, it is a research and innovation pipeline that could offer higher efficiencies, with lower thermodynamic losses, and novel technology routes that allow for decentralized production of solar fuels and chemicals with low capex.

Third, going into a 'cooperation type business model' could be a promising route for the integration and implementation of decentralized production of solar fuels and chemicals. This is not a new model, and it has been previously established in Europe for solar energy. But based on the discussions during the 'SUNER-C Workshop Towards an Innovation Ecosystem for Solar Fuels and Chemicals in Europe' that took place in July 2024 in Ghent, where an energy cooperative from Belgium, 'ZuidtrAnt', had been invited for an interview, energy cooperatives can provide an alternative solution to the hurdles of the economies of scale. The idea of energy return on investment (EROI) model is in a way economies of scale in a different form, and we need to learn how to move away from that towards a model composed of a mix of centralized and decentralized production facilities. In this perspective, limited decentralization makes most sense. Not total decentralization, but rather an intermediate approach. This could also involve focusing on municipal facilities, waste facilities. Further output from the above-mentioned workshop in Ghent includes off-grid systems. These systems can help close cycles and operate independently from the grid. Lastly, thinking in terms of a protected marketplace has also been discussed during this workshop. The path to the future is likely disruptive rather than gradual displacement, since coupling solar to chemistry and DAC is a process upstream in the economy, enabling other, downstream processes.

Finally, it is important to connect to the Hydrogen community through the IEA Hydrogen Technology Collaboration Programme - Hydrogen TCP.

5 Conclusion

Based on the efforts within the SUNER-C consortium, including various deliverables (including but not limited to D1.1, D1.2, D1.3, D2.1, D2.2, D3.1, D3.4) and numerous working sessions with our consortium partners, in the this deliverable we have presented a multiannual strategic plan, a blueprint, to specify the strategy and plans for addressing the challenge of coupling solar conversion to chemistry and direct air capture (DAC) in an economically viable manner with the sound scientific underpinning, based on the SUNERGY roadmap. The blueprint now defines the action points for implementation of the PRDs and sub-PRDs, including KPIs, and resolves the

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financial instruments in the EU ecosystem by proposing calls for RIAs, IAs and EIC Pathfinder actions, together with suggestions for relevant stakeholders that could be involved.

6 Appendix

Table A1: List of projects that fall under the scope of SUNER-C, with total EU funding budgets, number of their partners, and the project end dates. The decimals have been replaced with zero.

Projects	Total budget	Number of partners*	Ending date
A-LEAF	7,980,861.00	13	30-6-2021
ALFAFUELS	4,757,391.00	14	31-12-2027
ALGAESOL	3,997,156.00	7	30-4-2027
BIOCTANE	2,951,957.00	6	31-10-2026
CarbonNeutralLNG	3,306,160.00	11	31-8-2026
CATART	2,871,775.00	9	31-8-2026
CONDOR	3,989,116.00	10	31-8-2025
CONFETI	3,992,976.00	9	31-10-2026
DAM4CO2	2,975,275.00	7	31-10-2026
DECADE	5,198,757.00	14	30-4-2024
DESIRED	3,058,752.00	7	31-10-2026
e-CODUCT	7,022,265.00	9	31-8-2025
ECOMO	3,776,701.00	5	31-10-2026
eQATOR	7,535,960.00	14	30-10-2025
E-TANDEM	3,334,885.00	11	30-4-2026
FIREFLY	11,078,742.00	16	31-12-2026
Flexby	3,993,682.00	10	30-4-2028
FlowPhotoChem	6,993,315.00	14	30-9-2024
Fuels-C	3,774,066.00	11	30-11-2027
FuturoLeaf	2,949,433.00	6	31-8-2023
HYDROCOW	3,963,836.00	4	31-8-2027
ICONIC	3,964,666.00	6	31-10-2027
LICROX	3,199,603.00	7	31-8-2023
METHASOL	3,999,634.00	14	31-12-2024
Mi-Hy	2,890,605.00	6	31-10-2027
NEFERTITI	3,844,428.00	10	30-6-2025
NIAGARA	3,965,334.00	10	30-4-2028
Photo2Fuel	2,493,171.00	8	31-8-2025
PHOTOSINT	4,993,752.00	15	31-8-2027
POWER2Hype	10,173,341.00	12	31-12-2026

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REFINE	3,925,221.00	10	31-10-2027
S2B	4,015,911.00	8	30-9-2028
SoFiA	3,205,280.00	9	30-6-2023
SolarCO2Value	2,373,125.00	1	31-5-2025
SolDAC	2,073,781.00	8	31-8-2025
SOMMER	4,711,516.00	8	31-10-2027
SOREC2	3,084,266.00	8	31-10-2025
SPOTLIGHT	5,604,959.00	13	31-12-2023
Steelanol	10,192,515.00	4	31-3-2024
SUN2CHEM	2,998,445.00	15	30-4-2024
SunCoChem	6,617,645.00	14	30-4-2024
SUNGATE	4,897,007.00	12	30-9-2027
SUN-PERFORM	4,022,148.00	9	31-10-2028
SUN-to-LIQUID II	4,880,120.00	6	31-10-2027
Sun-To-X	5,198,757.00	9	29-2-2024
SUPERVAL	3,571,708.00	8	31-10-2026
TAKE-OFF	4,998,788.00	10	31-12-2024
VIVALDI	6,969,835.00	16	31-5-2025
C5**	*ca* € 4 M	-	recently funded
PHOTONIA**	*ca* € 4 M	-	recently funded
PREDICT**	*ca* € 4 M	-	recently funded
SOLEAS**	*ca* € 4 M	-	recently funded
SUN2CN**	*ca* € 4 M	-	recently funded
SUNPERFORM**	*ca* € 4 M	-	recently funded
BIOHYBRID**	*ca* € 4 M	-	recently funded
Total budgets	**250,368,622.00**		

*The average number of partners is *ca* 10.

**The last 7 projects are the recently selected projects for EIC Pathfinder Challenges, Challenge 1: "Solar-to-X" devices, https://eic.ec.europa.eu/news/eic-pathfinder-challenges-eu116-million-awarded-pioneering-research-projects-2025-03-27_en.

Table A2: List of solar fuels devices that are mostly at the lab scale, for the production of hydrogen, carbon-based fuels and chemicals, and ammonia, with their solar-to-fuel conversion efficiencies, end products and fundamental device structures presented.

Reference details	Publication year	End product	Cell design	STF conversion efficiency
Nature Energy | Volume 8 | June 2023 | 586–596	2023	H_2	concentrator PV + PEC electrolyzer	20.3%
Nature Communications | (2023) 14:3797	2023	H_2	monolithic with conductive adhesive barrier	20.8%
Nature Communications | 7:13237 | DOI: 10.1038	2016	H_2	PV + electrolyzer	30.0%
ACS Energy Lett. 2018, 3, 1795-1800	2018	H_2	monolithic with photocathode	19.7%
Nature Communications | 6:8286	2015	H_2	monolithic with photocathode	14% (17% assisted)
Adv. Mater. Technol. 2023, 8, 2201131	2023	H_2	PV + electrolyzer	>21%

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Adv. Energy Mater. 2021, 11, 2101053	2021	H_2	PV + electrolyzer	20%
ACS Appl. Mater. Interfaces 2020, 12, 55856-55864	2020	H_2	PV + electrolyzer	21.20%
Appl. Phys. Express 8, 107101 (2015)	2015	H_2	concentrator PV + electrolyzer	24.40%
Joule 3, 2930–2941	2019	H_2	PV + electrolyzer	18.70%
Adv. Energy Mater. 2020, 10, 2000772	2020	H_2	perovskite photovoltaic biased silicon photocathode	17.60%
Adv. Mater. 2018, 30, 1707261	2018	H_2	PV + electrolyzer	17.90%
J. Phys. Chem. B 2000, 104, 8920-8924	2000	H_2	PV + electrolyzer	18.30%
ACS Appl. Mater. Interfaces 2019, 11, 33835-33843	2019	H_2	PV + electrolyzer	17.52%
J. Mater. Chem. A, 2021, 9, 14085–14092	2021	H_2	PV + electrolyzer	21.32%
Angew. Chem. 2020, 132, 14912 – 14918	2020	H_2	PV + electrolyzer	18.30% (15 suns) 13% (207 suns)
Nature | Vol 598 | 14 October 2021|304-307	2021	H_2	particle-based	0.76%
Nature Energy 2, 17087 (2017)	2017	CO	PV + electrolyzer	13.4% (CO)
Nano Lett. 2022, 22, 3340-3348	2022	CO	PV + electrolyzer	12.5% (CO)
Nature Communications | (2022) 13:5898	2022	CO	PV + electrolyzer	19.61% (CO)
ACS Energy Lett. 2016, 1, 764-770	2016	HCO2-	photoanode with a tandem III–V photoabsorber	~10% (Formate + H_2)
PNAS | May 14, 2019, | vol. 116 | no. 20 | 9735–9740	2019	Hydrocarbons	PV + electrolyzer	2.3% (ethane + ethylene)
Energy Environ. Sci., 2021, 14, 6349–6359	2021	NH_3	PV + electrolyzer	11%

Table A3: List of organizations in the 'SUNERGY community mapping tool' as a guiding coalition, forming a part of the SUNERGY community. The table is also considered when identifying relevant stakeholders in the blueprint. Many of these organizations are also partners of the projects shown in *Figure 2*. Further information about the SUNERGY community mapping tool can be found in deliverables D1.2 and D1.3.

Stakeholders taking part in the SUNERGY mapping tool		
Organization Name	**Country**	**City**
AIT Austrian Institute of Technology	Austria	Vienna
UCLouvain	Belgium	Louvain-la-Neuve
Belgian Nuclear Research Centre	Belgium	Mol
H2WIN	Belgium	Nivelles
CO2 Value Europe	Belgium	Brussels
Ghent University	Belgium	Gent
IMEC	Belgium	Leuven
EERA	Belgium	Brussels
Toyota Motor Europe	Belgium	Zaventem
European research Institute of Catalysis a.i.s.b.l. (ERIC abbreviated)	Belgium	Brussels
TotalEnergies One Tech Belgium	Belgium	Feluy
Bond Beter Leefmilieu	Belgium	Brussels
Solhyd	Belgium	Leuven
Engie Laborelec	Belgium	Linkebeek
European Research Institute of Catalysis	Belgium	Brussels

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CO2 Czech Solution Group	Czech Republic	Prague
J. Heyrovsky Institute of Physical Chemistry	Czech Republic	Prague
Association of chemical industry of the Czech Republic (SCHP ČR)	Czech Republic	Prague
Danish Board of Technology	Denmark	Copenhagen
2-0 LCA	Denmark	Aalborg
University of Turku	Finland	Turku
Åbo Akademi University	Finland	Turku
Solar Foods Oyj	Finland	Vantaa
Atomic and Alternative Energy Commission (CEA)	France	Grenoble (head office Paris)
Nantes Université	France	Nantes
Univ Grenoble Alpes / CDP-CO2challenge	France	Grenoble
Laboratoire d'Electrochimie Moléculaire - CNRS - Université Paris Cité	France	Paris
IFP Energies nouvelles	France	Rueil Malmaison
Specialty Operations France	France	Saint-Fons (69190)
IMT Atlantique	France	Nantes
French Solar Fuels Network	France	Paris
Université Paris Cité	France	Paris
CEA-Saclay	France	Gif sur Yvette
VICAT	France	L'Isle-d'Abeau
DECHEMA Society for Chemical Technology and Biotechnology e.V.	Germany	Frankfurt
Forschungszentrum Jülich GmbH	Germany	Jülich
University of Stuttgart	Germany	Stuttgart
Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau	Germany	Kaiserslautern
German Aerospace Center (DLR)	Germany	Cologne
ESy-Labs GmbH	Germany	Regensburg
Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB	Germany	Stuttgart, Straubing and Leuna
Projekttraeger Juelich (FZ Juelich)	Germany	Berlin
Fraunhofer ISC	Germany	Würzburg
Uniper	Germany	Duesseldorf
Fraunhofer ISI	Germany	Karlsruhe
Technische Universität Ilmenau	Germany	Ilmenau
Paderborn University	Germany	Paderborn
Friedrich-Alexander-Universität Erlangen-Nürnberg	Germany	Erlangen
University of Bayreuth	Germany	Bayreuth
Covestro Deutschland AG	Germany	Leverkusen
Siemens Energy	Germany	Munich
Helmholtz-Zentrum Berlin für Materialien und Energie GmbH	Germany	Berlin

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WIP Renewable Energies	Germany	Munich
SYNEST PC	Greece	Thessaloniki
HUN-REN Biological Research Centre, Szeged	Hungary	Szeged
BARDS Acoustic Science Labs Ltd.	Ireland	Cork
Tel Aviv University	Israel	Tel Aviv
Weizmann Institute of Science	Israel	Rehovot
Politecnico di Torino	Italy	Turin
Consiglio Nazionale delle Ricerche	Italy	Bologna
Alma Digit SRL	Italy	Messina
University of Messina (CASPE Catalysis for Sustainable Production and Energy)	Italy	Messina
Luxembourg Institute of Science & Technology	Luxembourg	Esch-Belvaux
ArcelorMittal	Luxemburg	Luxemburg
University Mohammed VI Polytechnique	Morocco	Ben Guerir
Green Energy Park	Morocco	Ben Guerir
Leiden University	Netherlands	Leiden
TNO	Netherlands	The Hague
Utrecht University	Netherlands	Utrecht
Photanol	Netherlands	Amsterdam
Nordsol	Netherlands	Bunnik
NORCE	Norway	Stavanger
Jerzy Haber Institute of Catalysis and Surface Chemistry PAS	Poland	Kraków
Warsaw University of Life Sciences - SGGW w Warszawie	Poland	Warsaw
Centre of New Technologies, University of Warsaw	Poland	Warsaw
Universidade de Aveiro	Portugal	Aveiro
Necton S.A.	Portugal	Olhão
University of Bucharest	Romania	Bucharest
ICFO	Spain	Barcelona
Institute of Chemical Research of Catalonia (ICIQ-CERCA)	Spain	Tarragona
IMDEA Energy	Spain	Madrid
CIC energiGUNE	Spain	Vitoria-Gasteiz
SOLDAC EU PROJECT (Coordinated by COMET GLOBAL INNOVATION)	Spain	Barcelona
Universitat Jaume I	Spain	Castellón de la Plana
Institute of Advanced Materials, Universitat Jaume I	Spain	Castelló de la Plana
LEITAT	Spain	Barcelona
Orchestra Scientific	Spain	Tarragona
Chalmers University of Technology	Sweden	Gothenburg
Uppsala University	Sweden	Uppsala
Copper Lavender AB	Sweden	Uppsala
Liquid Wind	Sweden	Gothenburg
Swiss Federal Laboratories for Materials Science and Technology (Empa)	Switzerland	Duebendorf
EPFL	Switzerland	Lausanne

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Universität Zürich	Switzerland	Zürich
Carbyon	the Netherlands	Eindhoven
Universiteit Utrecht	the Netherlands	Utrecht
Avantium	the Netherlands	Amsterdam
University of Amsterdam	the Netherlands	Amsterdam
TU/e-EIRES	the Netherlands	Eindhoven
Wageningen University	the Netherlands	Wageningen
DIFFER	the Netherlands	Eindhoven
Bogazici University	Türkiye	Istanbul
University of Cambridge	UK	Cambridge
Imperial College London	UK	London
University of Salford	United Kingdom	Manchester
University of East Anglia	United Kingdom	Norwich
Phase Change Material Products Ltd (PCMP)	United Kingdom	Peterborough
University of St Andrews	United Kingdom	St Andrews
Imperial College London	United Kingdom	London
University of Liverpool	United Kingdom	Liverpool

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