LC-SC3-RES-1-2019-2020
Developing the next generation of renewable energy technologies

CONDOR

COmbined suN-Driven Oxidation and CO_2 Reduction for renewable energy storage

Starting date of the project: 01/11/2020
Duration: 48 months

= Deliverable D8.2 =

Socio-environmental impact

Dissemination level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006839

DISCLAIMER

Any dissemination of results reflects only the authors' view and the European Commission, or the Climate, Infrastructure and Environment Executive Agency (CINEA) is not responsible for any use that may be made of the information Deliverable D8.2 contains.

Executive Summary

This report, "Deliverable 8.2: Socio-environmental Impact," provides an in-depth analysis of the environmental and societal implications of the CONDOR project, an initiative under the Horizon 2020 program that aims to create a renewable, solar-driven fuel production system. The CONDOR project integrates a photoelectrochemical (PEC) cell to convert CO_2 and water into hydrogen and syngas, then processed into sustainable fuels like dimethyl ether (DME). The primary goals of this deliverable include evaluating the life cycle environmental performance of the CONDOR system and understanding societal acceptance challenges associated with low-TRL (Technology Readiness Level) renewable technologies.

The **Life Cycle Assessment (LCA)** follows ISO 14040/14044 standards, measuring the environmental impact of DME production in terms of greenhouse gas emissions, resource use, and waste across the life cycle. Findings indicate that DME produced through the CONDOR process demonstrates significantly lower climate impact compared to conventional methods, particularly when renewable energy sources power the system. However, challenges such as dependency on critical resources necessitate continued innovation.

The **societal insights** section examines social acceptance, positions PEC technology within existing energy narratives, and compares it with competing low-carbon solutions. Given the early TRL of PEC systems, addressing societal and infrastructural acceptance will be essential for widespread adoption. The report applies a foresight exercise based on European Commission scenarios for 2040, evaluating potential future challenges and opportunities for PEC technology in diverse political, social, and economic landscapes. This foresight analysis provides guidance for aligning PEC development with evolving societal and environmental priorities.

In conclusion, the CONDOR project demonstrates a promising approach to renewable fuel production, aligning with EU sustainability goals. Successful implementation will depend on optimizing environmental efficiency and societal acceptance as the technology matures and approaches market readiness.

Table of Contents

1. Introduction

This report, "Deliverable 8.2: Socio-environmental Impact," is part of the CONDOR project, an EU-funded initiative under the Horizon 2020 program to advance renewable energy technologies. The CONDOR project, which stands for "Combined Sun-Driven Oxidation and CO2 Reduction for Renewable Energy Storage," focuses on the development of an innovative photoelectrochemical (PEC) system to convert CO2 and sunlight into renewable fuels, specifically methanol and dimethyl ether (DME). These fuels provide sustainable energy storage and address the need for scalable solutions to reduce CO2 emissions in the energy sector.

Deliverable 8.2 assesses the environmental performance and societal impacts of the CONDOR system. This document includes a Life Cycle Assessment (LCA) to measure environmental indicators such as greenhouse gas emissions, resource usage, and waste production across the device's lifespan. Additionally, the report explores the social acceptance challenges related to adopting low-TRL (Technology Readiness Level) technologies like PEC systems. By integrating environmental and societal dimensions, this deliverable aims to identify both the technological advantages of the CONDOR system and potential barriers to its adoption. This dual approach informs future development stages and offers insights for stakeholders considering PEC technology's role within broader energy and climate goals.

2. Life Cycle Assessment (LCA) of a CONDOR System.

Emission reduction is a critical issue because of its direct impact on global climate change, public health, and environmental sustainability. Thus, reducing emissions is essential to mitigate the worst impacts of climate change and limit global temperature rise to 1.5°C or 2°C, as targeted by the Paris Agreement (COP21). The **International Energy Agency (IEA)** and **Conference of the Parties (COP)**, key global players in climate policy, aim to drive the world toward a low-carbon economy [1]. The chemical industry is at a crucial stage where it must significantly accelerate its decarbonization efforts to meet the IEA and COP targets. By developing innovative technologies, improving energy efficiency, and shifting to sustainable practices, it can align with global climate goals.

CONDOR is aimed at the production of fuels by using carbon dioxide (CO_2) as feedstock and sunlight as the sole energy source. The project proposes a photosynthetic device made of two compartments: (a) a photoelectrochemical cell that splits water and CO_2 and generates oxygen and syngas, a mixture of H_2 and CO; (b) a (photo)reactor that converts syngas into methanol and dimethylether (DME) see Figure 1.

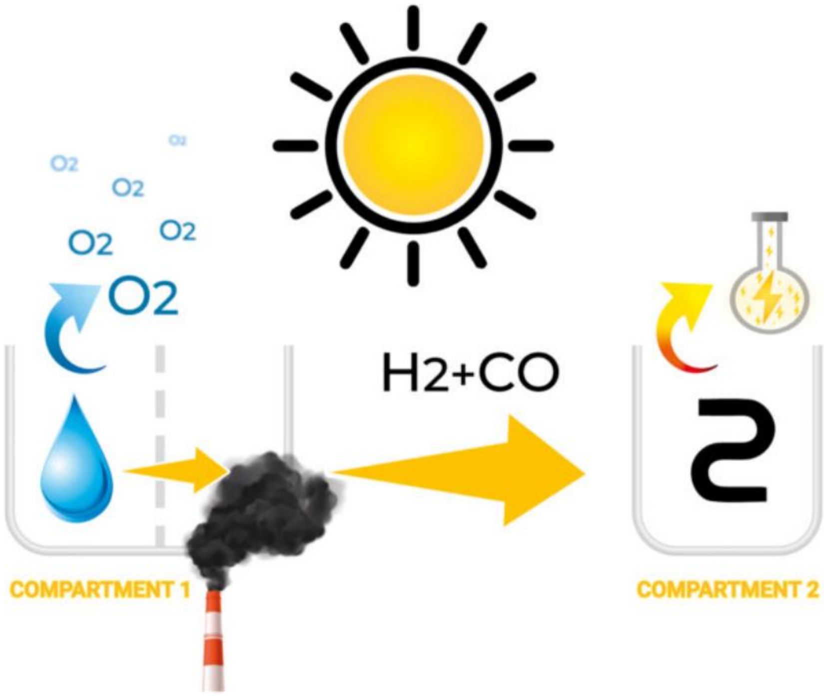


Figure 1: Scheme of the CONDOR device affording the solar driven conversion of CO2 and H2O into fuels [2]

This task aims at quantifying the life cycle environmental performance of the CONDOR project based on a standardized (ISO 14040/14044) methodology: Life Cycle Assessment (LCA). This assessment will be used to guide the development of the project through key environmental performance indicators and to inform future stakeholders on the performances to support their decisions.

This report encompasses a brief presentation of the methodology of LCA, the inventories collected from the project partners, an analysis of the results and the conclusions.

2.1. The Methodology of LCA

LCA is a methodology used for the analysis of the environmental impact of a product, process, or activity over the course of its lifetime by identifying and quantifying the energy and materials used and waste released to the environment.

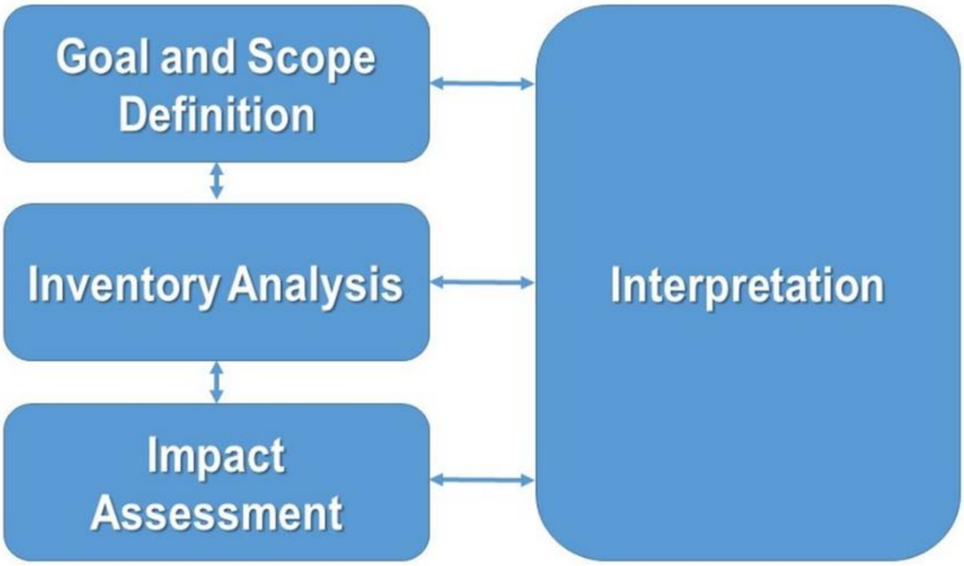


Figure 2: Description of the LCA methodology (ISO 14044, 2006)

The LCA methodology is supported by two ISO standards: ISO 14040 (ISO, 2006) and ISO 14044 (ISO, 2006) [3], [4]. The methodology is divided into four steps as shown in Figure 2.

The different steps will be detailed in the following sections.

2.1.1. Goal and scope definition

The first step of the methodology is to define the goal and scope of the study which encompasses:

- The context and goal of the study;
- The scenarios to be assessed;
- The definition of the functional unit: quantitative description of the service provided by the system;
- The description of the system boundaries: which steps/processes are included or excluded from the study;
- The list of the selected indicators and the chosen impact evaluation methods.

2.1.2. Context and goal of the study

The objective of this LCA is to assess the environmental performance of the technological bricks used in the CONDOR project and to compare them with alternative scenarios. It is important to realise that this LCA is performed at a very early stage of development of the technologies assessed, which have relatively low technology readiness levels (TRLs) of 3-5. Therefore, the goal of the study is to provide a first overview of the most-impacting phases of the project, of the performances of some bricks of the system and the overall system when compared with other production technologies and to guide on where efforts should be made to reduce the environmental impacts. These results should not be used for communication outside the project since the technologies are not mature enough to be compared to classical alternative technologies and no external review has been performed.

The conclusion of this study should be used to highlight the main hurdles encountered by the technology when upscaled and hint material and process research towards efficient and viable solutions.

2.1.3. Scenario Compared

The base scenario is the production of DME from PEC-produced hydrogen, as defined in the CONDOR project. DME is a liquid hydrogen carrier that responds to the challenges of hydrogen storage and transport, and can be seen as a player for decentralized energy use and storage.

The environmental impacts of this base scenario are analysed and compared with the conventional process of DME production. Some sensitivities analyses are also considered.

The study follows a cradle-to-gate approach meaning that it covers all processes from the raw materials extraction to the production of the DME production.

2.1.4. Definition of the functional units

According to ISO 14044:2006, the functional unit is a “quantified performance of a product system for use as a reference unit”. Generally, a functional unit shall be precise and quantifiable.

The functional unit is: The production of 1 kg DME.

A lifetime of 20 years for the production installation is considered in this study.

2.1.5. System boundaries

ISO 14040 defines the system boundary as a “set of criteria specifying which unit processes are part of a product system”.

The main steps of the base scenario are presented in Figure 3.

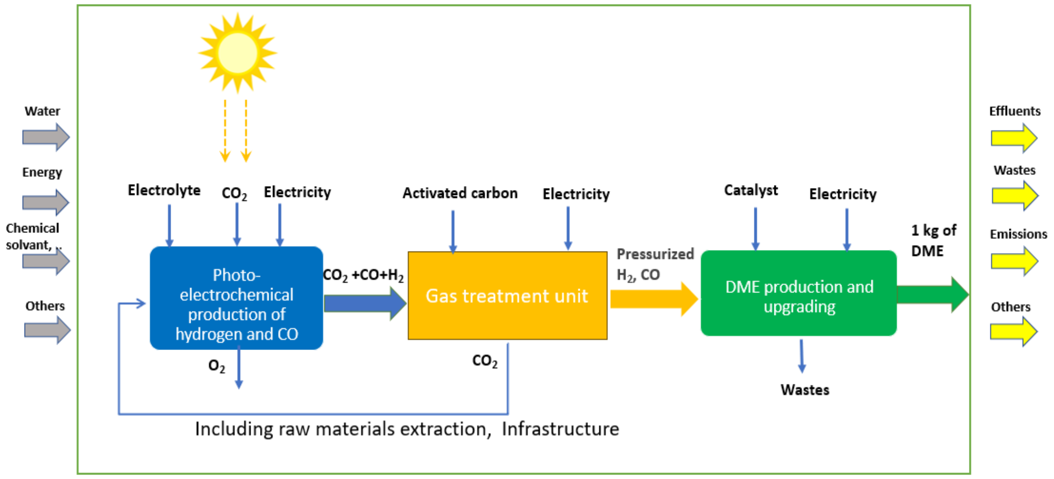


Figure 3: Boundaries of the CONDOR (base scenario)

The steps that are accounted for in the study:

- The extraction of the raw materials and their transportation based on average global market data;
- The material and energy inputs during the various production processes;
- The specific equipment and infrastructure used during the production phases.

2.1.6. Geographical and temporal scopes

To align this study with the Techno-economic assessment (TEA), the system is assumed to be installed in Italy, so electricity consumed from the grid is assumed to be originating from Italy is assumed to be from the consumption electricity grid mix in Italy. Some sensitivities analyses on energy sources are also considered.

The assessment is made for the current technologies and design.

2.1.7. Selected indicators and impact assessment method

An impact assessment method enables to the transformation of the inventory (energy and material inputs, emissions) into environmental impacts that are presented as indicators.

The Environmental Footprint (EF) method (version 3.1) [5] is used as it is one of the most recent and updated methods currently available. The list of indicators available in this impact assessment method is presented below:

Table 1: List of the EF method indicators

Indicator	Unit
Climate change	kg CO_2 eq
Ozone depletion	kg CFC11 eq
Ionising radiation	kBq U-235 eq
Photochemical ozone formation	kg NMVOC eq
Particulate matter	disease incidences
Human toxicity, non-cancer	CTUh
Human toxicity, cancer	CTUh
Acidification	mol H^+ eq
Eutrophication, freshwater	kg P eq
Eutrophication, marine	kg N eq
Eutrophication, terrestrial	mol N eq
Ecotoxicity, freshwater	CTUe
Land use	Pt
Water use	m^3 depriv
Resource use, fossils	MJ
Resource use, minerals and metals	kg Sb eq
Climate change – Fossil	kg CO_2 eq
Climate Change – Biogenic	kg CO_2 eq
Climate change – Land use	kg CO_2 eq
Human toxicity, non-cancer – organics	CTUh
Human toxicity, non-cancer – inorganics	CTUh
Human toxicity, non-cancer – metals	CTUh
Human toxicity, cancer – organics	CTUh
Human toxicity, cancer – inorganics	CTUh
Human toxicity, cancer – metals	CTUh
Ecotoxicity, freshwater – organics	CTUe
Ecotoxicity, freshwater – inorganics	CTUe
Ecotoxicity, freshwater – metals	CTUe

For ease of interpretation, the most relevant indicators need to be selected. It was chosen to concentrate the analysis on two indicators presented below. This choice was made based on ENGIE expertise and since these indicators encompass major environmental issues like global warming, and resource use (see Appendix 1 for more information on these indicators):

- **Climate change**: this indicator deals with the emissions of greenhouse gases (GHG) like carbon dioxide, methane, N_2O etc.
- **Resource use – minerals and metals:** assessment of the depletion of the minerals and metals used in the system expressed in kg Sb-eq.

2.1.8. Software and database used

The systems were modelled in Simapro 9.6 using the Ecoinvent (3.10) database for all background processes. This LCA database proposes inventories for various processes (material production, energy production, waste treatment, etc.).

2.2. Life Cycle inventory

The Life Cycle Inventory (LCI) is the data collection step of Life Cycle Assessment (LCA) where inputs and outputs for a specific product system are collected and quantified over its life cycle. The ISO lists the following data types that must be collected see Figure 4:

- energy, raw material flows and other inputs (e.g., chemicals)
- products and co-products
- waste flows
- flows that can be recycled or valorized
- emissions to air, water, and soil
- other environmental characteristics

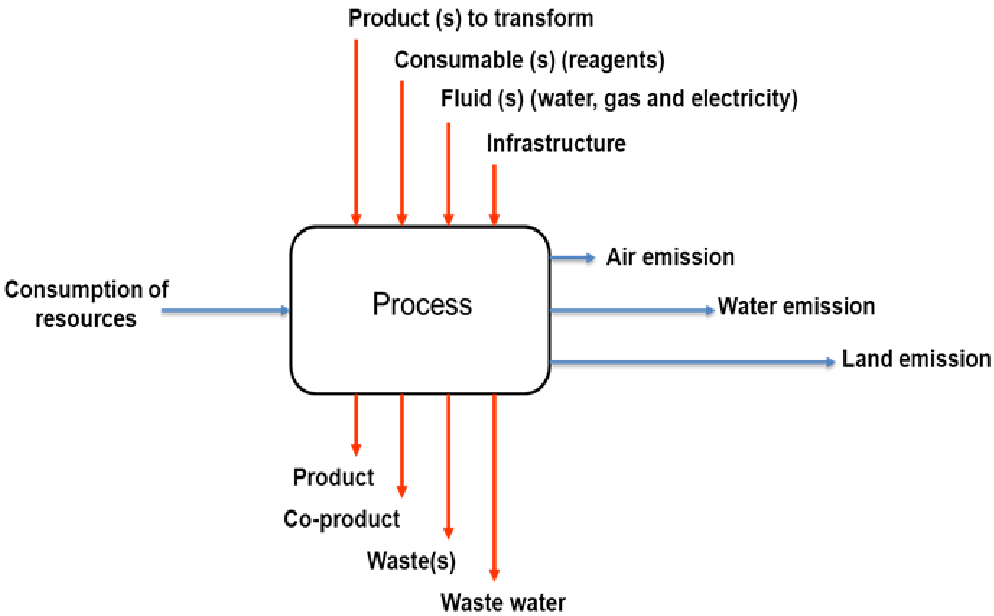


Figure 4: Life-cycle inventory

The inventories of each step of the model will now be presented in the form of tables that list the inputs (energy and material flows) and outputs (air emissions, waste). These flows were given by the partners of the projects based on Excel data collection files provided by ENGIE. The objective was to have data representative of an industrial scale as much as possible which was not easy as only demonstrator-level data was available. Some values had to be estimated, all explanations are provided in the last column of the tables. The data finally used are in line with the calculations of the TEA study.

Two difficulties arose from this data collection step:

- The data were, sometimes, not directly available or hard to quantify so assumptions based on expertise or literature review were therefore necessary.
- The flows that needed to be modelled could not always be found in the LCA database. The LCA database (ecoinvent v 3.10) proposes inventories which are already gathered, for various processes (materials, energy, waste in such cases assumptions had to be made, either by taking a similar product accessible in the database or by searching in scientific publications.

The inventories for each step are presented in the next sections.

2.2.1. Photoelectrochemical production of hydrogen

The CO_2 to syngas (H_2:CO) photoelectrochemical cell (PEC), designed in Condor project, is currently composed of three parts: the photocathode, the photoanode, and a membrane. The photocathode reduces CO_2 into syngas while consuming H^+ ions and photons, which excite the electron catalyst. The photoanode oxidizes water through electron excitation via photon absorption, producing O_2 and supplying H+ ions to the cathode. The membrane ensures the transport of H^+ ions from the anode to the cathode. Additionally, in industrial implementation, a photo concentrator is foreseen to increase the yield of electron excitation from the photons.

The PEC was modelled to produce 36.5 ton/year for a lifetime of 20 years and the PEC components are assumed to be replaced once in this lifetime. Therefore, the quantity of all the components except the housing part has been doubled. Wiring was excluded because no data were available.

Table 2: Data Photoelectrochemical production of hydrogen (source expertise from H_2 lab)

	Component	Flow/Process	Value	Unit	LCI dataset	Comments
Infrastructure	Cathode	Cooper	1034	kg	Copper {GLO}| market	The thickness is 250 micron, surface 25 cm^2, density is 8.96 g/cm^3. The total cells needed are 92942 cells.
	Anode	Glass	23236	kg	Flat glass, uncoated {GLO}| market	
		FTO	2	kg	Indium tin oxide powder, nanoscale, for sputtering target {RER}| market	
		Hematite	0.98	kg	Iron ore concentrate {GLO}| market	
	Membrane	Zirfon	1354	kg	Zirconium oxide {GLO}| market for zirconium oxide	
	Casing	Polypropylene	8532	kg	Polypropylene, granulate {GLO}| market	Housing window to let light in
		polymethyl methacrylate	11188	kg	polymethyl methacrylate, beads {GLO}| market	
	Piping for water	Polyvinylidenchloride	7998	kg	Polyvinylidenchloride, granulate {GLO}| market	We considered a total piping length PVC of 1034 m, standard diameter of pipes of 0.5 m and thickness of pipes of 10 mm
	Piping for H_2	Chromium steel	61880	kg	Chromium steel pipe {GLO}| market	We considered total piping length of 1034 m, standard diameter of pipes of 0.5 m and thickness of pipes 10 mm
Operation	Electrolyte	KHCO3	20168	kg	Potassium carbonate {GLO}| market	
		Electricity	2409000	kWh	Electricity, medium voltage {It}| market	It is used by pumps, compressors and control systems needed for the PEC plant
		CO_2	6000	kg	Carbon dioxide, liquid {RER}| carbon dioxide production, liquid	CO_2 is assumed to be captured from an ammonia production plant where carbon is released during the process.

						CO_2 losses upon capture are not included because they are counted by the CO_2 producer who would have emitted them anyway. Electricity was adapted with Italian mix. Infrastructure of carbon capture and liquefaction plant was excluded. It was considered that 90% of CO_2 was recycled from the gas treatment unit into the PEC
Hydrogen production plant	Amount of hydrogen produced during the total lifetime		730000	kg		36500 kg / year
	Lifetime of the plant		20	Years		

2.2.2. CO_2 capture, compression and liquefaction accounting

As illustrated in the previous table, CO_2 capture and compression was accounted with the market process from ecoinvent that considers a capture, compression and liquefaction from an ammonia plant. The electricity sources were adapted to consider the Italian grid mix.

It must be noted that the electricity consumption at this step will highly depend on the considered source of CO_2 and especially its level of purity.

Another important aspect of this step (CO_2 Capture, compression and liquefaction) is the way to account for captured CO_2.

In this study, it has been considered that the captured CO_2 used in the process would benefit from a -1 emission factor (EF) considering that it has been captured and thus its release would have been avoided. This benefit consideration implies that the producer of CO_2 (the previous system) has to account for its emission to respect the global CO_2 accounting. This is illustrated in Figure 5.

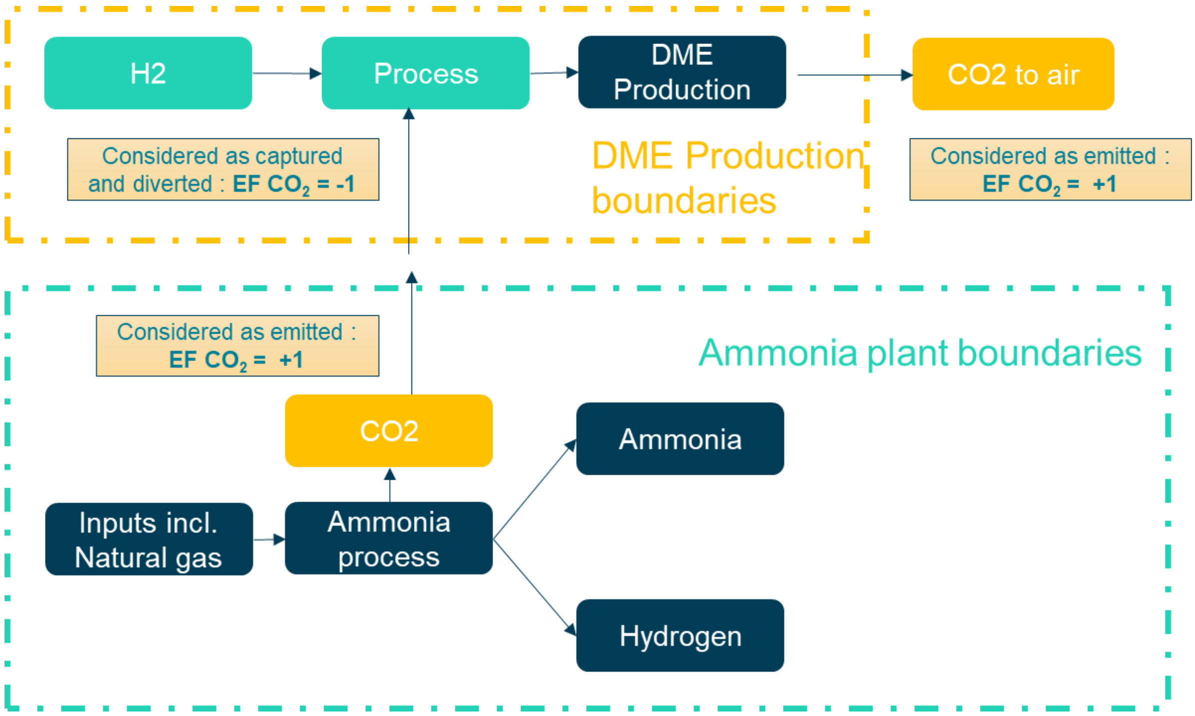


Figure 5 : System boundaries and CO_2 flow accounting (base case)

As a sensitivity, it has been considered that the CO_2 producer (former system boundaries) has already claimed for the benefits of capturing its CO_2, resulting in no emission from its side. This is the case illustrated in Figure 6. In this case, the CO_2 user (the DME producer) cannot claim for the -1 emission factor in its CO_2 capture accounting. Consequently, the emission factor for the captured CO_2 flow is set to 0 However, all the utilities (energy consumptions etc.) of the CO_2 capture, compression and liquefaction are still accounted for.

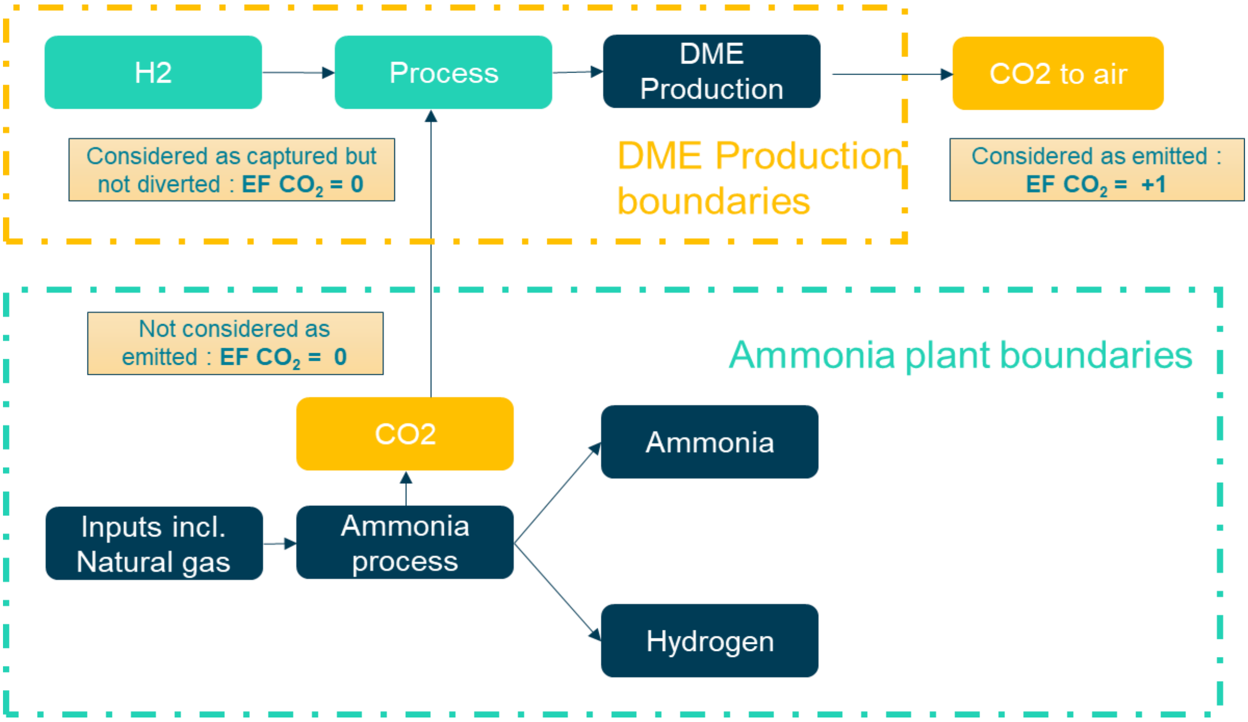


Figure 6 : System boundaries and CO2 flow accounting (sensitivity case)

2.2.3. Pressure swing absorber (PSA) for gas treatment

After the CO_2 to syngas PEC, we obtain a syngas (H_2:CO) with unreacted CO_2. This unreacted CO_2 will not be beneficial for the production of DME in the next photochemical reactor. Therefore, CO_2 is removed by a pressure swing absorber (PSA) and recycled back to the CO_2 to syngas PEC. The PSA, fed with pressurized CO_2 charged syngas, uses activated carbons, zeolites, or molecular sieves to absorb the CO_2 while letting the CO and H_2 syngas molecules pass through. Once the adsorption capacity is reached, the vessel is isolated while another one starts its adsorption cycle. Then the pressure is increased and CO_2 is released. The vessel is then ready to start a new adsorption cycle.

The gas treatment unit is composed of 4 vessels of 150L with 10mm thickness. Data related to the infrastructure and energy consumption is presented in the table below.

Table 3: Pressure swing absorber (PSA) (source expertise from HYGEAR and Laborelec)

	Component	Flow/Process	Value	Unit	LCI dataset	Comments
Infrastructure	Vessels	Steel	368	kg	Steel, low-alloyed {GLO}| market	We have considered 20% of margin
Operation		Activated carbon	420	kg	Activated carbon, granular {GLO}| market	4 vessels of 150 liters filled with activated carbon density of ~700kg/m3
		Electricity	10108	GJ/year	Electricity, medium voltage {It}| market	

2.2.4. DME production and upgrading

The DME reactor receives syngas with a 2.41 ratio (H_2:CO). It mimics the incumbent thermo-catalysis conversion of syngas into DME/Methanol. After the DME reactor, the outlet stream from the second reactor is composed of unreacted syngas, CO_2, methane, methanol, and DME. This mixture is not suitable for sale as it does not meet DME product specifications. The product upgrading phase separates the different products and concentrates them to reach these specifications. It is composed of 3 steps. A first stripping distillation recovers gases with the lowest boiling point, including H_2, CO, and CH_4, at the top. The liquid mixture composed of methanol, DME, and water exits the bottom of the first distillation, receives additional heat, and enters the second distillation column. The second rectification distillation column further purifies DME to specification. DME exits at the top, ready for storage and shipment to the market. Meanwhile, the mixture of methanol and water exiting at the bottom can be further refined but is considered as waste. Table 4 presents data related to DME production and upgrading. Infrastructure for upgrading was excluded because no data was available. Table 4 presents data related to DME production and upgrading.

Table 4:DME production and upgrading. (source expertise from HyGear and Laborelec)

	Component	Flow/Process	Value	Unit	LCI dataset	Comments
Infrastructure	Reactor	Stainless steel	765	kg	Steel, chromium steel 18/8 {GLO}|	Assuming all walls of the tube to be of stainless steel 316 with 2 mm thickness and the shell to be 10 mm thick, the total weight of the shell and tube (including a 20% margin)
Operation for DME production	Catalyst material	copper zinc alumina (CZA)	105	kg	Copper cake {GLO}| market Zinc {GLO}| market	105 kg of which 27 kg of copper and 13 kg of Zinc and thus 65 kg of alumina for the production of 36.5 t/year of DME. Catalyst is assumed to be changed every 4 years.
		Electricity	6.64E11	cal/year	Electricity, medium voltage {It}| market	
Operation for DME upgrading		Electricity	1.2E12	cal/year	Electricity, medium voltage {It}| market	

2.2.5. Reference technology: 1 kg of conventional DME production

This process was taken from the Ecoinvent (3.10) database Dimethyl ether {GLO}| market and adapted with Italian electricity mix. This process includes raw materials and chemicals used for production, transport of materials to manufacturing plant, estimated emissions to air and water from production (incomplete), estimation of energy demand and infrastructure of the plant (approximation). It considered the production from methanol with a process yield of 95%.

2.3. Impact assessment results

In the following sections, the environmental impacts from DME production is presented.

2.3.1. Environmental impact of 1kg of DME produced in the CONDOR project

2.3.1.1. Climate Change impact

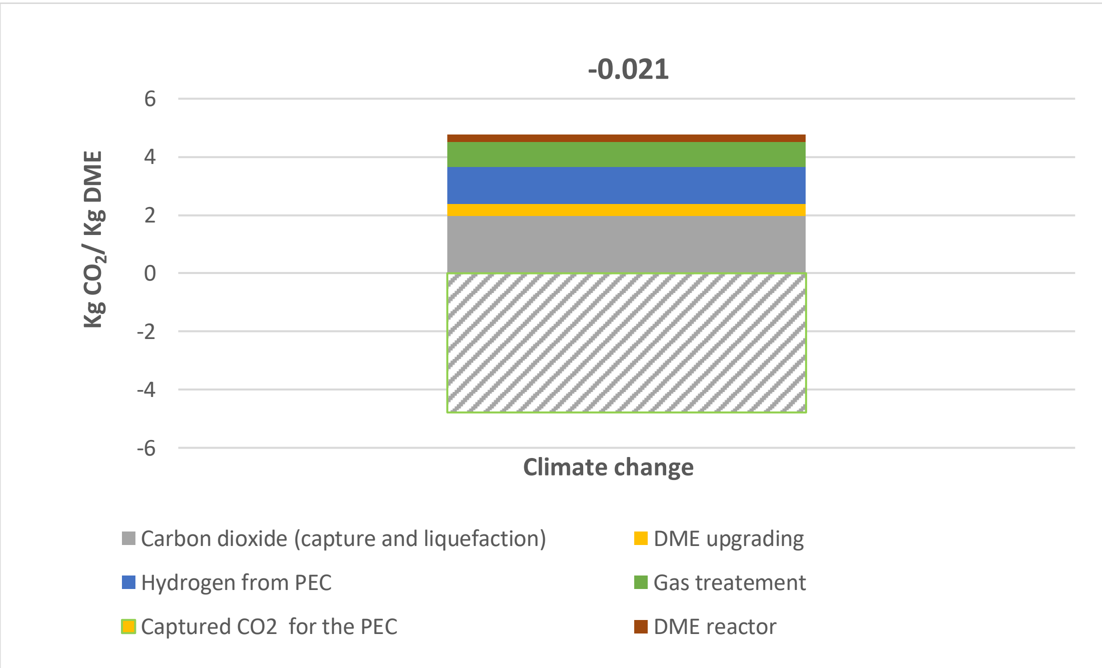


Figure 7: Climate change impact of the production of 1kg of DME in the CONDOR project

As presented in Figure 7 above, the production of 1 kg of DME within the CONDOR project has a total impact of -21 g of CO_2 eq. The main source of GHG emissions comes from the capture and liquefaction process of the CO_2 as it requires heat consumption from natural gas (combustion) and Italian electricity. This process represents 21% of the total climate change indicator. Regarding the negative impact, it is important to highlight that the quantity of CO_2 captured is considered as a negative contribution to the climate change indicator, as introduced in Figure 7. This justifies -43% of the total climate change performance. The hydrogen produced from PEC also has an important impact (14 % of climate change impact), mainly due to the electricity consumption. Those contributions will be further detailed per phase of the DME production within the CONDOR project.

2.3.1.2. Resource use mineral and metals impacts

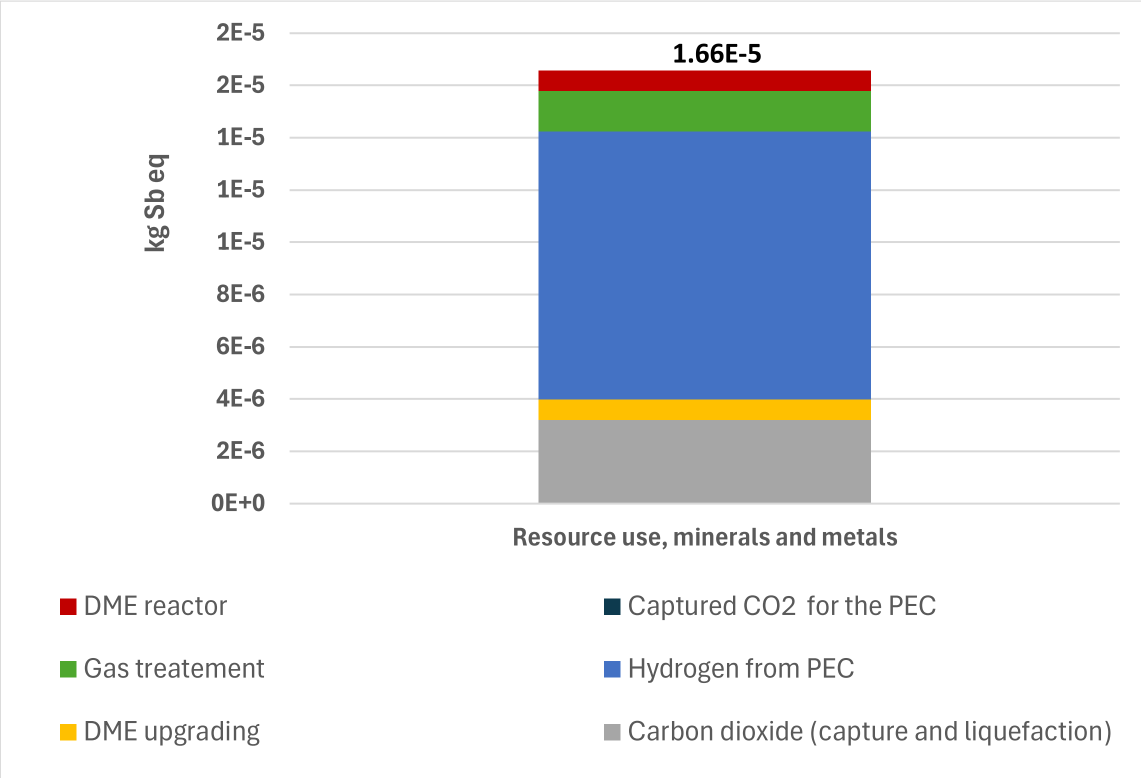


Figure 8: Resource use, minerals and metal impact of the production of 1kg of DME in the CONDOR project

Related to the impact on resource use, minerals and metal, the main impact comes from the hydrogen produced from PEC (62%), The CO_2 (capture and liquefaction Plants) also has an important impact (18 % of resource use, mineral and metals). see Figure 8. Those contributions will be further detailed per phase of the DME production within the CONDOR project.

2.3.2. Focus on the environmental impacts of the hydrogen produced from PEC

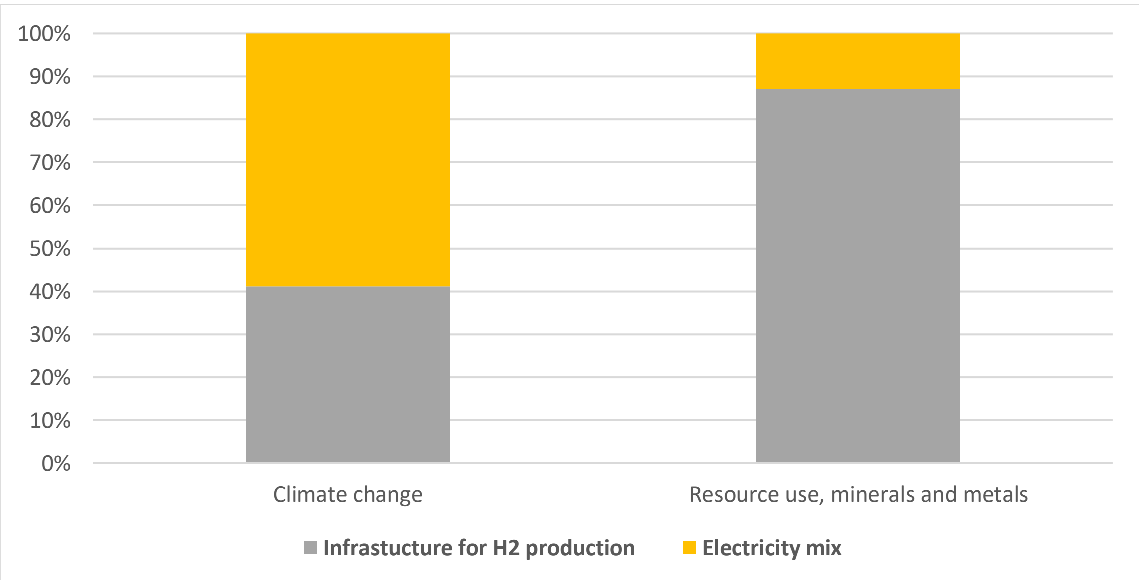


Figure 9: Environmental impacts of hydrogen produced from PEC

As illustrated Figure 9, regarding the climate change impact, most of the pollution of the production of Hydrogen (through PEC) (60%) comes from the electricity consumption to produce 1 kg of H_2. The process used in the modelling comes from the ecoinvent v3.10 database that considers the consumption mix of the country in 2021 according to the IEAreports. In Italy, the main source of electricity is the natural gas (43%) and its combustion releases CO_2 emissions. There are also 8% of oil and coal in the electricity mix that are responsible for CO_2 emissions. Hence, optimising the process efficiency and the source of energy mix are crucial to minimising climate change impact.

Regarding the resource use, minerals and metals, indicator, the manufacturing of chromium steel pipes shows a relatively large part of the impacts of resource use mineral and metals. Therefore, a major axis to minimise the impact of the infrastructure for hydrogen production would be the decreased use of chromium steel pipes.

2.3.3. Focus on the environmental impacts of the carbon capture and liquefaction plant

The results are then analyzed at the capture, compression and liquefaction step. It must be noted that this paragraph will only study the utilities at this step and will not mention the negative flow of CO_2 at the absorption.

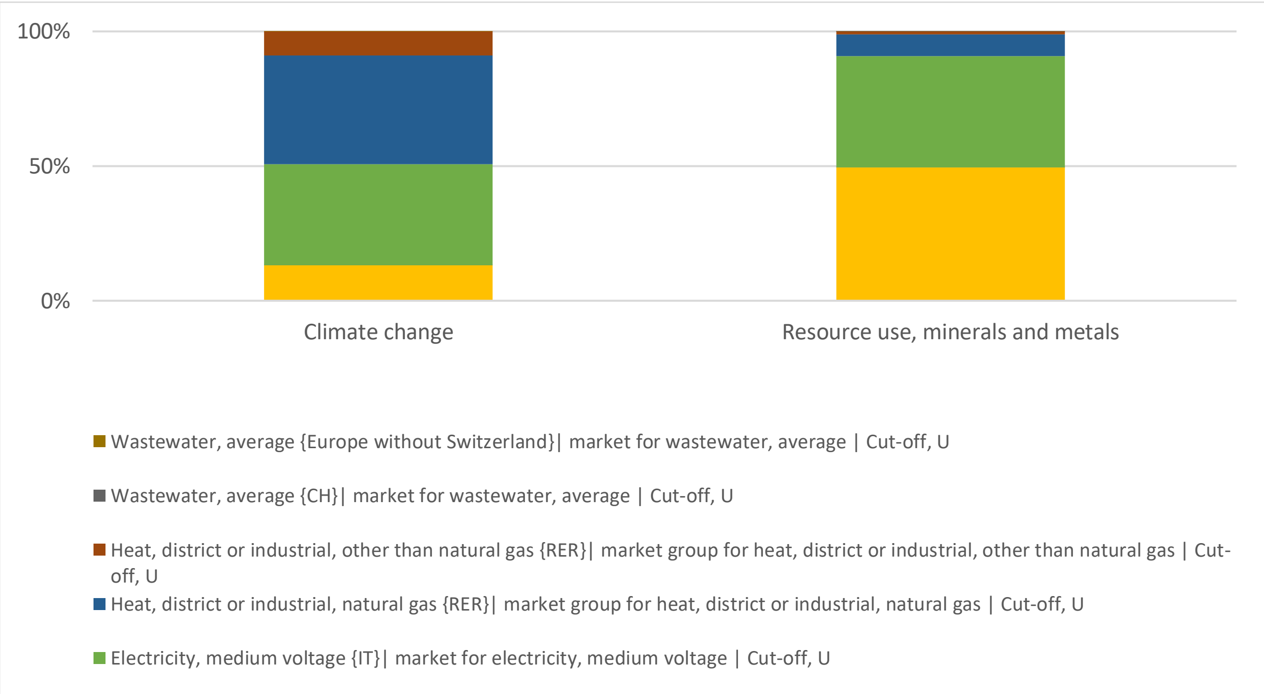


Figure 10 : environmental impacts of carbon capture and liquefaction plant

As shown in Figure 10, the climate change impact comes from the consumption of heat (40%) and electricity (40%) during the capture, compression and liquefaction phases.

The impact on the resource use, minerals and metals, indicator is primarily due to the use of monoethanolamine for post-combustion carbon capture (50% of the total impact). Monoethanolamine, a compound used in chemical absorption methods for capturing CO2 from exhaust gases, requires infrastructure and civil work for its production. It must be noted that the infrastructure needed for the monoethanolamine production has not been excluded because it is directly modelled by the ecoinvent database and it does not represent a particular plant (approximation), thus its importance must be carefully interpretated. Additionally, the production of electricity needed for the operation of carbon capture systems, is an important contributor to this indicator as well (40%) as it involves the use of significant amounts of copper for the transmissions.

2.3.4. Comparison with conventional DME production

As mentioned earlier, the production of 1 kg of DME from PEC-produced hydrogen was compared to 1 kg of conventional fossil DME, which operates using Italian electricity. The results are presented in Figure 11.

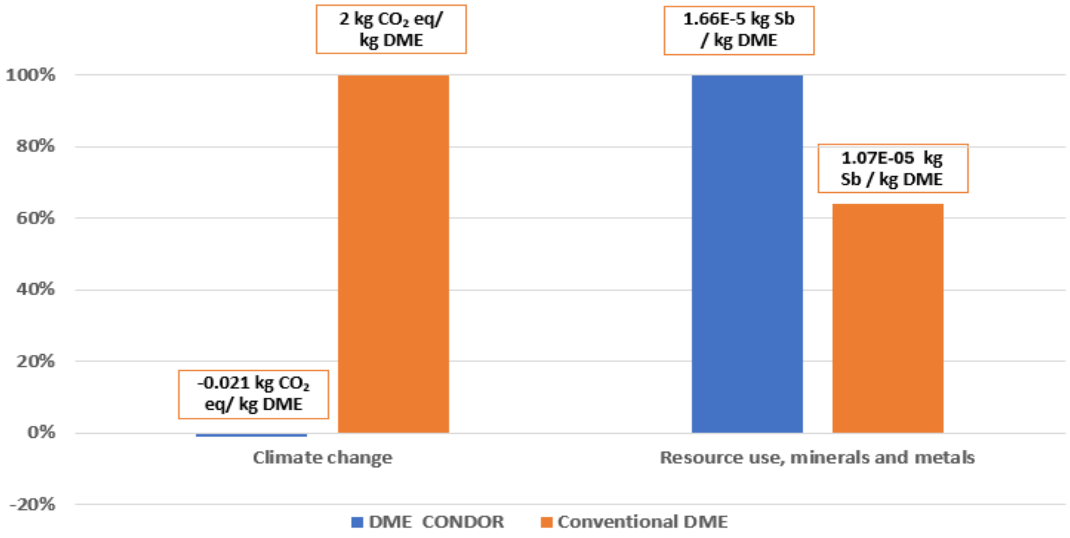


Figure 11: Comparison of environmental impacts for 1 kg of DME from PEC-produced hydrogen & conventional DME

The climate change impact of DME from PEC-produced hydrogen, operated with an Italian electricity mix and considering that the captured CO2 is characterized as an avoided emission (emission factor of -1), is lower than that of conventional DME. The climate change impact for the DME produced in the CONDOR project is -0.02 kg CO2 eq/kg DME, compared to 2 kg CO2 eq/kg for conventional DME, operating in Italy as well.

However, for the impact on resource use, minerals and metals, the DME produced in the CONDOR project has a 36% greater impact than conventional DME. The main source of pollution for the CONDOR project is the use of chromium pipes for the PEC process.

2.4. Sensitivity analysis

As presented in the analysis of the impact of the DME production, the energy consumption and thus energy source is a main contributor to the climate change indicator. The source of the electricity is thus studied under a sensitivity analysis to highlight the limits and the opportunities of such a parameter.

This score is completely driven by the strong assumption that the captured CO_2 flow could benefit from an emission factor of -1 due to its capture. As discussed in Figure 12, this hypothesis is strong and implies that the previous system (the CO_2 producer one) has not claimed for the benefits of the capture itself. A sensitivity analysis is led to show the importance of such an assumption on the calculation.

The key contributors on the impact of DME production analysis are CO_2 capture are liquefaction and energy consumption. Therefore, the sensitivity analysis focuses on the electricity mix used and whether the impact of the captured CO_2 is considered or not in the climate change indicator. For the electricity mix, three sources were analyzed: the Italian electricity grid mix as the base case, the French electricity mix a sensitivity towards a lower-carbon intense electricity (~70% of nuclear within the mix) and a sensitivity towards a green guaranty of origin with a 100% wind electricity source. Finally, this study compared 7 different scenarios:

- Scenario 1: 100% of Italian grid mix (386 gr CO_2 eq/ kWh) with negative impact of captured CO_2 (base case)
- Scenario 2: 100% of Italian wind electricity (21 gr CO_2 eq/ kWh) without negative impact of captured CO_2
- Scenario 3: 100% of French energy mix (79 gr CO_2 eq/ kWh) with negative impact of captured CO_2
- Scenario 4: 100% of Italian grid mix without negative impact of captured CO_2
- Scenario 5: 100% of Italian wind electricity without negative impact of captured CO_2
- Scenario 6: 100% of French energy mix without negative impact of captured CO_2
- Scenario 7: Conventional DME with 100% of Italian grid mix (reference case)

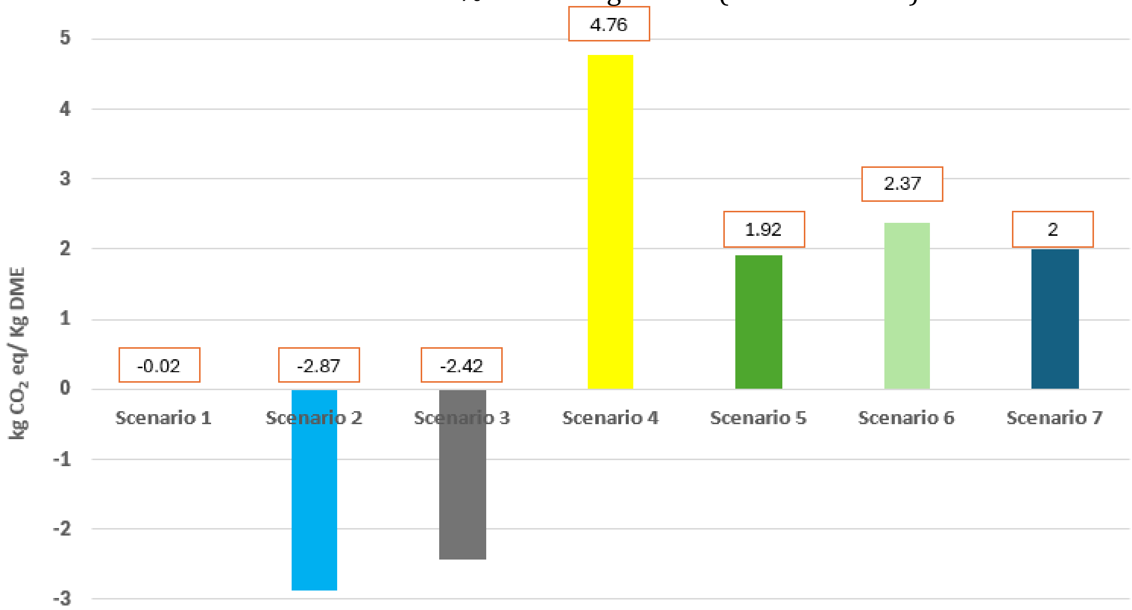


Figure 12 : Sensitivity analysis related to climate change impact

As shown in Figure 12, the first notable aspect is the significantly higher impact on climate change when using Italian grid electricity and not accounting for the negative impact of the captured CO_2 (Scenario 4: 4.76 kg CO_2 eq/ kg DME). This impact is approximately 50% lower when using French grid electricity (Scenario 3: 2.37 kg CO_2 eq/ kg DME). Climate change is drastically reduced when using wind energy and considering the negative contribution of capturing the CO_2 to the climate change indicator (Scenario 2: -2.87 kg CO_2 eq/ kg DME). This difference highlights the structural influence of electricity supply needed for PEC operation and whether the impact of the captured CO_2 is considered.

2.5. Conclusions

This study aimed at computing the environmental performance of the e-DME produced within the CONDOR project. The climate change indicator and the resource use, minerals and metals, indicators were studied, leading to a base environmental score of -0.02kg CO_2eq./ kg DME and 1.6E-5 kg Sb eq./kg DME. Conventional DME, produced in Italy, has an environmental score of 2 kg CO_2 eq./kg and 1.07E-5 kg Sb eq./kg DME, representing a +100% and -36% difference, respectively, compared to DME produced through the CONDOR project.

This study shows that the choice of energy source plays an essential role in determining the overall impact of climate change. Using renewable energy sources, such as wind, drastically reduces climate change, especially when the CO_2 captured during the process is considered as a negative contributor to the climate change indicator (-2,87 kg CO_2 eq./kg DME). In contrast, the use of electricity from fossil-fuel-based grids, such as the Italian electricity mix, significantly increases the environmental burden.

3. Societal insights related to the development of a CONDOR System

The Horizon project Condor aims to develop a technological device that can produce DME from photo-electrocatalysis. Beyond the technical aspects of this project, which consist of identifying the relevant nanomaterials and catalysts for photo-electrocatalysis or building the pilot device, this project also considers societal and environmental aspects associated with this technology. This deliverable focuses on understanding the societal issues (e.g. potential transformation of current market and/or professional habits, sociopolitical transformation, hydrogen/DME consumption practices) related to this technology.

Research projects in the EU horizon framework usually examine a technology's societal aspects under the social acceptance framework. According to social science literature, such framing induces various challenges for social scientists, especially for low-TRL technologies.

In this deliverable, the first section will briefly discuss the issue related to the social acceptance framing to detail the approach and methodology implemented in the CONDOR project. Conversely, from the traditional approach of social acceptance, looking for a set of indicators (e.g. willingness to pay, risk perception, influence of information) to illustrate this notion, the research perspective adopted in this report focuses on the sociotechnical expectations related to CONDOR system regarding its current sociotechnical environment.

After clarifying the research approach and adopted methodology, the report details the expectations regarding the CONDOR system and challenges them regarding competing technologies and broader foresight ambitions. Regarding the context of this research and the time frame related to the commercial availability of Photo Electrocatalysis, we consider a foresight exercise managed by the European Research Council depicting the potential future of the EU in 2040. Finally, the conclusion of this report delivers strategic orientations to consider improving the primary understanding of socio-economic issues related to this emerging technology.

3.1. Considering the Social Acceptance of a Low TRL Technology: Conceptual and methodological issues.

Research and innovation related to the development of technology devices are increasingly considering these technologies' societal and environmental impacts. Social acceptance has been a rising issue within the renewable energy and low-carbon technology sectors since the late 1990s, as has wind power development (Wüstenhagen et al., 2007). These researchers say wind power benefits from a positive image for the public, as tested in opinion polls. Therefore, project developers had not anticipated the local contestation (Carlman 1982). Since then, managing research on social acceptance of renewable energy technology has become critical, especially regarding the European Union funding framework.

However, managing social acceptance research on a technology not currently used remains challenging. The literature about social acceptance of renewable energy technologies offers various methodological options for considering this issue but also has significant limitations. The following paragraphs detail how traditional research manages social acceptance issues. Then, limitations regarding these types of approaches will be discussed.

Research papers on the social acceptance of renewable energy focus on characterizing factors that consider a limited number of dimensions. Some researchers, for instance, analyse the best information to communicate to favour the acceptance of renewable energy projects (Itaoka 2009). Others take a more econometric approach, considering the potential factors influencing the willingness to pay for having more renewable energy in the energy mix (Choi kim et.al. 2024) . Finally, regarding more controversial low-carbon and renewable energy technological projects, some social acceptance research papers adopt a psychometric approach to characterize the drivers of risk perceptions associated with a technological artifact for a population sample (Abbas, Techato et.al. 2024; Linzenich, Arning et.al., 2021). Other research papers consider the perception of trust in technological project proponents (Huijts, Midden et.al. 2007;Karytsas, Polyzou et.al 2023).

Many of these research works adopt a quantitative approach to characterizing social acceptance indicators. According to the Social Studies of Science and Technology (STS), this constitutes a significant limitation to these research works.

Since the 1980s, Social Studies of Science and Technology have demonstrated that scientific discovery and the design of technological systems are not as independent from economic, political, or societal constraints as they pretend (Bijker, Pinch et al., 1987). In the energy domain, the research of T.P Hughes (1983) on the building of electric networks in various cities constitutes the first illustration of this type of research considering altogether science and technology and economics and society. As a historian, Hughes focused on the evolution of electrical systems in Chicago, London, and Berlin for fifty years, from 1880 to 1930. This historical approach enabled him to highlight how various stakeholders solved various sociotechnical issues. For instance, he stressed how sociotechnical issues are mainly managed by inventors and engineers during an initial period. However, during the large-scale development of a system, financial stakeholders played the most significant role.

In addition to this initial research, recent research works display similar insights related to the interdependencies between renewable energy technologies and the socio-economic dimension (Nadaï, Labussière 2018). Indeed, this book is an inquiry into energy transition's socio-economic and sociopolitical processes. The analysis of various renewable energy technologies and case studies enable the researchers who contributed to this book to highlight how energy transition affects various publics.

Therefore, the Social Studies of Science and Technology illustrates that technology, economy, politics, and society are deeply intertwined. Consequently, it has two profound implications for traditional social acceptance research focusing only on the lay public. First, they are taking for granted a sociotechnical design that will not be discussed anymore. However, STS literature and concrete project implementation demonstrate that this issue is mostly discussed. Then, the extensive use of quantitative approaches in social acceptance research builds a false representation of a situation. Indeed, perceptions and representations of innovative technologies are unstable. However, questionnaire surveys have a high degree of framing and are highly dependent on what project developers include in their questionnaires. In addition, the literature (Nadaï, 2009) and the concrete implementation of technological projects show the formation of a genuine public and stable opinion (Dewey, 1946)during the implementation phase. Nadaï distinguishes between “generic” and “situated” technologies in its paper on wind power. According to him, generic technologies generally relate to technology with its intrinsic attributes. For instance, he considers generic technologies to be those described in the International Energy Agency reports.

Conversely, situated technologies are those embedded within a heterogeneous network. It relates to specific projects dealing with the societal, political, and territorial ecosystem. To summarize our view, traditional social acceptance research are confusing the acceptance of a generic technology with the acceptance of a situated technology without considering the establishment of the heterogeneous network in their research.

Beyond illustrating the limits of traditional social acceptance research, STS literature also provides concepts to consider the social acceptance of innovative and not diffused technologies. Around the 2000s, STS academics designed the concept of sociological expectations of technologies. Borup et.al (2006) define “*technological expectations as real-time representations of future technological situations and capabilities*” (p. 286). In addition, they also consider that these expectations are performative and prefigurate the prominent use cases of a technology rejecting alternative options and organizing a technological trajectory. Expectations engage the network of stakeholders to share a common agenda regarding the technological capabilities required.

Considering the expectations of a technological device is critical regarding the issue of social acceptance. Indeed, shifting from characterizing social acceptance factors to understanding the expectations expressed by the project developers enables us to consider tangible sociotechnical aspects of a technological project. In this perspective, considering social acceptance of technology implies comparing expectations of technologies and project developers with expectations from the market and the territories. The various technological roadmaps of a defined sector enable the identification of various types of expectations from the market. Then, territories at various scales also manage projective exercises. For instance, in France, local communities established territorial master plans. In addition, quantitative greenhouse gas emission reduction targets are defined according to the regulation on energy transition. The French government has also managed Foresight exercises with a specific institution regarding long-term development. Regarding the context of this research project, territorial perspectives of the implementation of PEC technology have a very loose definition. Indeed, one of the primary goals of this project rely on demonstrating the system's reliability. That implies more lab-scale research with no actual use cases accurately defined. However, to enlarge the loose definition use cases by project developers and provide a context to a Condor system we therefore considered foresight exercises in the European Union. Despite it does not provide an accurate territorial context it enables to characterize barriers and levers regarding this low TRL technology. This context characterisation remains the main challenge regarding the consideration of the social acceptance of low-TRL Technology.

3.2. Methodology and approach

The theoretical approach described above illustrates expectations related to technologies. Market expectations, territorial master plans, and foresight exercises share a common nature: they all take a narrative form. Therefore, this qualitative research will analyse the collected narratives and illustrate consistency or discrepancy between PEC developers' expectations and competing narratives.

We mainly use the actantial methodological model defined by the linguist Algirdas Greimas (1977) to analyze these narratives. This researcher defined this analytic tool as a tool for analysing action in a narrative. He understood that each narrative is composed of six actant and three axes:

- The axis of desire: A subject (Actant 1) is directed toward an object (Actant 2). In the context of this research, it corresponds, for instance, to the developer of PEC systems.
- The axis of power links the helpers to a subject (Actant 3) and the opponents to the subject (Actant 4). In the context of research on a system combining PEC and DME production, helpers can correspond to all the elements supporting the system's development (e.g., regulations, stakeholders, etc.) or, conversely, for the opponents, hampering the (e.g., competing systems) technology's development.
- The axis of transmission: which links a sender (Actant 5), motivating the action of the subject to a receiver (Actant 6), which benefits from this action.

The following scheme illustrates this analytical tool.

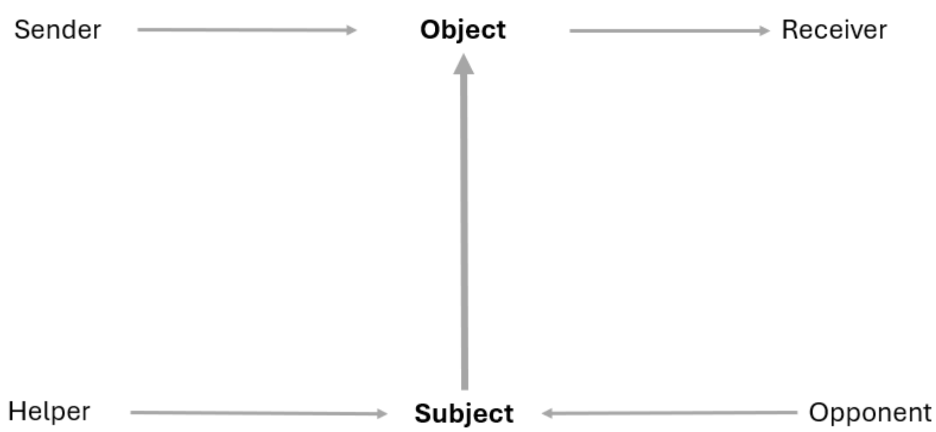


Figure 13 : Actantial model concept representation

In this research, we can apply this analytical tool to the narrative related to the technology developed within the Condor project, competing technologies, and territorial development pathways. Regarding the narratives considered in this report, we considered the project description and research reports from the Suner-C consortium to describe narratives related to the Photo-ElectroCatalysis system, a technological report dedicated to energy storage from MIT, and foresight exercises from the European Union research council. In addition, the results displayed in this report also benefit from previous research managed during the Sun To X project. To supplement our documentary analysis, we also tried to manage interviews with experts, but despite various solicitations, we were unsuccessful. Indeed, it also limits the management of social acceptance research on a low-TRL technological system.

3.3. Technoscientific promises related to CONDOR technological device

As described in the project summary, the technoscientific promise of the technology developed within the CONDOR project is to mitigate anthropogenic climate change by producing chemical molecules such as DME or methanol based on recycled CO2 and sunlight. According to the project developers, this process would not require critical material and no additional energy. Indeed, the chemical process only needs ambient temperature to happen. The following scheme illustrates this narrative.

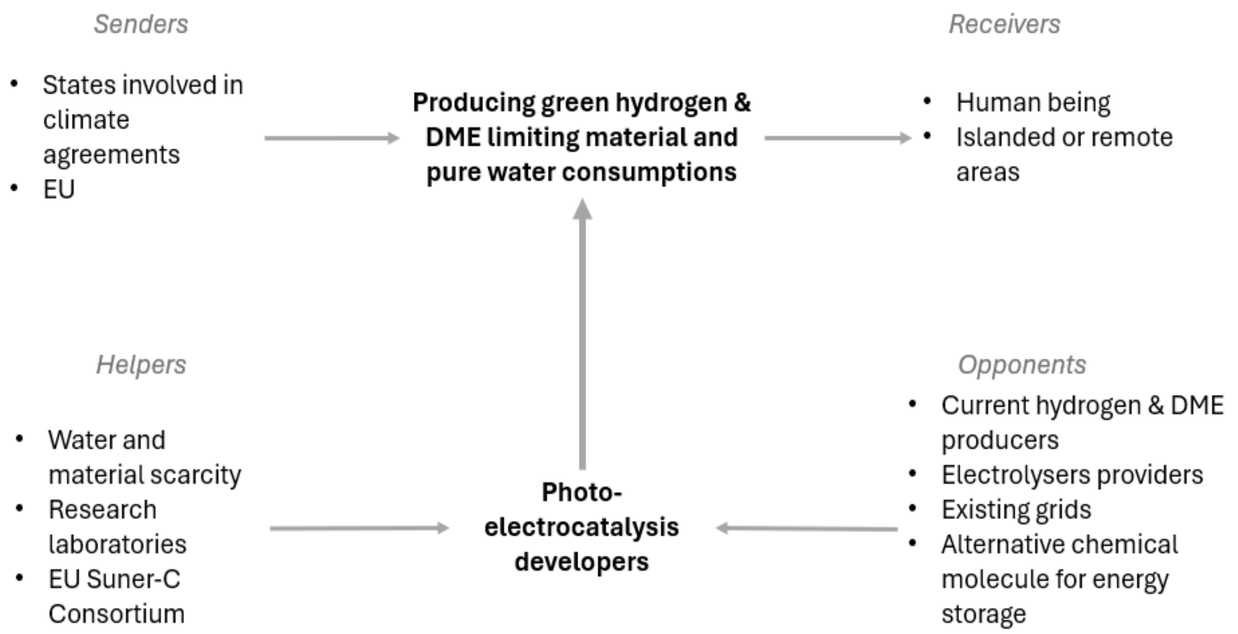


Figure 14 : Actantial model of the CONDOR project

Regarding this narrative, producing synthetic fuels through these technological devices is a relevant option that could be quickly adopted if technologically reliable and economically profitable. However, as with most innovative technologies, this approach to producing solar fuels creates tensions with :

- The existing fossil fuel production system
- The current Low-carbon and (emerging) renewable hydrogen production system based on water electrolysis
- The current energy storage system (considering an energy system dominated by variable renewable energies).

Indeed, each technological system contributes to co-produce (Jasanoff 2004) its socio-economic ecosystem. Therefore, describing alternative narratives of these competing systems is critical to considering the potential socio-economic challenges the CONDOR technological system could face.

3.3.1. Solar synthetic fuel production challenges the current fuel production system

The traditional fuel production system characterizes large-scale infrastructures and the centralization of fuel production units. Fuel is then distributed through pipeline networks or trucks to refuelling stations. As briefly described in the paragraphs above, Photo-electrocatalysis Technologies enable fuel production with small-scale devices that could be located near the consumption points and by path or at least challenge the established power of current fuel producers. In addition, they also have other technologies enabling them to remove carbon from fuel production with a lower disruption in their model. For instance, by inception, carbon capture and storage (CCS) technologies have been framed as technologies that enable a quick and dramatic reduction of carbon emissions without widely transforming the socio-economic system (Marchetti, 1977). Furthermore, CCS technologies have a higher TRL despite the few large-scale projects.

3.3.2. The photochemical Versus Multi-steps process

Beyond the fossil fuel industry, the proponents of photo-electrocatalysis projects also have to consider developing alternative solar fuels using multi-step technological systems. Kasper Ampe, in a deliverable of the Suner- C initiative, managed a qualitative survey (15 interviews) with stakeholders involved in solar fuel development to characterize sociotechnical visions of solar fuel. Through his research, he identified five sociotechnical visions.

However, before summarizing the results of Ampe's research results, it is critical to remember the distinction he made between the mode of production of solar fuel through:

- multi-steps process: aiming to combine solar photovoltaic and existing electrolysis to produce solar fuels
- direct process: aiming to integrate the same technological device, solar energy, and electrolysis.

To characterize these sociotechnical visions, Ampe identified key stakeholders (e.g., University, industry, civil society, political stakeholders) promoting this vision, described their framing of this vision and the knowledge and technologies needed, and, finally, the implication in terms of governance of this vision.

- **First vision: Anticipating the direct conversion of solar light into fuels and chemicals.**

As Kasper shows, this vision is primarily supported by chemists, biologists, and some industry stakeholders. The framing is that of a decentralized, small-scale hydrogen production system attempting to scale up laboratory-available technologies while distancing itself from energy-intensive technologies such as CCS, Haber-Bosch, and thermal cracking. What is challenging about this vision is that solar fuel users have concentrated fuel needs, which are different from those of these production systems. In terms of governance, this approach follows the logic of energy communities and prosumers.

- **Second vision: Hand in hand electrification and multi-step conversions to synthetic fuels and chemicals**

The proponents of this vision are more aligned with energy-intensive sectors such as aviation, maritime, and industry. They focus on life cycle assessment (LCA) issues and thermodynamic questions. They oppose various groups, including those advocating for direct conversion, those supporting CCS/CCU as a permanent solution with a more or less delay tactic, and those advocating for an exclusively hydrogen and electrical conversion solution.

The framing of this vision is linked to a representation of a significant increase in energy demand that cannot be met solely by renewable energy. Decarbonizing fuels with CCUS and mature technologies could help meet this ambition, though there is a risk of lock-in with these technologies without subsequent transformations toward other models.

This vision firmly separates science from politics, with policymakers holding or expected to hold scientific results. Decision-making relies more on LCA and TEA results and the definition of the merit order.

Regarding the challenges, the actors supporting this vision emphasize the need to define a coherent business model, as the technologies already exist. In terms of governance, proponents of this vision highlight the necessity of having a governance framework that facilitates the implementation of these technologies.

- **Third vision: Being agnostic to the technology to reach shared carbon emission reduction goals**

The proponents of this vision are mainly energy companies, along with some politicians and scientists, with an ambition to convince the supporters of Visions 1 and 2. The framing of this vision recognizes the absence of a single solution. Multiple solutions are, therefore, necessary to achieve the objectives. In terms of knowledge, the advocates of this vision emphasize the need to establish a consensus between science and politics, relying on scientifically proven observations that are compatible with companies' ESG criteria. Regarding technologies, multiple options are possible. The tipping point lies in deciding whether maximizing renewable production and minimizing transportation costs is better or the reverse. In terms of governance envisioned in this vision, a decision-making space is identified involving politics and the market, but it relies on scientists' decisions.

- **Fourth vision: Prioritizing renewable energy and electrification**

The proponents of this vision are primarily experts from energy institutes and NGOs who oppose the H_2 hype and see solar fuels as a delaying strategy by industries.

In terms of framing, the proponents of this vision highlight the paradox of using green electricity to produce hydrogen or synthetic fuels with reduced production efficiency and the paradox of importing hydrogen. Ultimately, the proponents of this vision agree on using solar fuels under certain conditions related to energy balance and their application in specific economic sectors where emissions are challenging to reduce.

Regarding knowledge, this vision is more guided by a comprehensive energy evaluation, but it can be open to third parties such as academics.

Regarding technologies, the proponents of this vision advocate for a focus on sectors that cannot be electrified and for maximizing the valorisation of CO_2. If importation proves necessary, it could also be an opportunity for the Global South to develop a renewable energy network and associated jobs.

In terms of governance, the proponents of this vision support adherence to a long-term European program focused on electrification. They also advocate for the broad involvement of stakeholders to ensure the viability of solutions not only from a climate, social, and environmental perspective but also economically.

- **Fifth vision: Building a just and electrified energy future**

The proponents of this vision are primarily NGOs, unions, and civil society groups that advocate for social justice in the context of energy transition. They oppose the powerful hydrogen lobby, which is closely tied to natural gas actors and the perspective of technological neutrality. They also limit their support for solar technologies used in synthetic fuels from the first and second visions.

Like the fourth vision, the proponents of this vision question the energy balance of synthetic fuel production compared to the efficiency of batteries and heat pumps. Moreover, they argue that technological neutrality should be challenged because no technology is ever neutral in terms of social impact, and therefore, industrial actors should not be allowed to choose the least expensive option simply.

Finally, they consider it necessary to reopen the discussion on the actual need for solar fuels, which the industry often presents as inherently necessary without questioning the requirements for renewables, the critical materials needed, and circularity issues. This vision's proponents emphasize the importance of social sciences in addressing these issues.

Regarding technical challenges, they mention the scarcity of renewable energy, which should guide the choice to prioritize electrification, limit the use of solar fuels to hard-to-convert sectors, and reject the import of solar fuels to avoid reproducing green neocolonialism.

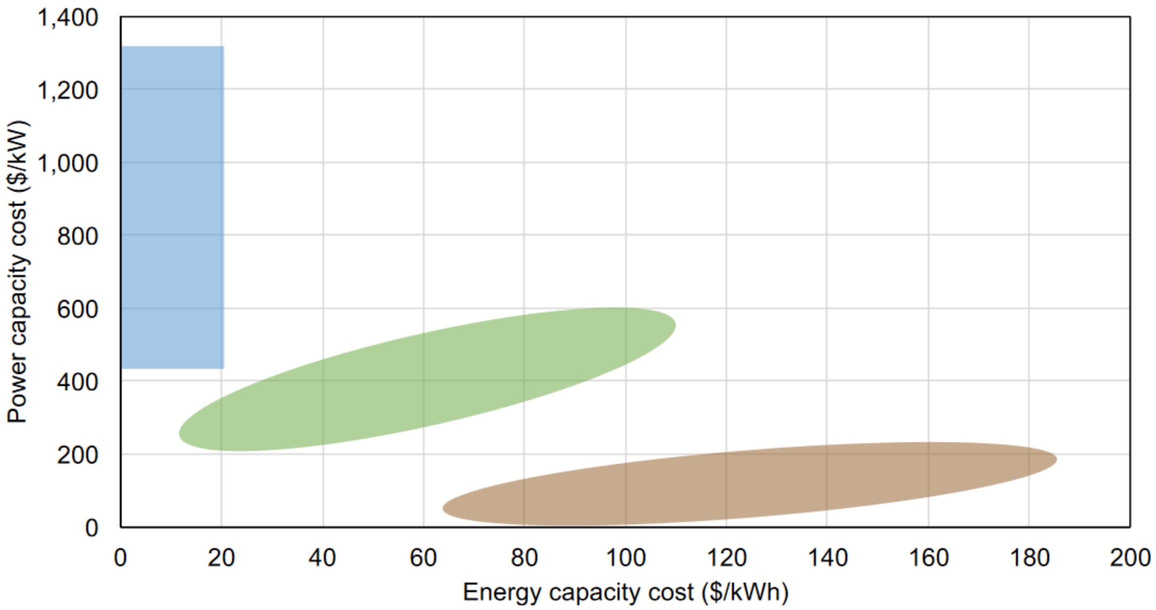
In terms of governance, the proponents of this vision stress the importance of considering different possibilities according to territorial contexts. Additionally, they emphasize the importance of democratic deliberation regarding these technical choices, which actors sometimes overlook when claiming urgency to act.

Ampe's characterization of these visions provides an exciting overview of sociotechnical issues to consider when developing solar fuel technologies. It perfectly illustrates a potential competition between technological approaches regarding the same purpose. Therefore, the technological devices developed in the CONDOR project must deal with these various competitive framings.

Alternative energy storage solutions

To supplement Ampe's overview, consider alternative technologies for energy storage. MIT recently released a report comparing various energy storage technologies in the context of an energy system based on Variable Renewable Energy (Armstrong, Chiang et al., 2022). The authors of this report consider two variables to characterize three groups of energy storage, as illustrated in the following chart.

The power capacity cost relates to the cost of technology in terms of the instantaneous power it delivers. The energy capacity cost can be define as the cost of operating an energy storage technology regarding their maximum power storage capacity. The energy capacity costs is the cost of discharge power. (the length of time over which the facility can deliver maximum power when starting from a full charge).



The blue region, with high power and low energy capacity costs, includes thermal, chemical (e.g., hydrogen), metal-air battery, and pumped hydro storage technologies. Lithium-ion batteries fall in the brown area, with low power, but high energy-capacity costs; flow batteries fall in the intermediate, green region. In addition to the two parameters displayed in this figure, other cost and performance attributes, e.g., charge and discharge efficiencies, are also important when comparing storage technologies within and across each class. The full set of characteristics used in system modeling are discussed in Chapter 6.

Figure 15 : Various groups of energy storage (Armstrong, Chiang, 2022 p.14)

According to this typology, DME processed in the CONDOR system belongs to the blue region of the previous chart. Lithium-Ion batteries to the brown region and flow batteries to the green region of this chart. This typology clearly places on the same perspective storage technologies like, thermal storage, chemical storage, metal air batteries and pumped hydro storage technologies. Regarding this blue category, the authors of this report shows that pump hydro storage are an important mean to store a large amount of energy during a long time period. However, due to the low energy density of this type of technology for energy storage, hydro pump storage infrastructure are expansive to build and had environmental impacts.

In this report the researchers from the MIT mainly focus on Hydrogen as a chemical storage molecule. According to these researchers hydrogen is an interesting molecule to store energy. Indeed, hydrogen need only one step to be produce with electrolysis. However, hydrogen is not easy to store but in combining it with CO_2 or Nitrogen makes transportation and storage easier.

This combination of hydrogen with other molecules constitutes a core issue of the CONDOR project which focuses on DME. This combination embeds the technological system in the current fuel infrastructure. In the context of CONDOR project the use of the DME produced remains a pending issue. Literature shows that DME is especially considered in China or Japan as a substitute for natural gas (Larson, Yang 2004) injected in the network or for mobility through fuel cells (In brief 2002).

Regarding a social science perspective the production of DME through PEC raises various issues. Regarding a potential use as a substitute for natural gas in network how the technology can overcome the challenges of an established network (of Power) (Hughes 1983)? Then, regarding a transportation option DME will also have to face the massive adoption of electric power in road transportation sector especially in Europe (Rivière, Pigeon 2023).

3.3.3. Conclusion of the first part of the analysis

This first part of the report illustrates the expectations of Condor project developers regarding their new device and the potential barriers they may encounter regarding the current energetic system. Indeed, Ampe has shown in his research for the Suner-C consortium the development of solar fuel technological devices. Multi-step pathways, CCUS, or full electrification have all their proponents, and photochemical technologies proponents must defend their vision to develop their devices. Although these other technologies also have to face debate, they benefit from more robust infrastructures, which limit questions regarding the technological pathways considered. Then the use of DME, remains pending in the context of the CONDOR project. However, as mentioned according to emerging use cases, the combination of PEC and DME raises uncertainties regarding the embeddedness of the technology in an existing network and its capabilities to overcome the massive investment in electric land mobility in the European Union.

3.3.4. Potential for photo-electrocatalysis implementation according to the European Union foresight scenarios

The previous section illustrated the potential sociotechnical issues that photo-electrochemical devices would likely face according to current technological development pathways related to competing hydrogen production technology and energy storage technologies. As the technological roadmaps consider the commercial availability of PEC technologies around 2040, we expand this initial analysis by considering foresight works to characterize the potential future beyond just technological consideration. As the CONDOR project is part of European Union funding, we refer in the following paragraphs to the reference foresight scenarios designed by the expert of the European Commission (Vesnic-Alujevic et al., 2023). We first provide an overview of the foresight methodology and then describe the defined scenarios more accurately. Finally, we will characterize the main implications regarding sociotechnical related to PEC development. The goal of presenting these foresight scenarios is not to consider one favourable to the others but to characterize trends that potentially have an influence on PEC development.

3.3.5. Methodology applied for this foresight exercise

The authors of this foresight report emphasize that, in light of the COVID-19 pandemic and the war in Ukraine, preparing for the unknown is more necessary than ever to improve decision-making in situations of uncertainty. To achieve this, the Joint Research Center facilitated the development of four foresight scenarios using the Oxford scenario planning approach and engaged more than 100 experts. Four scenarios were developed with a time horizon of 2040 for the European Union:

1. Storms
2. End game
3. Struggling
4. Synergies
5. Opposing views

According to the authors of this report, the scenario exercise supports decision-makers by:

- Stress-testing current and future policies
- Highlighting strategic decisions
- Discussing implications in a particular policy field or increasing knowledge of the future.

According to this foresight report, Scenarios are neither predictions of the future nor projections extrapolated from the present or the past. Exploratory scenarios, such as the set presented here, do not necessarily describe desirable futures, such as those based on political ambitions. Instead, they represent plausible futures with diverse trends, uncertainties, and events that interact coherently and systematically (Amer et al., 2013). (op.cit. p.7)

The joint research center used a participatory scenario-building process (the Oxford Scenario Planning Approach (Ramirez & Wilkinson, 2016)) with four main phases to build relevant scenarios.

1. Identifying and exploring assumptions
2. Research on relevant issues
3. Scenario development
4. Validation

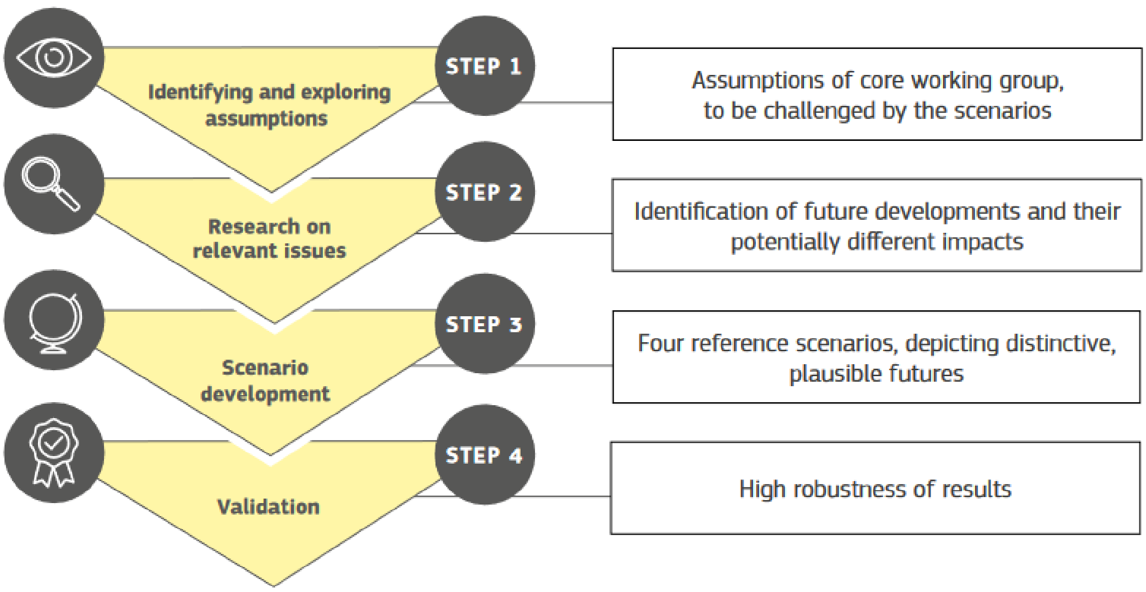


Figure 16 : Steps of scenario development process (p.9)

In the initial phase, the working group identified and explored 49 assumptions about the EU's standing in 2040. These assumptions were discussed and challenged in workshops to ensure they were comprehensive and relevant. The group also researched vital issues that could influence the EU's future, focusing on geopolitics, technology, environmental sustainability, economy, global social values, regulatory environment, and demography. This research formed the basis for developing factor cards that outlined potential future developments and their outcomes.

3.3.6. Description of each of the four scenarios

The scenario development process involved multiple workshops, during which participants created micro-narratives by selecting and connecting factor cards from different research areas. These narratives were then clustered into four comprehensive scenarios, each depicting different developments up to 2040. Expert workshops and interviews involving over 100 experts refined and validated the scenarios. This iterative process ensured that the scenarios were plausible, robust, and insightful for decision-makers.

After more accurately describing the scenario-building process, this section displays the main highlights of each scenario. Then, it considers the significant elements that may favor or hamper the development of a PEC system.

Storms Protect what you can

The following paragraphs display the micro-narrative of the storms scenario.

Global co-operation has collapsed. But was it ever real? Were we not always so insular, so distrusting of the 'other'? Isn't each region, each nation protecting its own way of life? Independence from outsiders is the modern credo that we see reflected in our mid-21st century society. Energy depends on what's available—fossils, wind, or sun. Global tech companies, their oppressive power long broken by jealous countries, have morphed into a multiplicity of local circular platforms and standards. We like our leaders to be strong, provided they look after us.

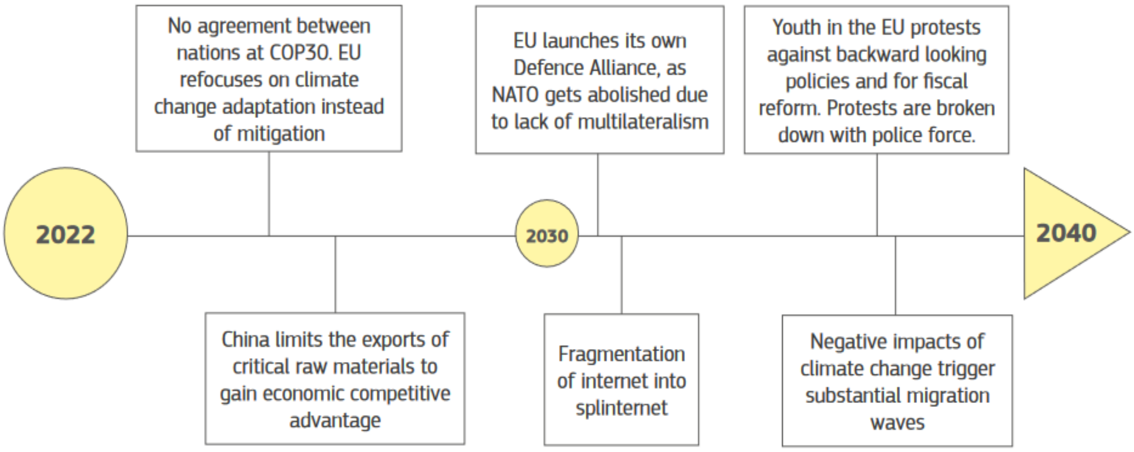
We live in a world of continuous deprivation. Weakened food supply chains, growing water scarcity, and spreading diseases prevail. Yet, rather than working together to save this planet, we have retreated into our selfish selves, instead focusing inwardly on survival and adaptation. Basic human instinct? Maybe. But still a choice. We choose to blame others rather than act unilaterally. We chose to do less than we could when others suffered. We choose to prioritise today over tomorrow.

The EU is an ageing winner but has to frame its hollow victories to protect its past successes. A collective empire jealously guards its citizens' way of life. All the while, humankind retreats into boardedup refuges, seeking some form of resilience by the environment it has so thoroughly destroyed.

Over here, on the old continent, we invested heavily in our strategic autonomy. We elected those who would prioritise our comfortable privileges—pensions, healthcare, and wasteful luxuries. And if that meant excluding youth from political power, then it was simple—the majority rules. True, we were pushed into replacing NATO because the US had its own dilemmas, but that worked out well for us in the end.

The truth is, we are comfortable here. We are much less impacted by climate change than are those in other regions. The choice of food is not what it was, but at least we have something to eat on our tables. Our children should be grateful for that.

This scenario illustrates a worldwide islanding process in which states have various consequences regarding climate change and renewable energy development. States not strongly affected by climate change are not considered or supported by strongly affected states. In addition, this fragmentation has prevented the implementation of a comprehensive climate policy, and a 3°C increase is anticipated, with more significant impacts in the southern regions.



EXAMPLES FROM THE PRESENT THAT INDICATE THE DEVELOPMENTS THAT COULD LEAD TOWARDS THIS SCENARIO

- Glocalisation of supply chains (e.g. the boost of domestic semiconductor production in the EU).
- Lockdowns in the EU during COVID-19 favoured protecting the aged.
- China is trying to fragment global internet space, and Russia is creating a cyrillic-based Internet.
- The US Inflation Reduction Act aims to develop mainly domestic energy production.
- China threatens to reduce solar panel exports to the EU.

Figure 17 : Major events until 2040 considered in the Storms scenario p.29

This world fragmentation also has consequences for worldwide supply chains. This situation favors the development of a circular economy, limiting the dependencies toward foreign regions or states. With a more specific focus on the renewable energy domain, this situation may hamper access to the critical raw material needed to build traditional renewable energy infrastructure or electrolyzers. Therefore, regarding the PEC technology, an increasing trend favoring a circular economy could benefit the development of this technology compared to other technological options.

Endgame : "Après moi le déluge"

The second scenario is entitled Endgame and it is summarized as follows:

Instant wealth is prioritised over long-term well-being. But how did we get here? Why did human ingenuity and technology not turn the situation around? The answer must lie in our deep human attachment to wealth. We crave it, even if it requires us to exploit each other and the planet on which we live. Escaping this trap would require individuals, corporations, and their nation states to cease this exploitation collectively. But how? Who polices it? Why now? These questions did not want to be answered.

We ignore uncomfortable truths, allowing private interests to dominate public policy by reframing proposals into the so-called winwin models where the GDP is the only mandatory winner. In short, exploitative economics remains king, polluters avoid consequences, and social capital is low. Our global financial institutions are intact and function well. Hyper-winning businesses are still being created. Global trade has boomed in recent decades. Material standards have risen for many despite the collapse of natural ecosystems.

Step by step, Big Tech has digitally managed to insert itself into an ever-broadening sphere of human activity by dominating public decision-making. Wealth has shifted away from the physical to the virtual world, mainly because nation states are weakened and they are no longer able collectively to impose *an effective, or fair, taxation model. Old Europe has been dragged along. The Eurozone rationale predominates, and pension and healthcare reform has closed the government deficits.*

Conflict is never far away. Rogue terrorists exploit disinformation to underpin cyberwars. For now, the US and the United Arab Emirates dominate the space race, with Europe following. China's (forced) devolution of power to the regions has been driven by demographics, debt, and enhanced global competition.

Scientists tell us that in the collapsed ecosystem, temperatures will rise by 4 °C within 60 years. The essence of our economic model is that damages to common goods, such as the environment, must be paid by society at large, not the polluter. We may live on a dying Earth, but at least some of us are wealthy.

The scenario above shows a pessimistic view regarding climate change and energy transition. Indeed, an extractive economy still dominates the world, which contradicts the circular economy supported by the solar fuel community in the Suner-C consortium. In addition, misinformation drags down efforts to manage energy transition.

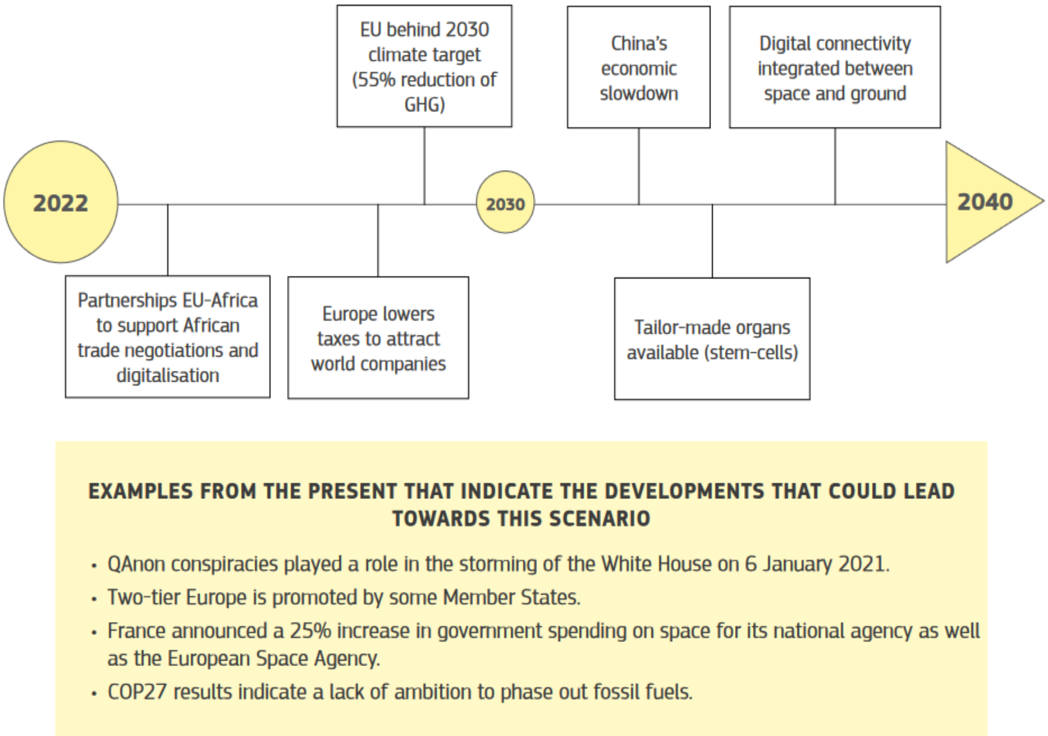


Figure 18 : Major events until 2040 considered in the Endgame Scenario (p.35)

Struggling synergies: imperfect consensus

The third scenario, designed by the European Union's expert teams, depicts the future of the EU as follows:

We live in a world of relative economic prosperity and multilateralism. Slowly, somehow, we jointly zigzag and navigate our way towards climate neutrality. Will our desires defeat our values? Can we stay aligned? Will we comply?

The world has inched forward in creating a more enduring planet. True, especially in Europe, we have acted faster when self-interest has been aligned with a better quality of life, such as in the energy sector. However, progress has been made. Yet, all around us, we see that this is an imperfect consensus. Our oceans and food supply chains need attention. Mental health is a major concern.

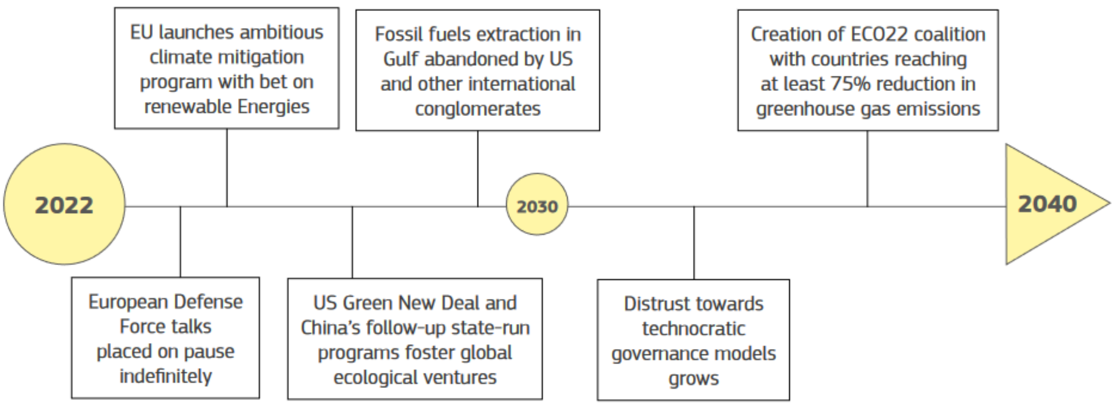
Construction, urbanisation, and technology have all helped emerging economies, as expected. The US is a pillar in the global debate, especially because of its competent, albeit aggressive, corporations. China, with its soft power and infrastructure network of allied nations, especially in Africa, is a global green leader. India's low-cost digital technology is omnipresent.

Europe is part of the global agenda. However, we have been slow and careful in all multilateral discussions, rules, and standards. There have been endless volumes of expert reports and a heavy compliance regime. Anger in a lonely civil society has been amplified by a conspiracy culture in which experts are considered the root of all evil, and some ancient fights on acquired social rights are resurrected.

The EU is now attractive to Eastern countries free of Russian influence, but elsewhere? The truth is, we are struggling, stagnating. Our new, veto-rich, semi-federal model is only just settling in, and EU membership has diminished. NATO defends us, and we enjoy the privilege, but there are costs.

We started this journey as moral leaders, and we might end it as ageing followers. Have we done enough? No. Will we be able to do what is still required? Maybe.

In this scenario, the global warming issue benefits from a consensus, and renewable energy is relatively widespread except in some states where the fossil fuels economy strongly influences the development pathway (e.g., the Arabic peninsula).



EXAMPLES FROM THE PRESENT THAT INDICATE THE DEVELOPMENTS THAT COULD LEAD TOWARDS THIS SCENARIO

- Renewable energy has expanded globally.
- President Biden won the US election, partly in support of his green agenda.
- The US rejoined the Paris Agreement.
- Global corporations shifted to stakeholder economics, where businesses are encouraged to create value for all stakeholders and put humans and environment first.
- Electric cars tripled their market share from 2019 to 2021.

Figure 19 : Major events until 2040 considered in the Struggling synergies scenario (p.41)

Opposing views. A bipolar world

The following paragraphs display the narrative of the opposing views scenario:

You need a lot of energy and courage to follow your principles. There is the constant doubt: Are we right? Would global alignment not be better? Was there, is there room for compromise? How can we persuade or co-opt others?

We Europeans have a deep sense of passing on a better world to future generations. But can we? Will the promised long-term gain ever materialise? Together with an alliance of like-minded countries, we *have co-created a world in which everything is carefully measured to deliver sustainability in the most effective ways.*

Our deep-seated sense of purpose has permeated our political discourse and every element of society. We are led by political and business leaders and cheered on by technological successes and cleaner cities. We are proud when the world's best and brightest beat a way to our shores to further our sustainability values. We feel secure in our new role as a net energy exporter and our leaps in a circular economy. At the same time, many people and economic agents attack this isolated green push and are frustrated that their counterparts in Brazil, India, Russia, and China focus solely on their economies.

Confronted with this divided world, we have sought allies. An important partnership is with the US. Japan is a solid Asian pillar. Chile and Argentina are our friends in South America, and we can rely on Australia and New Zealand in the Southern Hemisphere. However, we are also exploring new partnerships with a handful of North African states, with which we have formed a solar energy hub.

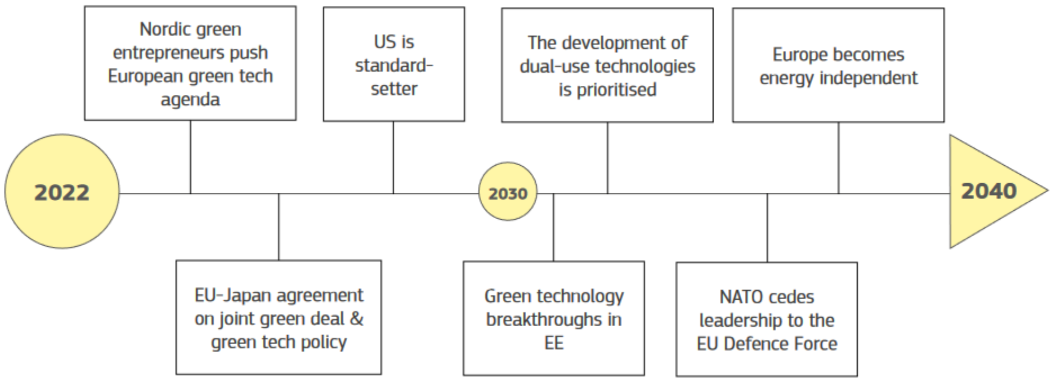
Trade with non-like-minded partner countries is pragmatic rather than protectionist. The focus is on finding substitute technologies or exchanging clean technology for imports. Despite a certain isolation and a few mistakes along the way, our ideas seem to work. We are poorer than others. We are frequently criticised on all sides. But there can be no going back.

This scenario describes a European Union that has successfully defended its values regarding sustainable development and the fight against climate change. It has strengthened specific alliances, particularly related to solar energy, but faces opposition from stakeholders interested in China, Russia, or India. Additionally, the European Union is poorer compared to other countries.

It highlights the contrast between a regenerative alliance, which relies on sustainability, and a circular economy, and an extractive alliance, which remains based on an extractive economy. The regenerative alliance has military and geopolitical capabilities that allow it to defend itself.

In the states of the regenerative alliance, happiness and environmental standards guide development strategies, with the EU serving as a model for these states, particularly in exporting green technologies. In the states of the extractive alliance, environmental standards are respected more for efficiency and cost optimization than genuine conviction.

Since only the countries of the regenerative alliance are taking action, an average global warming of around 2°C is anticipated. In this scenario, the EU produces 100% of its energy from renewable sources and exports its technologies. Additionally, the spread of vegetarianism has allowed it to become self-sufficient in its food system. Finally, pollution reduction has improved overall health. The regenerative alliance drives significant technological advancements in this scenario.



EXAMPLES FROM THE PRESENT THAT INDICATE THE DEVELOPMENTS THAT COULD LEAD TOWARDS THIS SCENARIO

- EU Member States upgraded green commitments.
- Solar panel sales substantially increased throughout the EU.
- Coal renaissance is advocated at Conference of the Parties (COP) 27.
- China, the world's biggest greenhouse gas emitter, is extending its emissions until 2030 to avoid limiting its economic growth projections.

Figure 20 : Major events until 2040 considered in the opposing views scenario (p.47)

3.3.7. Concluding remarks on foresights exercise

The foresight exercise managed by the European Union and summarized in this part enlarges our understanding of factors likely to influence the development of CONDOR technologies. If the first part of this report illustrated a significant domination of the current technological system challenging the emergence of PEC technology, this second part showed that various factors that may influence the development of a system like CONDOR. The following table summarizes which factors in each scenarios could influence the development of a CONDOR system equivalent.

	Factors potentially favorable regarding CONDOR project	Factors potentially unfavorable regarding CONDOR project
Storms : Protect what you can	• The energy management by multiplicity of local circular platform may favor decentralized hydrogen production • Focus on regional area may limit access to critical raw material and give priority to PEC technology	• The priority given to the present that may limit innovation.
End game : "Après moi le déluge"		• Domination of extractive economics (GDP maximization is a goal to rich) • No consideration for climate

Struggling synergies: imperfect consensus	• EU Ambitious climate mitigation program • US new Green Deal • Abandoned of fossil fuel extraction in the US	• Uncertainties regarding what types of low-carbon technologies are supported by the standards
Opposing views. A bipolar world	• EU has a leading position regarding sustainable development • Circular economy is central for EU • A solar energy hub is formed with North African country.	• The building of a solar energy hub can also be unfavorable regarding PEC if multi-steps process technologies are favored.

Except for the end game scenario, all the scenarios contain factors that may potentially favor the development of CONDOR equivalent system. However, each scenarios also contain uncertainties regarding regulation or priority given to innovation, which will potentially favor large scale and potentially multi-steps hydrogen production process (Struggling synergies, opposing views) or local small scale platform favoring decentralized system. Considering the scale issues framed by external factors (regulation or geopolitics) is also significant regarding the design of CONDOR system.

3.3.8. Conclusions

This research report explores the narrative related to Photo Electrocatalysis proponents and competing narratives other technology providers promote to produce hydrogen. It first illustrates that the development of PEC systems faces various competing narratives. Indeed, as displayed by the work of Ampe(2023), among the solar fuel community, PEC developers have to impose the direct conversion pathway against promoters of indirect conversion using electrolysis or against CCS promoters. This statement illustrates that PEC systems must find relevant use cases to be developed and diffused due to their decentralized purpose by design.

The exploration of potential futures, as described in the EU foresight exercise, illustrated those geopolitics, but also regulatory tools favouring or hampering the development of circular economy and or large scale system over decentralized one may have a significant influence on PEC systems development.

Regarding this context, the challenge for PEC development and acceptance is to identify use cases not addressed in the current "networks of power" (Hughes 1983) constituted by the existing fossil fuel production network or current renewable energy production network. Indeed, PEC systems are, by design, integrated hydrogen production systems. Therefore, considering areas with space constraints and hydrogen needs (e.g., islanded areas) could be a first territorial investigation opportunity. Then, regarding the purpose of CONDOR project to produce DME, a CO_2 available source will also be needed. The following map illustrates the geographic distribution of the CO_2 emissions in the European Union by activities. It allows us to identify large CO_2 emissions clusters. However, according to PEC system technical specifications, it may be more relevant to first test and develop the technology on small emissions points, trying to consider demonstration at the industrial scale of the technology and adopting a regional development strategy developing new markets and business with this new resource.

This territorial identification of available territory to develop the system constitutes the first step of the strategy to engage the socio-economic development of a CONDOR system. A supplementary task to engage after is the management of a systemic analysis of low-carbon and renewable hydrogen as well as DME production to consider what could be the leverage points[1] (Meadows, 1999) to act on to favour the development of the PEC system in the considered territorial area. Regarding the low-carbon and green hydrogen production system this system analysis could take into consideration the material structure of the system but also its rules, and the mindset or paradigm out of which the system (its goals, structure, rules, parameters arises). This analysis could then equip PEC technology developers to show how this technology could supplement and/or transform the current low-carbon and renewable hydrogen production process.

Finally, to engage relevant stakeholders (e.g., targeted industries, local elected people, environmental NGOs) towards a shift for CONDOR system, engaging in a design fiction prototyping could be a relevant approach. Indeed, the role of design is to define plans to arrange elements (practices, processes, and objects) toward a specific purpose (Montfort, 2017, p. 134). Design fiction focuses on prototyping believable futures to generate ideas and debate around potential development. For instance, according to the commercial availability of the technology estimated around 2040, considering a scenario accentuating the trends of the scarcity of available critical raw materials, the incentivize of circular economy practices as well as the limitation of networks to supply the expected quantity of solar fuel could constitute a relevant base to design a scenario.

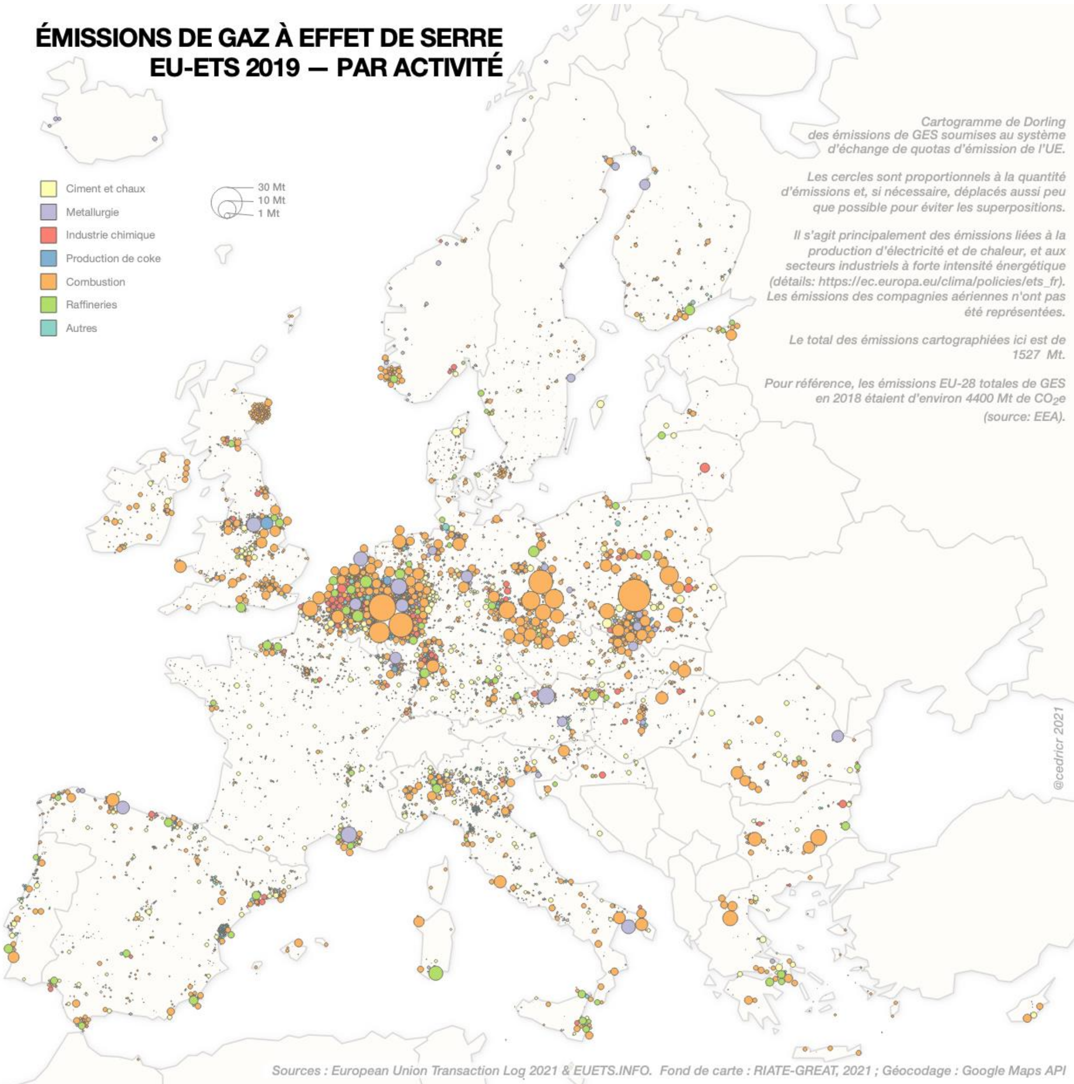


Figure 21 : Map of the EU CO2 emission based on ETS (Cedric Rossi 2021)

[1] Donnella Meadows defines leverage points as "places within a complex system (a corporation, an economy, a living body, a city, an ecosystem) where a small shift in one thing can produce big changes in everything" (p.3).

4. General conclusion

The CONDOR project demonstrates significant potential to address environmental and societal challenges by developing photoelectrochemical (PEC) technologies that convert CO_2 and sunlight into sustainable fuels such as DME. The Life Cycle Assessment (LCA) results indicate that DME produced through the CONDOR system can achieve a lower climate impact than conventional DME, particularly when renewable energy sources power the process. This result highlights the importance of sustainable energy inputs to minimize overall emissions and environmental burdens. However, resource use remains a challenge, emphasizing the need for further innovation to reduce the dependency on critical materials.

The societal insights presented in this report underscore the complexity of social acceptance of low-TRL technologies like PEC systems. As the CONDOR system progresses, addressing potential barriers related to societal perceptions and competing technological narratives will be crucial. This statement includes positioning PEC systems within existing energy frameworks and ensuring compatibility with infrastructure and consumer needs.

In conclusion, the CONDOR project offers a promising avenue for sustainable fuel production, contributing to the EU's circular economy and climate goals. Strategic efforts to optimize both environmental performance and societal integration will be vital for the successful deployment of PEC technology in the years ahead.

5. Degree of progress

Degree of fulfilment of the task activities respect of what reported in the DoA.

6. Dissemination level

Confidential

7. References

7.1. Reference of the LCA part

[1]https://www.iea.org/news/at-iea-event-cop28-president-and-other-climate-and-energy-leaders-identify-priority-actions-to-deliver-on-dubai-outcomes

[2] https://condor-h2020.eu/project/

[3] ISO 14040. Environmental management - Life cycle assessment - Principles and framework, 2006.

[4] ISO 14044. Environmental management - Life cycle assessment – Requirements and guidelines, 2006.

[5] Fazio, S. Biganzioli, F. De Laurentiis, V., Supporting information to the characterization factors of recommended EF Life Cycle Impact Assessment methods, EUR 28888 EN, European Commission, Ispra, 2018

7.2. Reference of the social science part

Abbas, S., Techato, K., Chiang Hsieh, L.-H., & Sadeq, A. M. (2024). Integrating relational values in social acceptance of photovoltaic energy storage systems : A consumers' perspective assessment using structural equation modeling. *Energy*, *304*, 132092. https://doi.org/10.1016/j.energy.2024.132092

Amer, M., Daim, T. U., & Jetter, A. (2013). A review of scenario planning. *Futures*, 46, 23 40. https://doi.org/10.1016/j.futures.2012.10.003.

Ampe, K., Paredis, E., Van Hauwert, T., & Reynaert, K. (2023). *D18-D6.1-Identification-of-important-socio-technical-cross-cutting-issues-and-relevant-stakeholders*(Research report D6.1; p. 48).

Armstrong, R., Chiang, Y.-M., & Gruenspecht, H. (2022). *The Future of Energy Storage an interdisciplinary MIT Study* (Research Report p. 404). MIT.

Bijker, W. E., Hughes, T. P., & Pinch, T. (Éds.). (1987). *The Social Construction of Technological Systems : New Directions in the Sociology and History of Technology*. MIT Press.

Borup, M., Brown, N., Konrad, K., & Van Lente, H. (2006). The sociology of expectations in science and technology. *Technology Analysis & Strategic Management*, 18(3 4), 285 298. https://doi.org/10.1080/09537320600777002

Carlman, I. (1982). *Wind energy potential in Sweden: the importance of non-technical factors.* United Kingdom.

Choi, J., Kim, J. J., & Lee, J. (2024). Public willingness to pay for mitigating local conflicts over the construction of renewable energy facilities : A contingent valuation study in South Korea. *Energy Policy*, *185*, 113930. https://doi.org/10.1016/j.enpol.2023.113930.

Dewey, J. (1946). *The Public and its problems. An Essay in Political Inquiry* (Gateway Books). https://archive.org/details/in.ernet.dli.2015.190550/mode/2up

Ellis, G., Cowell, R., Warren, C., Strachan, P., Szarka, J., Hadwin, R., Miner, P., Wolsink, M., & NadaÏ, A. (2009). Wind Power : Is There A "Planning Problem"? Expanding Wind Power: A Problem of Planning, or of Perception? The Problems Of Planning—A Developer's Perspective Wind Farms: More Respectful and Open Debate Needed, Not Less Planning: Problem "Carrier" or Problem "Source"? "Innovative" Wind Power Planning. *Planning Theory & Practice*, *10*(4), 521-547. https://doi.org/10.1080/14649350903441555

Faber, C., Allahverdiyeva-Rinne, Y., Artero, V., Baraton, L., Barbieri, A., Bercegol, H., & Fleischer, M. (2020). *Sunrise Technological Roadmap : Solar Energy for Circular economy.* (p. 78).

Greimas, A. J. (1977). *Sémantique structurale : Recherche de méthode* (Éd. 1977). Larousse

Hughes, T. P. (1983). *Networks of power : Electrification in western society, 1880 - 1930* (Softshell Books ed). John Hopkins Univ. Press.

Huijts, N. M. A., Midden, C. J. H., & Meijnders, A. L. (2007). Social acceptance of carbon dioxide storage. *Energy Policy*, *35*(5), 2780-2789. https://doi.org/10.1016/j.enpol.2006.12.007

In Brief. (2002). *Fuel Cells Bulletin*, *2002*(11), 3-7. https://doi.org/10.1016/S1464-2859(02)11009-1

Itaoka, K., Okuda, Y., Saito, A., & Akai, M. (2009). Influential information and factors for social acceptance of CCS : The 2nd round survey of public opinion in Japan. *Energy Procedia*, *1*(1), 4803-4810. https://doi.org/10.1016/j.egypro.2009.02.307

Jasanoff, S. (2006). *States of Knowledge : The Co-production of Science and the Social Order* (New édition). Routledge.

Karytsas, S., Polyzou, O., Oikonomou, T. I., & Karytsas, C. (2023). A transnational study on the determinants of social acceptance of carbon capture, transport, and storage (CCS). *IOP Conference Series: Earth and Environmental Science*, *1196*(1), 012092. https://doi.org/10.1088/1755-1315/1196/1/012092

Labussière, O., & Nadaï, A. (2018). *Energy transitions : A socio-technical inquiry*. Palgrave Macmillan.

Larson, E. D., & Yang, H. (2004). Dimethyl ether (DME) from coal as a household cooking fuel in China. *Energy for Sustainable Development*, *8*(3), 115-126. https://doi.org/10.1016/S0973-0826(08)60473-1

Linzenich, A., Arning, K., & Ziefle, M. (2021). Acceptance of energy technologies in context : Comparing laypeople's risk perceptions across eight infrastructure technologies in Germany. *Energy Policy*, *152*, 112071. https://doi.org/10.1016/j.enpol.2020.112071

Marchetti, C. (1977). On geoengineering and the CO_2 problem. *Climatic Change*, *1*(1), 59-68. https://doi.org/10.1007/BF00162777

Meadows, D. H. (1999). *Leverage Points. Place to Intervene in a System*. Sustainability Institute. https://donellameadows.org/archives/leverage-points-places-to-intervene-in-a-system/

Meadows, D. H. (2009). *Thinking in systems : A primer*. Earthscan.

Nørskov, J. K., Latimer, A., Dickens, C. F., & Nielsen, K. (s. d.). *Research needs towards sustainable production of fuels and chemicals*.

Ramírez, R., & Wilkinson, A. (2016). *Strategic Reframing : The Oxford Scenario Planning Approach*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198745693.001.0001

Rivière, C., Pigeon J. (2023). *Crise du gaz : défis et opportunités pour la mobilité lourde,* Research Report, 21 pages.

Vesnic-Alujevic, L., Muench, S., & Stoermer, E. (2023). *Reference foresight scenarios on the global standing of the European Union in 2040.,* European Commission. Joint Research Centre., Publications Office. https://data.europa.eu/doi/10.2760/490501

Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation : An introduction to the concept. *Energy Policy*, *35*(5), 2683-2691. https://doi.org/10.1016/j.enpol.2006.12.001