Just Transition Platform Working Groups

Action 13: Towards a carbon cyclic economy for chemicals and fuels

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Regional and Urban Policy

Action 13: Towards a carbon cyclic economy for chemicals and fuels

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Category: Chemicals (and fuels).

The **Just Transition Platform (JTP) Working Groups (WGs)**, established in November 2021, bring together all stakeholders from across Europe with a common concern for the people and places affected by the transition to a climate-neutral economy. The WGs for **Steel, Cement and Chemicals** each have a focus on a specific carbon-intensive sector that is heavily impacted by the transition, while a fourth WG focuses on **Horizontal Stakeholder Strategy**.

After finalising their Scoping Papers, outlining the focus areas and objectives of their WG, the WG members developed a common Implementation Plan, which sets out their 17 Actions. This plan was finalised and published in April 2023. Throughout the rest of the year, the Action leaders, together with other WG members contributing to the Action, have been implementing their respective Actions.

This document presents the final output of Action 13.

Introduction

Challenges addressed by Action 13

The chemical industry (CIn) in EU-27 will progressively decrease the use of fossil-C as source of energy and feedstock. Energy can be provided by green electricity (generated by sun, wind, hydro, geo-thermal) and vectors (hydrogen), while feedstock demands a replacement with alternative carbon sources. This paper identifies alternative sources of carbon for the EU-27 CIn and tools to convert the transition into an opportunity.

Objectives of Action 13

Action 13 makes an analysis of the potential of three alternative carbon sources, namely: waste plastics, biomass and carbon dioxide (as building block and source of carbon for fuels). Tools for driving the transition in most affected regions are discussed: Hubs that merge large industries, innovators (small and medium-sized enterprises (SMEs) and start-ups), universities and research organisations (RTOs), and social parties are identified as drivers of change and sites of formation (reskilling, reorienting centres) of workers.

Stakeholders targeted by Action 13

Action 13 has targeted EU associations of industries, regional governments, innovators, and large industries of Just Transition Fund (JTF) regions, as per the list below.

List of contacted organisations and their status:

1. CO_2 Value Europe (CVE) (partnered by over 100 industries and RTOs). Collaboration established.
2. AdI (largest steel producer in Italy and in EU-27). Collaboration established.
3. SUNERGY (Association of over 60 institutions, industries, RTOs for solar energy utilisation in CO_2 conversion), SUNER-C (EU-CAS)). Collaboration established.
4. DESIRED (an EU-funded project within Horizon 2020 aimed at converting CO_2 and water under solar irradiation into fuels and chemicals). Collaboration established.
5. Apulia regional government. Collaboration established.
6. CO_2 Czech Solution Group (SZ-CO2CZ). Collaboration established.
7. SCHP CR (Association of Chemical Industry of the Czech Republic). Collaboration established.
8. CINEA (the authors are Members of the Working Group on Solar Fuels through the Project DESIRED).
9. European Carbon Dioxide Capture and Storage Laboratory Infrastructure (contacted).
10. Zero Emissions Platform (contacted).
11. European Industrial Insulation Foundation (contacted).
12. European Chemical Industry Council (contacted).
13. European Association for Storage of Energy (contacted).
14. The Association of European Renewable Energy Research Centres (contacted).
15. FutureCarbonNL (contacted).
16. Carbon2Value (contacted).

A very positive reply and direct engagement came from organisations 1–8, 50 % of the total. The contact with the remaining organisations will be reinforced.

How this Action was implemented

The authors have carried out research of EU Regulations, Directives and Plans and have accessed documents listed in the literature cited in the text. They have also contacted the organisations listed above and have had physical meetings with them (at national and international levels) to explain the concept of Action 13. The contribution by the active stakeholders has been included in the main text or Annex, which outlines how a Hub should be organised. The example of Hub is located at AdI – the major steel plant in Europe, planning to increase its production from actual 4.5 Mt/y to over 10 Mt/y) located in Taranto, Apulia, Italy. In implementing the getting-away-from-fossil-C strategy, AdI has already deployed activities for workers reskilling/reorienting through its academia, integrated with a large modern laboratory for materials characterisation and research, and has planned actions that will bring to build: an offshore wind park, large-scale H_2-production, CO_2-capture, CO_2-utilisation, all functional to a Hub on CCE. Such an opportunity can be integrated with two other key activities present in the Apulia Region close to AdI, namely a plastic recycling plant (Brindisi, 80 km away from AdI) and a biomass valorisation for energy production (Foggia, 200 km away from AdI). Waste plastics, biomass and CO_2 are the three sources of carbon alternative to fossil-C and their integration in the same regional area may represent a unique opportunity for demonstrating the future.

Table of contents

Figures

Tables

Towards a carbon cyclic economy for chemicals and fuels

Recommendation paper on carbon capture and utilisation (CCU) in JTF regions

1. Introduction

1.1 The EU CIn: market-share, energy consumption, raw materials

The EU-27 CIn had a budget of EUR 499 billion in 2022, with EUR 9.4 billion investment in research and innovation, setting itself as the fourth largest production actor with 7 % of turnover output.[1] The EU CIn employs 1.2 million workers and supports 3.6 million jobs indirectly and five times more jobs through the various supply chains.[2] It has been affected by the COVID-19 pandemic and the recent energy crisis due to the Ukraine war with a capacity utilisation that reached the value of 76.4 % in the third quarter of 2022, down from 83.2 % reached in the same quarter of last year.[3] In the same period, even consumer confidence started to climb in response to the decline in gas prices. The overall energy consumption has been estimated at 589 TWh in 2020, keeping the same level as in 2015, but with a 1 % decline per year with respect to 1990. Most interestingly, during the same period (1990–2020) the Specific Energy Consumption Index fell by 45 %, indicating the attention of the EU CIn towards efficient innovative processes. Also, the use of non-fossil energy has more than doubled since 2020.

1.2 Use of fossil-C in the CIn

All that standing, in 2021 the EU CIn was the third highest emitter of CO_2 in the EU-27 after the cement and iron/steel industries with 120 Mt_{CO2} released from both the use of energy and the C-feedstock conversion to produce chemicals and materials, with respect to 269 Mt in 1990. The world's CO_2 emission was 935 Mt in 2021. The overall C-input share energy-feedstock resulted to be close to 50 %. The CO_2 emissions originate one quarter from the manufacture of chemicals, with the rest coming from fuel combustion for providing energy to the chemical processes. NH_3 (ammonia) production is responsible for the highest share of emissions, followed by high-value large-volume chemicals (i.e. ethene, propene, benzene, toluene, and mixed xylenes) and methanol.

The carbon intensity (CI) represents the ratio of t_{CO2} emitted per $t_{chemical}$ produced. As shown in Figure 1, its value has grown from 2010 to 2021. The CI is a version of the E-Factor as defined by Sheldon[4] that gives the ratio of waste/product in a synthetic process. The E-Factor varies within a wide range (1–500) with the lower values typical of the petrochemical industry and the highest (up to 500) for the pharmaceutical industry.

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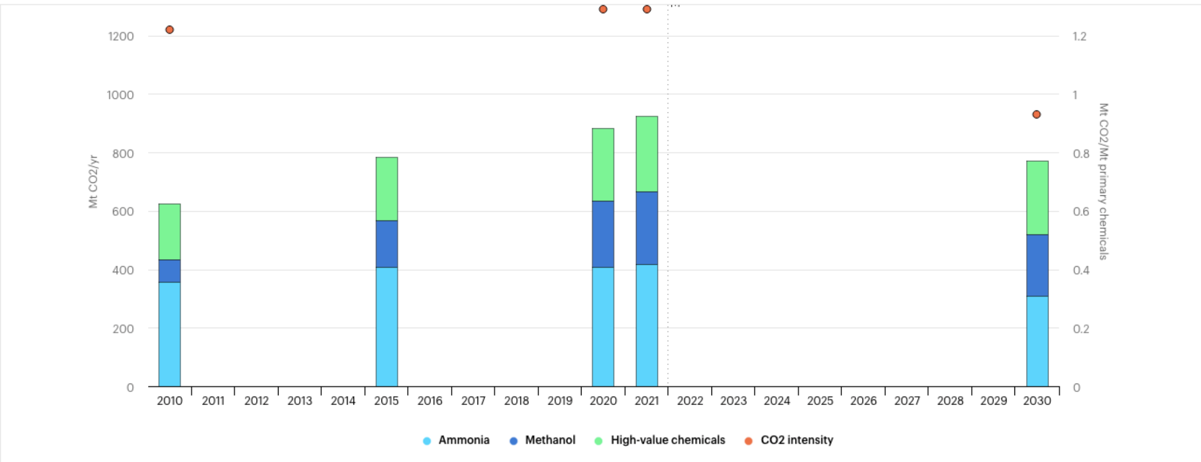
[1] CEFIC, 2022. The European chemical industry: a vital part of Europe's future. Facts & Figures 2022.
[2] https://single-market-economy.ec.europa.eu/sectors/chemicals_en
[3] https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/growth-and competitiveness/#:~:text=According%20to%20Business%20Survey%20data,%25%2C%201995%2D2019 (last accessed on December 5, 2023).
[4] R.A. Sheldon, Green Chem., 2017, 19, 18.

Figure 1: Relative emissions of CO_2 for most important production sectors in the CIn and the overall Carbon Intensity5



It is worth noting that both the CI and E grow with the complexity of the structure of the target product and, thus, the number of steps required to make it from raw materials. The latter depends on the modification of the complexity of the chemical structure in the conversion of a raw material into the end product.

1.3 Implications of the European Green Deal

The European Green Deal presented in December 2019 is a roadmap to a sustainable economy (Figure 2), converting climate change and environmental pollution challenges into opportunities, even making a just transition inclusive for all, not leaving anyone behind.

As a matter of fact, two key points of the European Green Deal are the circular economy and the Net Zero Industry Act (NZIA), both implying the shift away from fossil-C, the latter having a fundamental role in the CIn as an energy source and raw material supply, as announced in previous paragraphs.

Figure 2: The European Green Deal at glance

The ambitious target of NZIA by 2050 adds another burden on the production cycles, as de-fossilisation demands a profound change not only in production technologies (that must become less energy intensive) but also in raw-materials supply.

The snag is that if it is possible to decarbonise energy, it is impossible to decarbonise the CIn and our life. Therefore, the CIn urges to find new C-sources, alternative to fossil-C. Being the industrial sector that generates the largest surplus equal to EUR 161 billion in 2021, the CIn plays a key role in the EU-27 economy and requires the largest attention in order not to lose its power upon implementation of the European Green Deal mandates.[5] A positive element is that the EU CIn has planned a net reduction of the C-intensity of its production within 2030 (Figure 1) and has effectively implemented the greenhouse-gas reduction[6] targeting the 2050 NZIA. By 2030 a 17 % CO_2 emission reduction must be reached, despite the growth in the overall production.

1.4 Recycled carbon as raw materials: waste plastics, biomass (grown and waste), CO_2 (recycled from continuous point sources and the atmosphere)

The question to answer is thus: How to substitute fossil-C? A start for an answer is an approximate quantification of the amount of fossil-C so far used on an annual basis for producing chemicals in the EU-27. The overall (not hazardous and hazardous) amount of chemicals produced in the EU-27 during the decade 2012-2021 presented a waiving trend, from 279.5 Mt to 299.4 Mt.[7]

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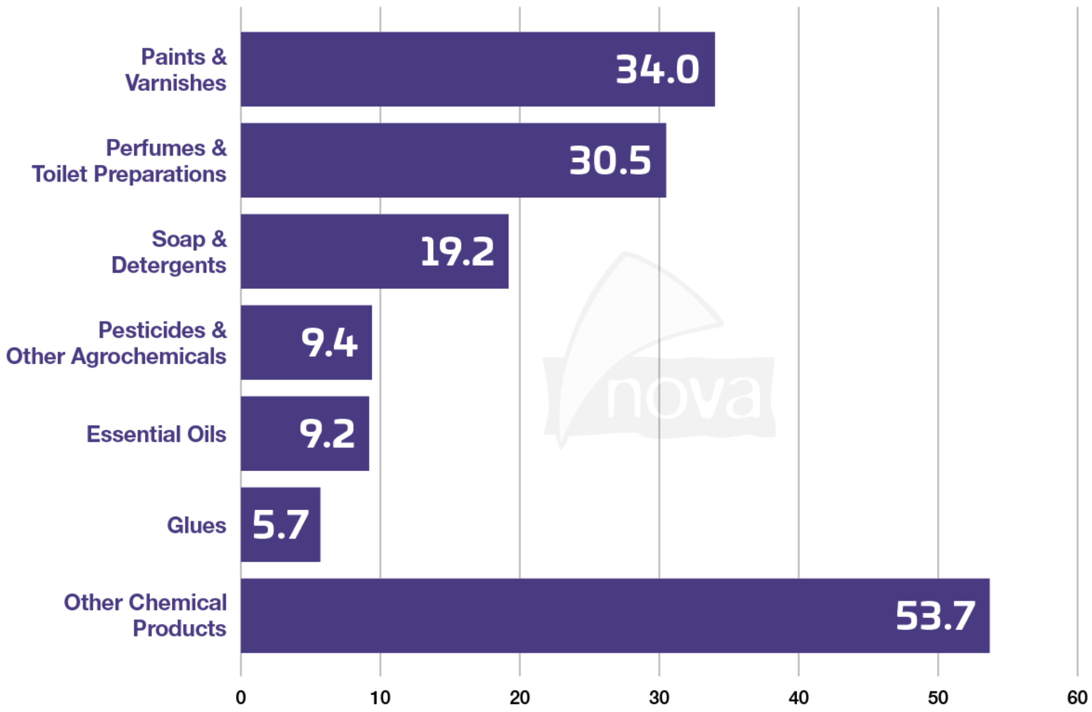
5 https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/ (last accessed on 5 December, 2023).

6 https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/environmental-performance/ (accessed on May 16, 2024)

7 https://ec.europa.eu/eurostat/databrowser/explore/all/all_themes (last accessed on 5 December, 2023).

Figure 3: The estimated Organic Chemicals EU27+UK market in 2021



The production of organic chemicals equalled EUR 162 billion in 2021 distributed as in Figure 3.[8] The use of fossil-C by the CIn was around 287 Mt_{oile} (oile=oil equivalent, counting all fossil-C used as oil). Therefore, the need of carbon is evident. Assuming that fossil-C would progressively not being accessible, which source could then be used? Mainly two sources are listed in early EU documents: waste plastics and biomass (either recycled or expressly grown). As we shall see, captured CO_2 (of bio-origin or captured from the atmosphere) will necessarily be used to fill the gap.

1.5 The cyclic economy and the CCE

CCU is considered as an alternative to Carbon Capture and Storage (CCS) for mitigating the impact of anthropic activities on climate.[9] As a matter of fact, CCU and CCS respond to two quite different economic strategies. The latter is the end of pipe in a linear economy (practised for over two hundred years), while the former is the basis for the implementation of a human-made carbon cycle that may complement the natural carbon cycle. Carbon recycling has been practised in the CIn since the late 1860s: the Solvay process (Production of sodium carbonate, invented by Ernest Solvay, a Belgian Chemist, 1838-1922) is an interesting example. As for today, carbon dioxide is used at a rate of ca. 230 Mt/y.[10] This represents over 25 % of the emitted CO_2 by the CIn worldwide with a large improvement margin of up to giga-tonnes per year if large-

[8] https://renewable-carbon.eu/ (last accessed on 5 December, 2023).
[9] J. Mertens, A. Dibenedetto et al. (14 more authors), Joule, 2023, 7 (3), 442–449.
[10] M. Aresta and A. Dibenedetto, The Carbon Dioxide Revolution, Springer 2020.

scale CO_2-conversion technologies are deployed that require non-fossil-C energy sources and water as reducing agent of CO_2.[11]

Recycling carbon is essential for the development of a sustainable economy, and the CCE is at the heart of the circular economy that is the core of the European Green Deal. The debate on the assessment of the potential contribution of alternative carbon sources to fossil-C is still ongoing and this includes the utilisation of CO_2, tentatively set at ca. 200 Mt/y in work-documents. Early support to the use of CO_2 can be found in documents produced by EU organisations that have a primary consultative role for the Trilogue (European Parliament, European Council, European Commission), namely the EESC (European Economic and Social Committee) and CoR (European Committee of the Regions), both advocate in favour of CCU.

The EESC writes in its comments to the NZIA: 'The EESC welcomes the approach to priority investment in and support for clean technologies. However, the list of technologies supported by the NZIA proposal largely ignores the decarbonisation of energy-intensive industries and the circularity dimension. We cannot reach the 2050 climate goals without building a competitive circular economy: using waste, captured carbon, or renewable resources as feedstock are all viable ways to reduce emissions across all industries and cut the EU's dependence on raw materials imports. The EESC, therefore, calls on the legislators to expand the list of strategic net-zero technologies accordingly.'[12]

The CoR also supports the view of CCU as a strategic technology for the future of our society: '[…] in this context, also notes the crucial importance of supporting future-oriented industries and/or economic activities. A particular emphasis should be put on the most affected regions and territories in order to avoid growing regional disparities and to ensure that no one and no region is left behind. Thus, net-zero technology manufacturing projects in and around "less developed and transition regions", including outermost regions, and JTF Territories as well as territories neighbouring JTF Territories should be considered net-zero strategic projects if they fall within the scope of the Annex. In addition, the CoR sees potential for additional strategic net-zero technologies as part of the Annex (e.g. CCU); […].'[13]

These two authoritative views and recommendations have represented solid pillars on which Action 13 in support of CCU, or even better CCE, being considered a strategic technology for the future of our society, has been built.

The big step is moving from making chemicals from CO_2 (that was meaningful in an economy based on fossil-C) to making fuels from CO_2 (that had no sense so far). The shift requires the use of perennial energy sources (solar, wind, hydro, geo-power) as primary energy and water as a source of protons and electrons.[14] It is worth remembering, the emission of CO_2 from the fuel sector amounted to 14.6 Gt_{CO2} in 2022, some 16 times higher than that from the CIn.[26] The amount of recycled carbon is almost close to zero in the Energy Sector. It is evident that the use of CO_2 for making fuels would be highly

[11] M Aresta, in 'Advances in CO_2 utilization: from fundamentals to application', G. Zhang, A Bogaerts, J Ye, C.-J. Liu Eds, Springer Nature, 2023.
[12] EESC([COM(2023)]161 final-2023/0081(COD).
[13] COR2023-02189-00-01-AC-TRA(EN)1/28COM82023).
[14] M. Aresta, A. Angelini, A Dibenedetto, JCOU, 2013, 3–4, 65–73.

beneficial and would represent a great innovation in this sector, avoiding significant amounts of fossil-C.

2. Defossilisation versus decarbonisation

Before getting into specific topics, we find it worth commenting and clarifying the terms 'defossilisation' and 'decarbonisation', often used as synonyms. They represent two quite different practices or tactics to implement the strategy of reducing the CO_2 atmospheric level, even if the real impact on climate change must be demonstrated.

2.1 Defossilisation and decarbonisation

Defossilisation of human society targets the progressive move away from fossil-C as a source of energy and chemicals, strongly reducing its impact on the economy (today 82+ % of the energy comes from fossil-C and 90+ % of hydrogen). Stopping using fossil-C will avoid carbon being transferred from the deep ground to the atmosphere, with a positive impact on climate.

Decarbonisation means 'tout court' elimination of carbon. The term decarbonisation is, thus, in net contrast with the use of biomass that is based on carbon. It makes sense to speak in terms of decarbonisation of the atmosphere if the target is to reduce the content of carbon (CO_2) in the atmosphere.

The use of the two terms must be carefully managed to avoid misunderstandings and, even worse, contradictions in terms. In this paper, defossilisation will mean reduction of the use of fossil-C, and decarbonisation will stand for reduction of sources based on carbon.

2.2 Defossilisation and decarbonisation in powering the CIn

That said, one has to ask whether the two terms can be used as synonyms and how they apply to the CIn. It makes sense to speak in terms of defossilisation of the energy and chemistry sectors, planning a progressive reduction of the use of fossil-C in both sectors. In particular, defossilising the CIn means reducing the use of fossil-C in both powering and feeding the CIn with fossil-C. When we go to decarbonisation, for the CIn its use should be limited to powering processes as it would not be impossible to decarbonise processes.

2.3 Defossilisation in feeding the CIn

Defossilisation of chemical processes is not impossible, supposed that alternative sources of carbon are found, such as biomass-waste-CO_2. It is impossible to decarbonise the CIn for what was said in previous paragraphs and for the fact that human life is based on carbon. Every day humans eat carbon, dress with carbon, work with carbon, travel with carbon and so on and so forth. Every day humans emit CO_2 at a rate of *ca.* 1 kg/pax.day.

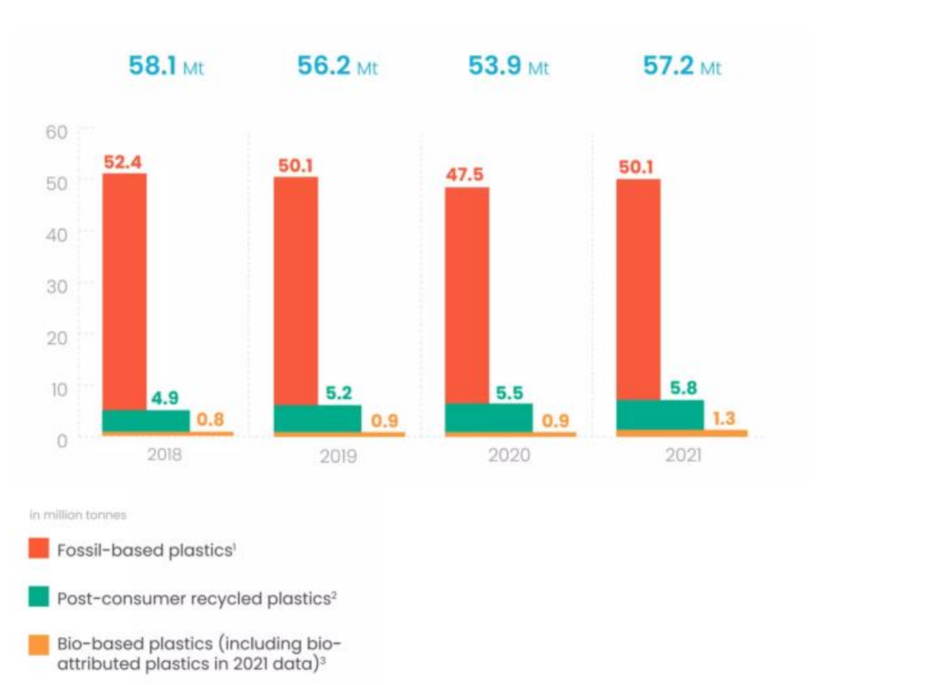
3. Alternative sources of carbon for the CIn

In this chapter the alternative sources to fossil-C will be considered that may support the progressive elimination of it.

3.1 Waste plastics and the need to improve the recycling

The EU market of plastics has been estimated at 57.2 Mt (1.3 Mt of bio-origin) in 2021 (Figure 4),[15] 39 % of which is used in packaging,[16] with an average use of 150 kg/pax and an emission of 13.4 Mt_{CO2}. The plastics sector employs > 1.5 million persons and has a volume of EUR 405 billion with a EUR 14.4 billion trade balance.[17] Only 9.6 % of the waste plastics are recycled.

Figure 4: European plastic production evolution

1. Includes fossil-based thermoplastics, thermosets and PUR used for plastic parts and products; 2. data on recycled plastics in EU27+3 had been developed in 2018 and 2020, data for other years are estimations. 3. including bio-attributed plastics in 2021 data.	

Due to the strong environmental impact (microplastics have been found even in heart tissues of humans[18]) their recycling is strongly recommended in a plastics circular economy strategy.[19] Figure 5 shows the actual situation in EU-27 for the plastics market.[20]

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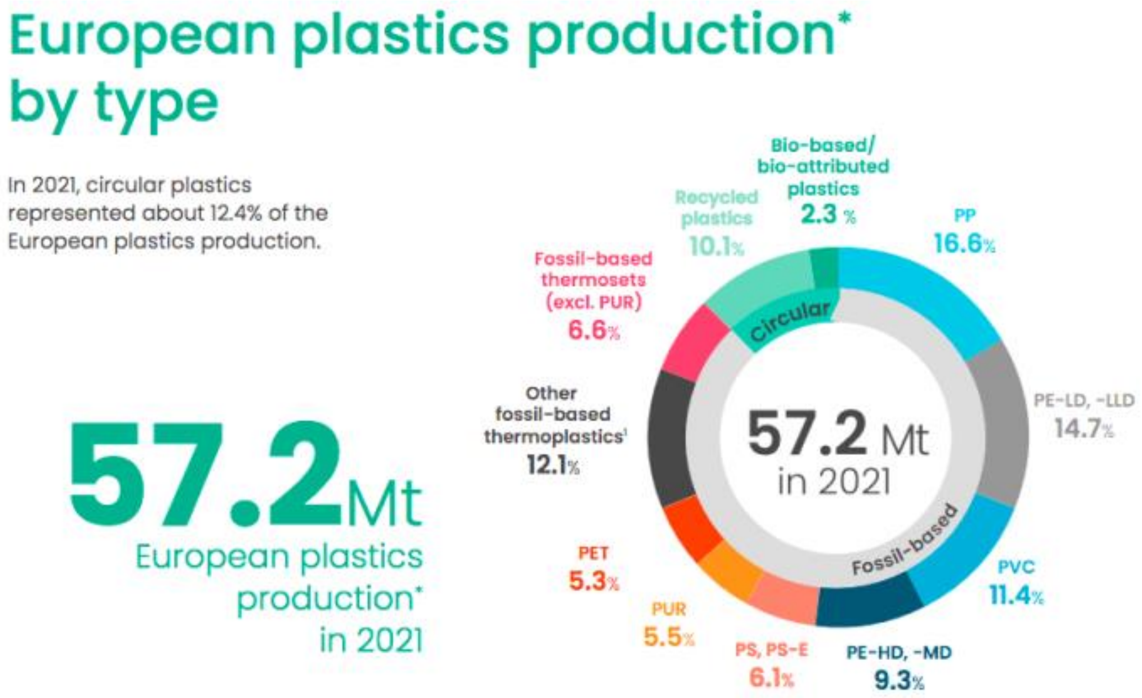
[15] https://plasticseurope.org/wp-content/uploads/2022/10/PE-PLASTICS-THE-FACTS_V7-Tue_19-10-1.pdf (last accessed on December 5, 2023).
[16] https://www.eea.europa.eu/en (last accessed on December 5, 2023).
[17] https://plasticseurope.org/ (last accessed on December 5, 2023).
[18] https://www.plasticpollutioncoalition.org/ (last accessed on December 5, 2023).
[19] M. Crippa, B. De Wilde, R. Koopmans, J. Leyssens, J. Muncke, A.C. Ritschkoff, K. Van Doorsselaer, C. Velis, M. Wagner, M. (2019). A circular economy for plastics: Insights from research and innovation to inform policy and funding decisions. Publications Office of the European Union: Luxembourg. ISBN 978-92-79-98429-7.
[20] https://plasticseurope.org/ (last accessed on December 5, 2023).

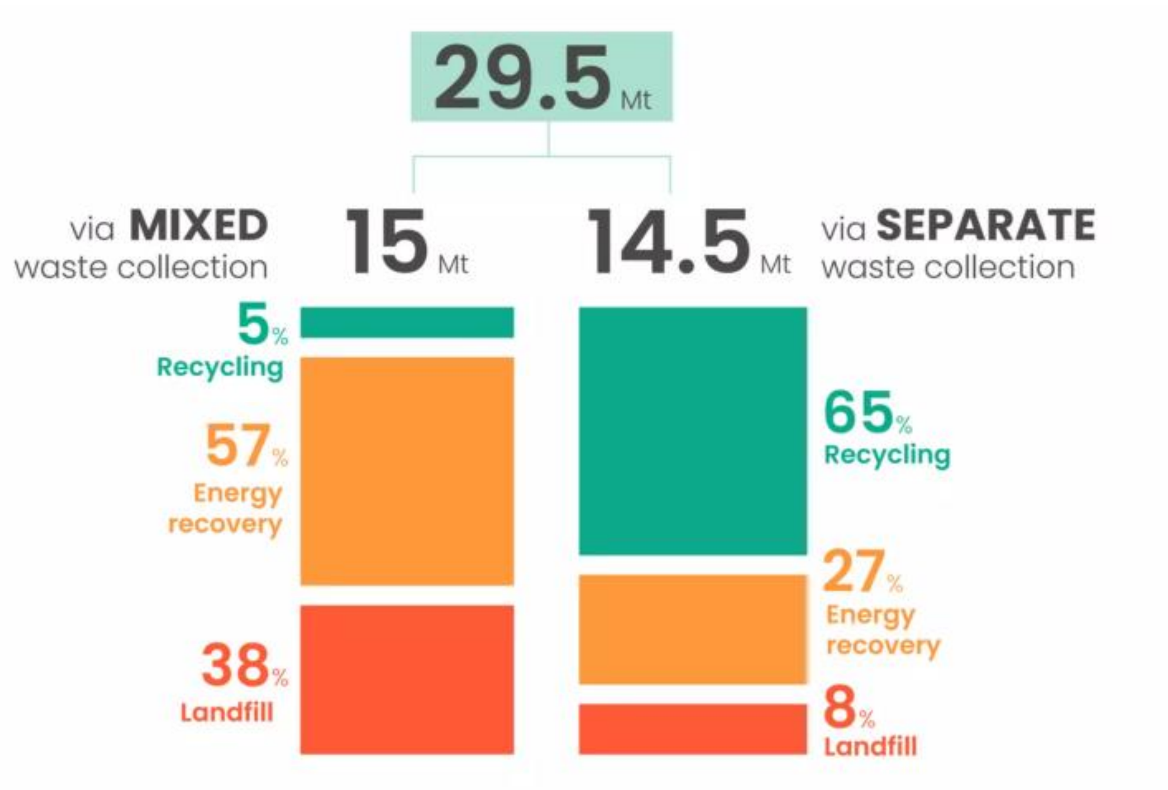
Figure 5: EU-27 plastics production, their sources and composition



3.1.1 Issues to address for plastics recycling

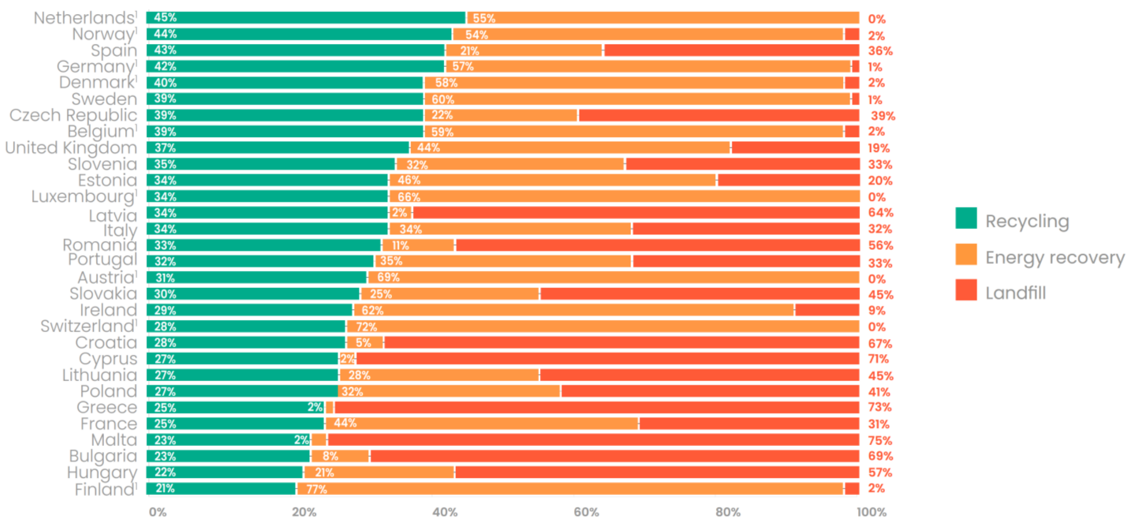
An interesting parameter to address is the plastic waste recycling rate. It has been stated that this parameter is 13 times higher, compared to mixed waste collection schemes, when plastic waste is collected separately (Figure 6). Also interesting is that in 2020 (EU27+3) 35 % of post-consumer plastic waste was sent to recycling.

Figure 6: Mixed and separate post-consumer plastic waste in 2020 (EU27+3)



Considering data availability only four countries have recycling rate above 40 % (The Netherlands, Norway, Spain and Germany) (Figure 7).[21]

Figure 7: Post-consumer plastics waste treatment per Country in 2020



To increase the rate of recycling is important to design (avoid different plastic types that sometimes are difficult to separate and recycle) and manufacture (ensure that end-of-

[21] https://plasticseurope.org/ (last accessed on December 5, 2023).

life products are easier to disassemble and recycle) plastic materials so more plastics can be kept in circulation and, also, find the added value that plastic recycling creates.

3.1.2 Best options to implement

The main method of recycling plastic waste is represented by mechanical recycling which is limited by the collection method, pre-treatment, and type of plastic. Chemical recycling is an alternative to mechanical procedures for plastic waste. In mechanical recycling, the plastic waste is divided into smaller sections which then are combined and moulded together to produce lower-grade plastic products. In chemical recycling, the plastic is broken down to the molecular level, namely 'platform molecules' which become useful to create other plastic matters. Chemical recycling (based on catalytic disassembling of plastics at moderate temperature) may produce better quality plastics, especially when the contamination aspect is considered. In fact, disassembling the waste plastic may enable the elimination of contaminants much better than when mechanical recycling is applied. The chemical recycling can produce plastics of the same quality of original plastics (primary recycling), while the mechanical recycling may produce plastics of lower quality (secondary recycling). Moreover, plastics cannot be infinitely recycled, not utilising traditional methods at least.

Biodegradable plastics are considered the main and eminent method for solving the problem related to the environmental impact of plastic waste. Polyhydroxybutyrate (PHB) (Figure 8A) is a short-chain polyhydroxyalkanoate (PHA) (Figure 8B) that is naturally produced by several microorganisms as a reserve material for carbon and energy.

Figure 8: A: Polyhydroxybutyrate (PHB); B: Polyhydroxyalkanoate (PHA)

These biopolymers are the most promising alternatives to petroleum-based plastics due to their mechanical and thermoplastic properties, comparable with polypropene and polyethene. Furthermore, PHB is renewable, biodegradable, and biocompatible.[22]

Biodegradability, caused by microorganisms such as bacteria or fungi, may vary depending on humidity, temperature, and other conditions. Ideally, plastics can degrade by aerobic and anaerobic organisms all the way to CO_2, methane, water, and feed biomass/compost. The latter makes the plastic compostable.

Another category of plastic is bio-based plastic which is made from biomass, which can be or not be biodegradable. In fact, biodegradability depends on the properties of the plastic at hand, including chemical structure and crystallinity. Correctly, bio-based plastics can be a more sustainable alternative to fossil-based, non-biodegradable plastics.[23] At the waste

[22] S.S. Ali, T. Elsamahy, E.A. Abdelkarim, R. Al-Tohamy, M. Kornaros, H.A. Ruiz, T. Zhao, F. Li, J. Sun, Bioresource Technology, 2022, 127869.
[23] A.F. Sousa, A.J.D. Silvestre, Current Opinion in Green and Sustainable Chemistry, 2022, 33: 100557.

management step, one can speak in terms of waste plastic circularity if the plastic matter is reused or recycled. Considering that plants use CO_2 for growing, which is then emitted during the biodegradation, bio-based and biodegradable plastics can be described as an example of plastic circular economy.

3.2 Biomass (grown and waste): the real potential

Every year, nature converts 4 500 EJ of solar energy[24] and 120 Gt of carbon[25] from the atmosphere into biomass – eight times as much as the global energy needs. Animals and microorganisms break down most of the plant biomass to CO_2 and water as part of the natural carbon cycle, while the rest of the biomass could, in principle, be used to satisfy human needs.

The use of biomass as an alternative source of carbon for the CIn is no longer linked to the price of crops (if low) and/or oil (if high) but is due to the need to produce chemicals by using renewable carbon. Therefore, biomass can be used as a raw material for the manufacture of materials, energy products, and higher-added-value chemicals. To this end, both terrestrial (residual or waste) and aquatic biomass can be used.

Terrestrial biomass, depending on its characteristics, can be categorised as lignocellulosic biomass, fresh vegetables, and oily biomass, which can be used for different purposes. Lignocellulosic biomass is, in general, used to produce biofuels, mainly bioethanol. It is composed of carbohydrate polymers (cellulose and hemicellulose) and lignin (an aromatic polymer). The carbohydrate polymers, by using the right processes, are depolymerised into C_n-polyols which then are used to obtain chemicals fuels, and materials.[26]

Terrestrial biomass conversion technologies can be categorised into two main classes such as thermochemical, and biochemical conversion. The first one includes the use of heat and chemicals to convert biomass into products and involves, as for today, two major stages:

1. the conversion of biomass into Syngas (a mixture of CO and H_2) that is then converted into long chain hydrocarbons using the established Fisher-Tropsch process; and
2. the liquefaction of biomass directly by using high-pressure, high temperature.

The type and amount of biomass may suggest the way to process it as well as the desired energy product. Thermal processes, which were the most popular so far, are now under scrutiny for their environmental impact and do not represent the best choice for future, even because they are highly energivorous. Hydrogenation of biomass is still considered for its potential to convert raw materials into fuels. Biochemical conversion uses microorganisms and chemicals to convert biomass into energy products. It can be done *via* anaerobic digestion (wet organic matter and oxygen-free environment are required) or fermentation (in the presence of yeast). The anaerobic digestion produces biogas with a composition that may vary with the type of feedstock and the type of anaerobic digester. It is mainly composed of CH_4 (40–75 %) and CO_2 (60–25 %), with minor impurities such as H_2O, H_2S, NH_3, among others.[27] Biogas can be upgraded to bio-methane by separating

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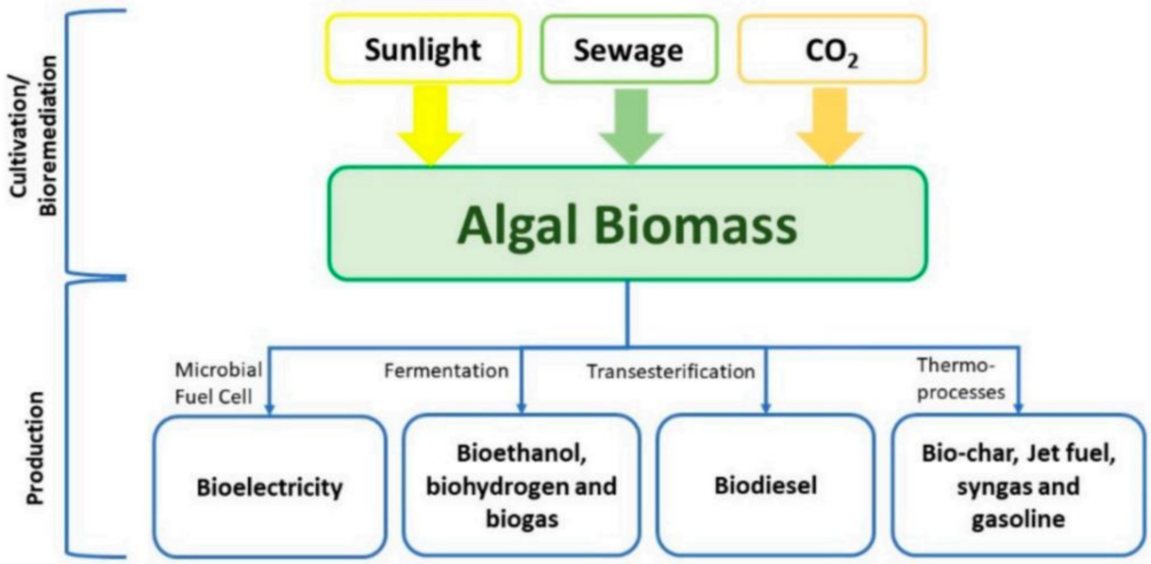
[24] (a) R. Sims, Bioenergy options for a cleaner environment: In developed and developing countries. UK, 2014. (b) M. Aresta, A. Dibenedetto, F. Dumeignil, Biorefinery: from Biomass to Chemicals and Fuels, De Gruyter, 2022.
[25] IPCC, Fourth Assessment Report: Climate Change. 2007.
[26] M. Aresta and A. Dibenedetto, The Carbon Dioxide Revolution, Springer 2020, chapter 11;
[27] Q. Sun, H. Li, J. Yan, L. Liu, Z. Yu, X. Yu, Renew. Sustain. Energy Rev., 2015, 51, 521-532.

CO_2, an energy costly process. The global bio-methane market in the year 2021 was valued at USD 2.11 billion and is predicted to reach USD 4.17 billion by the year 2031 at an 8.1 % compound annual growth rate (CAGR) during the forecast period.[28]

By using yeast, the fermentation converts carbohydrates into alcohol (bioethanol). For fermentation, feedstock rich in sugar and starch is required. Interestingly, the global market of bioethanol is estimated to grow at a CAGR of 11.69 % between 2022 and 2027. Market growth depends on several factors, including improving demand for the continuous supply of clean fuel, atmosphere, and energy security matters, and favourable government policies.[29] Aquatic biomass, in particular microalgae and cyanobacteria, has been identified as third-generation feedstock and an efficient source of biodiesel and of bioethanol, biohydrogen, biogas, jet fuel, syngas (Figure 9) by using different conversion technologies.[30]

Figure 9: Conversion processes of algal biomass and products (with the permission of ref 28 Creative Commons Attribution (CC BY) licence)



Although algal biomass can be classified as an efficient source of biodiesel with respect to terrestrial plants either in terms of oil content or land area need (Table 1), it cannot be used to make biodiesel only as it is not economic.

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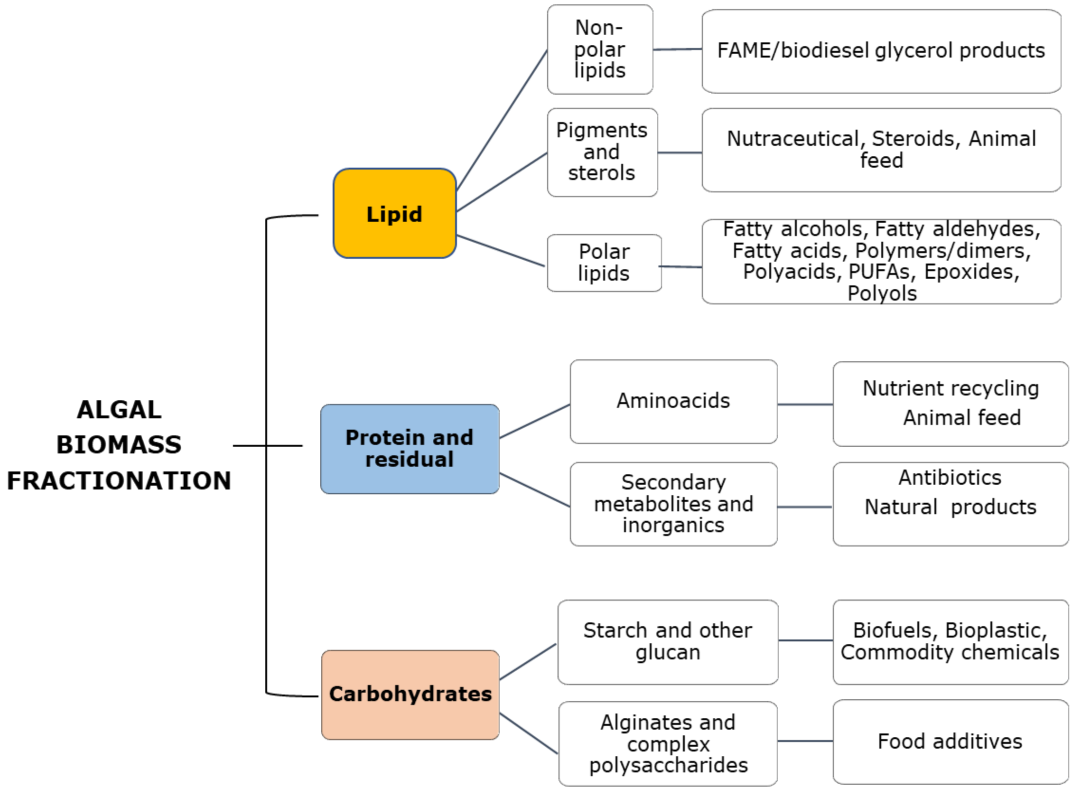
[28] https://www.insightaceanalytic.com/report/global-biomethane-market/1250 (last accessed on December 5, 2023).
[29] https://www.technavio.com/report/bioethanol-market-industry-analysis?utm_source=prnewswire&utm_medium=pressrelease&utm_campaign=vendor-v2_wk28_005_&utm_content=IRTNTR41041 (last accessed on December 5, 2023).
[30] M.G. Saad, N.S. Dosoky, M.S. Zoromba, H.M. Shafik, Energies, 2019, 12(10), 1920.

Table 1: Oil productivity and land area required for growth of oil-producing biomass

Crop	Oil yield ($l\ ha^{-1}yr^{-1}$)	Land area needed for oil yield (M ha)
Corn	172	1540
Soybean	446	594
Canola	1190	223
Oil palm	5950	45
Coconut	2689	99
Jatropha	1892	140
Microalgae	136,900	2

If fractionation strategy is applied (Figure 10), and all components of algal biomass are used the process may become economically feasible.

Figure 10: Algal biomass fractionation



Bioethanol, biodiesel, and biogas can be valid alternatives to fuels derived from fossil-C supposed that the conflict food-energy is solved and soil is used wisely, reserving fertile soil for growing food and devoting marginal soil to grow biomass for industrial applications.

3.2.1 The limits of biomass: terrestrial and aquatic

The main limitations of terrestrial biomass are land availability[31] and sustainability of crop production. To produce food, feed, fibres and energy we use almost a quarter of all terrestrial net primary production, and such demand is projected to increase significantly

[31] K.H. Erb, S. Gingrich, (2022). One Earth, 2022, 5(1), 7–9.

in as little as 30 years, which, given current farming practices and dietary habits, will require more land. Furthermore, additional land (an estimated 50–60 % by 2050) must be conserved and restored if we are to avert the biodiversity loss crises and safeguard ecosystem services, including the carbon sequestration potential required to avoid dangerous levels of climate change.

Moreover, biomass contains a high level of moisture that makes it unsuitable for thermal conversion processes. So, to increase the calorific value, pre-drying should be carried out. Unfortunately, the drying process is associated with additional high costs and energy input. High moisture content affects biological degradation, the development of fungi, mould, bacteria, and other microorganisms, as well as the loss of organic substances. The disadvantage of the water content can be solved by densifying the material in pressing processes.

3.2.2 Selection of options

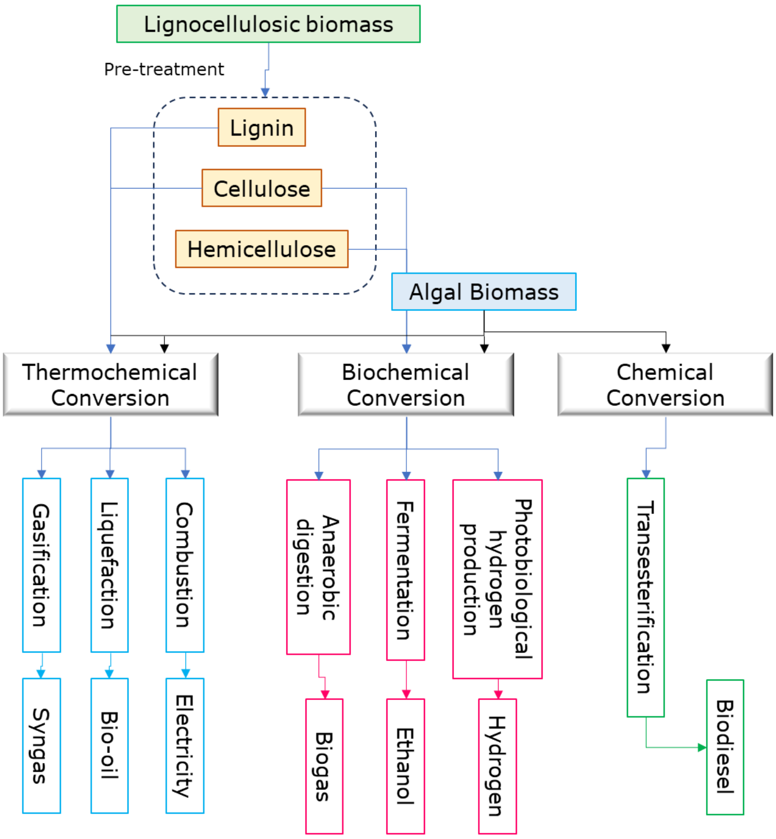
Numerous processes (Figure 11) have been devised for converting biomass into synthetic gas, biofuels, and chemicals. Among such technologies, the gasification process appears to be quite promising due to its apparent numerous advantages, even if it is an energivorous process and should be fed using non-fossil energy for meeting the target of energy and CO_2 reduction. Gasification is a thermal process that converts biomass into a gaseous fuel mixture (30–55 % N_2, 16–30 % CO_2, 12–30 % CO, and 2–10 % H_2) in the controlled presence of an oxidant (air, oxygen or water vapour). The gasification of biomass can be performed in fixed, moving, or fluidised bed reactors at high temperatures (670–850 °C).[32] *In general,* the thermal efficiency for biomass gasification varies from 70–80 %. The fuel gas obtained through the conversion of different feedstocks can then be used in conventional equipment (e.g. boilers, engines, and turbines) or advanced equipment (e.g. fuel cells) for the generation of heat and electricity.

The selective hydrogenation (using "green hydrogen") of biomass-sourced molecules (such as hydroxymethylfurfural derived from C6 sugars or other polyol-derived species) can represent a better option for the valorisation of biomass and producing biofuels.[24b] Even the selective hydrogenation of polyunsaturated fatty acids (PUFA) plays a role for converting PUFAs into saturated species, more suited for biodiesel production. The key issue is to use low-energy and selective routes that can save energy both in the process itself and in post-process operations necessary for target-product isolation.

A systematic life-cycle assessment should be performed to ensure that, beside their intrinsic performances, bio-based products bring both societal and environmental benefits. The whole supply chain, from collection and transportation to the valorisation process and to the end of life of chemicals and fuels must be considered, in addition to soil carbon-depaupeartion. The utilisation of renewable carbon is not *per se* a guarantee of sustainability.

[32] R.C. Brown, (ed.). Thermochemical processing of biomass: conversion into fuels, chemicals and power. John Wiley & Sons, 2019.

Figure 11: Technologies for the conversion of biomass



3.3 Recovered CO_2 and its potential

CO_2 can be used either as C_1 building block for chemicals and materials or as a source of carbon for the synthesis of energy products. The energetics of chemical conversion of CO_2 says that the synthesis of carboxylates and lactones (RCOOR'), carbamates (RR'NCOOR"), urea (RR'NCONRR'), isocyanates (RNCO), and carbonates [ROC(O)OR'], requires minor external energetic input, if not zero.[33] While formates, methanol or methane, and hydrocarbons require energy and hydrogen.[34] Nature uses carbon dioxide and water to make a large variety of energy-rich products using energy from the sun or from chemicals, either in plants or using microorganisms. Cyanobacteria represent a good example of microbial platforms as they can use organic substrates and CO_2 to afford several useful compounds.[35] They can easily be genetically manipulated and used to produce quite different classes of products, such as fuels or polyhydroxyalkanoates (PHA), both made from carbon dioxide or in a mixed regime where an external organic substrate is also provided.

Several companies are using microorganisms for the direct conversion of CO_2 to respond to market requirements. The Dutch company Photanol is producing alternative products in the flavour and fragrance market, while Phytonix produces n-butanol which can be used to produce fuels and chemicals, including jet fuels, bioplastics, and synthetic rubber.

[33] M. Aresta, A. Dibenedetto, Dalton Trans., 2007, 2975.
[34] M. Aresta, A. Dibenedetto, A. Angelini, Chem. Rev., 2014, 114(3), 1709-1742.
[35] a) S.R. Subashchandrabose, B. Ramakrishnan, M. Megharaj, K. Venkateswarlu, R. Naidu, Environ. Int. 2013, 51: 59–72; b) A.P. Yelton, S.G. Acinas, S. Sunagawa, P. Bork, C. Pedrós-Alió, S.W. Chisholm, ISME J., 2016, 10, 2946 – 57.

NOVAMONT since 2016 is producing 1,4-butanediol (1,4-BDO) on an industrial scale directly from sugars and using bacteria.[36] Noteworthy, 1,4-BDO is today largely produced from fossil sources and finds application both as a solvent and to produce plastics, elastic fibres and polyurethanes. The global 1,4-butanediol market size was valued at USD 6.19 billion in 2015 and is expected to grow at an estimated CAGR of 7.7 % from 2016 to 2025.[37]

4. Potential of CCU in EU: opportunities and challenges

4.1 Energetics of CO_2 conversion

CO_2 is a stable molecule (DG^0_f = 396 kJ/mol) and from the energetic point of view, the conversion of CO_2 will require an amount of energy that depends on the downward steps of the oxidation state of carbon from +4 in CO_2 to that of the target product. In general, if CO_2 is incorporated as the entire moiety into a compound (carboxylation reactions) the energetic of the process is around to be favourable, while if we reduce carbon, energy (and even hydrogen) will be required. Therefore, the reactions in which CO_2 is involved can be divided into three main classes[14] namely: i) low-energy processes (in which the oxidation state of C remains equal to +4), essentially devoted to chemical production (carbonates and carbamates, or the derived polymers); ii) average energy processes in which C-C bonds are formed (by either reacting CO_2 with olefins and dienes or by insertion into a C-H bond); and iii) high-energy processes, which also need hydrogen (as in fuel synthesis). It is worth mentioning that fuels have a market that is ca. 16 times larger than that of chemicals and the manufacture of fuels converts significantly larger volumes of CO_2 (several Gt/y) than that of chemicals (> 300 Mt/y in the short term).

4.2 Short-, medium-, and long-term options

As several potentially promising processes of CO_2 catalytic conversion are reported in the literature, a key challenge is to identify those that are the most advanced, mainly in terms of technology availability for future deployment, and short- to mid-term implementation at industrial levels. The implementation of such technologies should be related not only to techno-economic parameters but also to environmental aspects considering the risk of generating new CO_2 emission sources and/or increasing energy consumption.

The use of CO_2 as a building block for added-value products does not require hydrogen. Such products have short- (order of months, such as urea), medium- (order of year, most chemicals), long-life (order of decades, such as organic polymers). For several compounds the Technology Readiness Level (TRL) level is nine, in other cases, lower TRL are achieved, but bottlenecks are well-known and remedies, opening a good prospective in the exploitation of technologies in the short-medium term (5–10 years). Nevertheless, the overall market of chemicals is limited, ranging from actual 210 Mt/y CO_2 to over 350–400 Mt/y within 2030.[25] Apparently, such use of CO_2 will not contribute significantly to controlling the CO_2 atmospheric level. Nevertheless, if we consider not just the used but the avoided CO_2, assuming an average avoided/used ratio of 2.8,[26] even considering the potential technology innovation, then we can conclude that close to 1 Gt/y of CO_2 will be

[36] https://www.novamont.com/eng/read-press-release/mater-biotech/ (last accessed on December 5, 2023).
[37] https://www.grandviewresearch.com/industry-analysis/1-4-butanediol-market (last accessed on December 5, 2023).

avoided by 2030: this represents a more significant contribution which is coupled to a lower extraction of fossil-C.

In the longer term, let us say by 2040, a different prospective can be built on the fact that by then the availability of large volumes of Renewable-H_2 (namely generated using photovoltaic, wind, waterpower) at a cost close to MSR-H_2 may be a reality. (MSR: methane steam reforming) The conversion of CO_2 into fuels may, thus, grow to high levels, (2–3.5 Gt/y). Co-processing CO_2 and water may also serve to produce large-scale chemicals other than fuels. Of interest is the case of the synthesis of C_2 and C_3 olefins from CO_2 via electrolysis that would contribute to increase the amount of CO_2 used to *ca.* 1 Gt/y.

Moreover, in the long-term option, CCU technologies may mitigate climate change by removing CO_2 from the atmosphere or using carbon-containing flue gases (industrial off-gases, including fermentation processes). These flue gases are captured directly at point sources so that they do not enter the atmosphere and can instead be converted into chemicals. In December 2021, the Commission adopted the Sustainable Carbon Cycles[38] communication, which sets out an action plan on: (i) how to develop sustainable industrial solutions to increase carbon removals (using direct air capture and bio-based products with long lifetimes); and (ii) key actions to support the industrial capture and use (CCU) or storage of CO_2 (CCS). Both CCU and CCS technologies are key technological pathways for the defossilisation of energy-intensive industries, including the CIn. Their application potential has been identified as particularly high for the chemical sector.[39] The definition of the Carbon Industrial Management (CIM) text is ongoing, where CCU is under consideration as a 'strategic technology'.

4.3 Bulk and fine chemicals versus energy products

The utilisation of CO_2 can be classified as i) technological use or non-chemical use, and ii) chemical and biotechnological use. Technological uses occur when CO_2 is not chemically converted into other chemicals. From the physical point of view, the CO_2 molecule has useful properties: it is non-flammable, non-toxic, and relatively inert, and it can be used in mild conditions as supercritical fluid. It is used as: an additive to beverages to create carbonated drinks; in the food industry as a cooling agent; in food packaging and antibacterial; in fire extinguishers both as a propellant and an extinguishing agent; in the textiles sector as a dry-cleaning agent and so on.[25]

The chemical and biotechnological use of CO_2 requires chemical and biochemical reactions where CO_2 is converted to produce bulk chemicals such as organic carbonates, carbamates, carboxylates, ureas, polymers, and fine chemicals such as lactones, pyrones, and pharmaceuticals. Table 2 (Source: CO2CZ) reports several fine chemicals that are obtained by using CO_2 as a carboxylating agent of organic substrates in low-energy processes. The alternative synthetic routes would produce large amounts of waste as the introduction of a carboxylic moiety (COO) into an organic molecule is usually achieved by oxidative pathways of alkyl ($-CH_3$) or aryl ($-C_6H_5$) moieties.[25] Noteworthily, moving from

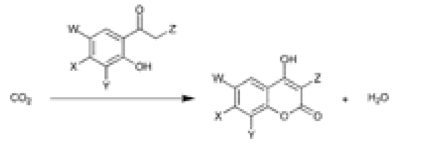
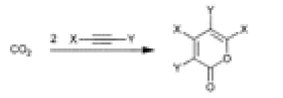
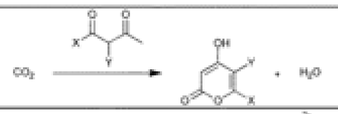
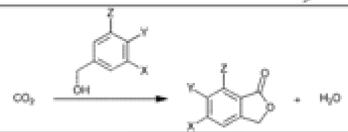
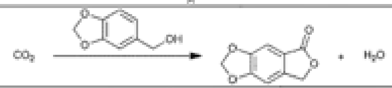
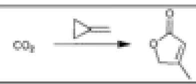
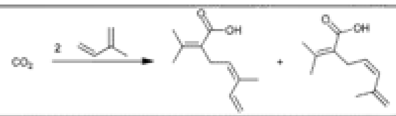
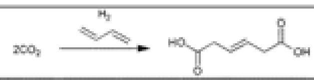
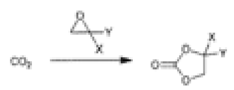
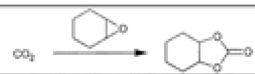
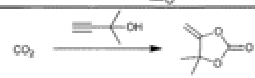
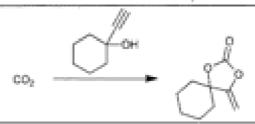
[38] COM(2021) 800 final. Commission communication on Sustainable Carbon Cycles, p. 19. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0800 (last accessed on December 5, 2023).

[39] Chapter 2 (p. 28) in ERA Industrial technology roadmap for low-carbon technologies in energy-intensive industries. Retrieved from https://op.europa.eu/en/publication-detail/-/publication/c9f70ebf-b48e-11ec-9d96-01aa75ed71a1/ (last accessed on December 5, 2023).

fuels to bulk chemicals, fine chemicals and pharmaceuticals the E-Factor (mass of waste/mass of product) may grow from a few units to 500. This implies that developing routes based on CO_2 may reduce the amount of waste organics produced and, thus, the CO_2 emission. An important aspect to consider is the carbon retention time for CO_2 use which can vary per product, ranging from less than one year for fuels, up to ten years for chemical intermediates, to tens of years for polymers, while storage in building materials could last for a hundred years.

Critically, the potential of CO_2 uses to contribute to climate goals will depend on how far, and how fast, these opportunities can be scaled up. Table 3 gives the actual use of carbon dioxide in the synthesis of chemicals (with a minimum market > 1Mt/y per each species) and the prospective use in 2030, calculated considering the expected market growth for the listed chemicals and assuming that the new technologies will be able to convert large volumes of CO_2.

Table 2: Short-list of commercial fine chemicals produced by using CO_2

ID	ProdCom No.	CAS	Product name	Reaction
18	20145210	1076-38-6	4-Hydroxycoumarin (W= X= Y= Z= H)	
19		18692-77-8	7-Methyl-4-hydroxycoumarin (W=H; X= CH_3; Y= H; Z= H)	
20		24631-83-2	8-Methyl-4-hydroxycoumarin (W= X= H; Y= CH_3; Z= H)	
21		15074-17-6	4-Hydroxy-3-methylcoumarin (W= X= Y= H; Z= CH_3)	
22		21315-28-6	3-Ethyl-4-hydroxycoumarin (W= X= Y= H; Z= CH_2-CH_3)	
23		1786-05-6	3-Phenyl-4-hydroxycoumarin (W= X= Y= H; Z= Ph)	
24		17575-15-4	7-Methoxy-4-hydroxycoumarin (X= O-CH_3; W= Y= Z= H)	
25		118157-94-1	3,6-Dimethyl-4-hydroxycoumarin (W=CH_3; X= Y= Z= H)	
26	21103110	65095-32-1	4,6-Dibutyl-2-pyrone (X=C_4H_9; Y=H)	
27		67530-99-8	Tetraethyl-2-pyrone (X= Y=C_2H_5)	
28		77664-31-4	Tetrapropyl-2-pyranone (X= Y=C_3H_7)	
29		675-09-2	4,6-Dimethyl-2-pyrone (X=CH_3; Y=H)	
30		675-10-5	4-Hydroxy-6-methyl-2H-pyran-2-one (X= CH_3; Y=H)	
31		50405-45-3	4-Hydroxy-5,6-dimethyl-2H-pyran-2-one (X=Y=CH_3)	
32		5526-38-5	4-Hydroxy-6-phenylpyran-2-one (X= Ph; Y= H)	
33		111395-92-7	1,4-Diethyl-5,6,7,8-tetrahydro-3H-2-benzopyran-3-one	
34		87-41-2	1(3H)-Isobenzofuranone (X=Y=Z=H)	
35		28281-58-5	7-Methoxy-3H-isobenzofuran-1-one(X= H; Y= H; Z= O-CH_3)	
36		569-31-3	6,7-Dimethoxyphthalide (X= H; Y= O-CH_3; Z= O-CH_3)	
37		3465-69-8	5,7-Dimethoxyphthalide (X= O-CH_3; Y=H; Z= O-CH_3)	
38		4741-65-5	Furo[3,4-e]-1,3-benzodioxol-8(6H)-one	
39		6124-79-4	4-Methyl-2(5*H*)-furanone	
40	20143310	108451-44-1	3-Ethenyl-2-methyl-cyclopentane-carboxylic acid	
41		108451-43-0	3-Ethenyl-2-methylene-cyclopentane-carboxylic acid	
42		134226-08-7	5-Methyl-2-(1-methylethylidene)-4,6-heptadienoic acid	
43		134226-09-8	6-Methyl-2-(1-methylethylidene)-4,6-heptadienoic acid	
44		15022-08-9	Diallyl carbonate (X=C_2H_5)	
45		3459-92-5	Dibenzyl carbonate (X=Ph)	
46		64057-79-0	Bis(methallyl) carbonate (X=C_3H_5)	
47	20143383	29311-53-3	3-Hexenedioic acid	
48	20145225	4437-85-8	4-Ethyl-1,3-dioxolan-2-one (X=C_2H_5; Y=H)	
49		66675-43-2	n-Butylethylene carbonate (X=n-C_4H_9; Y=H)	
50		4427-92-3	4-Phenyl-1,3-dioxolan-2-one (X=Ph; Y=H)	
51		931-40-8	3-Hydroxypropylene carbonate (X=CH_2OH; Y=H)	
52		4437-69-8	4,4-Dimethyl-1,3-dioxolan-2-one(X= CH_3; Y=CH_3)	
53		4427-96-7	4-Ethenyl-1,3-dioxolan-2-one (X= C_2H_3; Y=H)	
54		4389-22-4	Cyclohexene carbonate	
55		2453-03-4	2-Oxo-1,3-dioxane	
56	20145225	4437-80-3	4,4-Dimethyl-5-methylene-1,3-dioxolan--2-one	
57		92474-80-1	4-Methylene-1,3-dioxaspiro[4.5]decan-2-one	

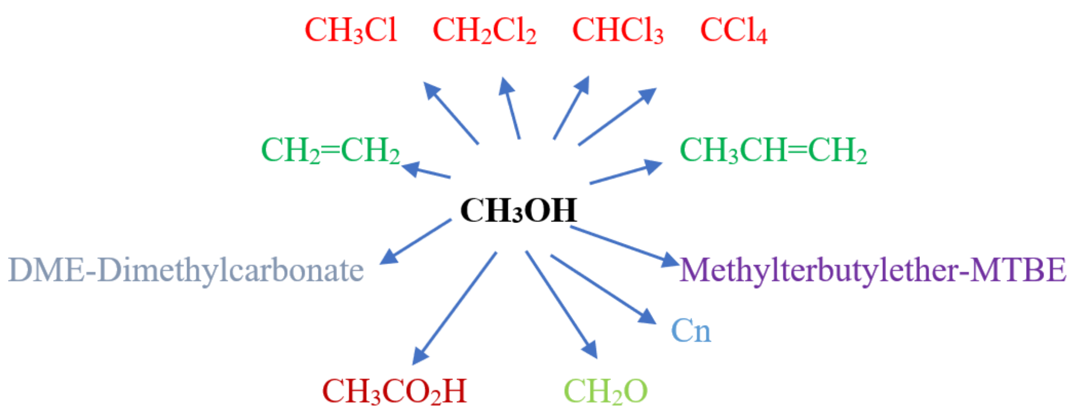
Today, close to 210 million tonnes (Mt) of CO_2 are converted each year compared to 935 Mt_{CO2} emitted worldwide by the CIn. The recycling rate equals 22.1 %, a significant figure.

Table 3: Perspective use of CO_2 to chemicals[25a]

Compound	Formula	$C_{oxstate}$	Actual Market Mt/y	CO_2 Use Mt/y	Market 2030 Mt/y	CO_2 use Mt/y
Urea	$(H_2N)_2CO$	+4	180	132	210	154
Carbonates linear	$OC(OR)_2$	+4	>2	0.5	10	5
Carbonates cyclic		+4				
Polycarbonates	$-[OC(O)OCH_2CHR]-n$	+4	5	1	9-10	2-3
Carbamates	RHN-COOR	+4	>6	1	11	*ca.* 4
Acrylates	$CH_2=CHCOOH$	+3	5	(0.5) ?	8	5
Formic acid	HCO_2H	+2	1	(0.9) ?	>10	>9
Inorganic carbonates	M_2CO_3 $M'CO_3$	+4	$CaCO_3$ 250	70	400	100
Methanol	CH_3OH	-2	60	10	120	>100
Total				207		>370

A particular interest has methanol as it seats on the border chemicals/fuels and can be used as feedstock to produce several chemicals, as shown in Figure 12.

Figure 12: Methanol as feedstock for the CIn



CO_2 in combination with hydrogen, can be used to produce fuels such as methane, methanol, gasoline, and aviation fuels. The process is energy intensive. Noteworthily, carbon-containing fuel is easier to handle than pure hydrogen and has a higher energy density by volume. Renewable-H_2 (or Green-H_2) is the preferred EU-strategy [40], nevertheless low-carbon hydrogen (or Blue-H_2) produced *via* MSR combined with CCS, may represent a fallback if external factors would slow down the production and up-scale

[40] A hydrogen strategy for a climate-neutral Europe

of electrolysers.[41] Several firms have already built demonstration and pilot plants producing methane and methanol from CO_2 and green hydrogen. Noteworthily, due to their large use, the production of both molecules alone would have the potential of converting hundreds- to thousands-million tonnes of CO_2 per year.

4.4 Crossing area: Green H_2 and CCU

As discussed, the conversion of carbon dioxide into energy products requires hydrogen and energy. So, only if perennial energy sources and hydrogen derived from water are used, the conversion of carbon dioxide into energy products becomes sustainable.

At the EU level, "renewable hydrogen" must respond to the requisites reported in the Delegated Acts dated 20 June 2023.[42] Broadley speaking, the environmental impact of H_2-production has been associated with colours. In common understanding, "Green-H_2" is produced *via* water electrolysis using non-fossil electricity, such as wind and solar electricity. Grey hydrogen is the most common form of hydrogen produced from natural gas and fossil fuel releasing CO_2 into the air. Blue hydrogen is produced by the same way as grey hydrogen, but CO_2 is not released but stored somewhere. This latter process emits the lowest amount of CO_2. Unfortunately, this option requires time to be scaled to the desired volume and cost reduction in producing PV. It is expected that by 2040, thanks to the reduction of cost of PV materials (organics instead of silicon) and to their higher efficiency (40 % instead of actual 20 %) the installed PV power will grow to over 4 000 GW making possible the scale-up of green H_2 production. Further barriers to overcome are the availability of materials to produce electrochemical cells and their stability and continuity. PV cannot be the only technology for H_2 production due to its discontinuity, it must be coupled with a continuous source of energy. Once hydrogen will be available it could be used for the reduction of CO_2 to fuels. Even if such conversion will cause the loss of 20–25 % efficiency with respect to the direct use of H_2, it will bear several benefits in terms of reduced capital expenditure (CAPEX) and operating expenditure (OPEX), lower demand of specialty materials necessary for storing, transporting, and using H_2, higher safety, continued use of existing infrastructures that will compensate the loss of H_2. Using H_2 for the reduction of CO_2 to fuels is one of the uses of H_2. Coupling CCU and green hydrogen will make easier reaching net-zero in the future.

Recycling carbon means avoiding the extraction of fossil carbon. A human-made carbon cycle would side the natural carbon cycle and provide energy and chemicals to our society. With respect to the natural cycle, the industrial conversion of CO_2 would be more selective towards a target product and faster.

4.5 Direct use of solar energy in CO_2-reduction

The use of solar energy for driving reactions in which CO_2 is converted into energy-rich products can be considered a sustainable approach. Solar energy is an inexhaustible (perennial) resource, which can provide about 100 000–120 000 terawatts (TW) of irradiation to the Earth's surface, 20 000 times more than the whole world's energy demand.[43]

[41] IEA, The Future of Hydrogen: Seizing Today's Opportunities, IEA, Paris, 2019.
[42] https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/renewable-hydrogen_en
[43] https://www.theprojectdefinition.com/p-solar-energy/ (last accessed on December 5, 2023).

To convert carbon dioxide using solar energy, three different approaches can be considered:

1. electrolysis of water by photovoltaic energy to generate hydrogen used, in turn, for the hydrogenation of CO_2 to gaseous or liquid fuels;
2. use of concentrated solar power for splitting CO_2 and H_2O at high temperature (>1 000 °C) (or even for biomass treatment under controlled conditions) and making Syngas used in turn for making hydrocarbons through the Fischer-Tropsch (F-T) process on stream, and;
3. the direct co-processing of water and CO_2 to energy-rich products under solar irradiation, either by using electrochemical devices, namely the electrochemical reduction of CO_2 in water (medium-term technology) or by direct photo(electro)chemical processes (long-term technology).

The former option, discussed in the previous paragraph, can be applied in the short term as both the electrolysis of water and CO_2 conversion are well-known processes; the second needs some further improvement of both the technology for concentrating solar energy and catalysts for H_2O and CO_2 splitting and may be applied in the medium term; the latter will most likely be exploited in the medium-long term as new, effective and stable electrocatalysts, photocatalysts and photo-electrocatalysts must be developed and advanced reactors need to be developed.[44]

4.6 Modelling CCU: a useful tool

The CCU's potential to mitigate emissions and recycle carbon must be assessed, via life-cycle assessments and modelling. Early studies on the production of chemicals[45a] and fuels[42b] from CO_2 go back to the 1990s. Recently, life-cycle assessment (LCA) (environmental, economic and social) has been used to assess the benefit of using CO_2 as raw material.[46, 47] It is worth saying that the modelling of CO_2 capture does not systematically include biogenic and atmospheric CO_2, and the modelling of CO_2 utilisation mainly addresses the production of fuels and chemicals while leaving aside other key utilisations for industry. To develop a real model, considering that CCU is not a mature technology, the scientific community must provide assessment studies from economic, social and environmental points of view.[48] Results so far achieved demonstrate that the use of CO_2 as either a building block or carbon source is largely positive from the environmental point of view. To make it fully economically sustainable, CO_2 must be recovered from concentrated sources (bio) and be converted into energy products by using green hydrogen or directly water. Direct air capture is still costly today, but a cost reduction in the medium term is foreseen by principal field actors.

5. Impact of defossilisation on the labour market

The defossilisation has a large impact on the labour market at different levels and with various consequences. The impact can be either direct (closing of extraction activities) or indirect (closing of activities connected to the use of extracted fossil-C). The

[44] Horizon Europe Research – DESIRED project (project code: 101083355).

[45] (a) M. Aresta, G. Galatola, J. Cleaner Production, 1999, 7 (3), 181-193. (b) M. Aresta, A. Caroppo, A. Dibenedetto, ACS Division of Fuel Chemistry, Preprints, 2001, 46, 1, 108-109.

[46] L. Desport, S. Selosse, Resources, Conservation and Recycling, 2022, 180, 106150.

[47] J. Artz, W. Leitner et al, Chem Rev, 2018, 118(2):434-504.

[48] https://co2value.eu/co2-value-europe-hosted-the-first-meeting-of-the-european-roadmap-for-ccu/ (last accessed on December 5, 2023).

decommitment from fossil-C has a serious impact on the production of energy and goods and on the overall work market.

5.1 Direct impact

Closing of extraction activities is a reality in several EU countries as seen in Figure 13.[49]

Figure 13: Fossil-C decommitment in EU-27

Since 2012, total coal power generation has dropped by almost a third in the EU. The declining use of coal has caused mines to close down and power plants to be decommissioned in a number of regions across Europe. The graph below depicts the current state of play of national coal phase-out commitments in the EU.

The most affected one is Poland, but several others will suffer a negative impact. In fact, closing extraction activities will have at the end (by 2040, not too far away) a serious impact in 11 EU countries (in parentheses the coal production as for 2015), namely: DE (183 Mt), PL (135), CZ (46), SK (1.8), HU (9.3), BG (35.6) EL (46), IT (0.1), ES (3.0), SI (3.2), RO (25.3). Ca. 150 coal mines are being dismissed and the extraction of 450–500 Mt/y of coal stopped. The total directly employed human-power (as for 2022) was close to 203 641 workers plus 130 793 related to them (induct).[50] The average ratio Induct/Direct ^{workers} is 0.64 spanning over a large interval (0.2-6.3) depending on countries and regions. The majority of direct jobs (181 385 or 89 % of the total) are concentrated in five countries, namely: DE (26 260), PL (107 722), CZ (17 829), RO (16 630), BG (12 944). Most jobs are in mining, a low qualification, even if specialised. This scenario raises

49 https://energy.ec.europa.eu/topics/oil-gas-and-coal/eu-coal-regions/coal-regions-transition_en (last accessed on December 5, 2023).
50 https://joint-research-centre.ec.europa.eu/system/files/2022-01/jrc127463.pdf (last accessed on December 5, 2023).

serious worries about the impact on society that will be real in 15 years or so in terms of lost jobs, impact on families, push towards new internal migration fluxes, migration outside EU-27, under-qualification in a society that is becoming more and more technological.

5.2 Indirect impact

Abandoning coal as a primary source of energy will also have serious indirect effect.[46] In fact, coal represents 16 % of energy consumed in EU, with a share of 24 % in electric power generation. The EU has close to 210 power plants fired by coal, with a total of over 53 000 employees. An additional 22 000 workers operate in activities linked to coal, with a total of over 75 000 jobs indirectly linked to coal.
Stopping the extraction of coal will have a serious impact on the economies of 20 countries (NL, DK, DE, SE, FI, PL, CZ, AT, SK, RO, BG, EL, HR, SI, IT, PT, ES, FR, HU) because of the shortage of energy (150 GW are produced from coal). It will demand a concomitant substitution with alternative energy sources, either perennial (SWHG) or renewable (biomass). The shift will require a strong economic effort, as both CAPEX and OPEX. New skills will be necessary, that most likely will not be available on the market. If cutting the use of other fossil carbon (oil, liquified natural gas) will be pursued, the energy crisis will become more serious if alternative sources will not be available that may provide the necessary power.

5.3 The need to reorienting workers for avoiding critical migration

In a short time (less than 15 years), over 200 000 workers will need to be re-oriented if a deep social crisis should be prevented. Education will most likely mostly concern a population of adults with a low educational level that will need to be educated and driven towards new professions. Even younger people will be concerned. All together it is not a simple task that will require a deep analysis of cases and best decisions for reorienting workers.

5.4 The creation of Hubs in JTF regions for mastering innovation and CCE deployment

A way to win the challenge, avoid social crisis and make an innovation-oriented job market of the EU is to build Hubs that may be at the same time a site of experimentation of innovative technologies and a centre for education to innovation. In this way, innovative technologies will be tested and developed to the application level, while people will be educated to their deployment. Such strategy will cover the entire value chain from mining of alternative carbon sources from different environments than deep ground, to the application of innovative technologies for its transformation using primary energy sources different from fossil-C to product marketing. Recycling will be the new key attitude that must be taught to workers who will become the dissemination agents. The Hubs will represent the pro-active attitude of the EU policy towards innovation and the merging site where research and development will meet education for a fast growth of innovative technologies that will push the deployment of a fossil-C free CIn oriented towards CCE.

Hubs will be built according to regional advocacies and the availability of primary energy sources. All together their objective will be energetic auto-sufficiency based on innovation while developing a new CIn. CEFIC, the European Chemical Industry Council, founded in 1972 and the voice of large, medium and small chemical companies across Europe reports the following on its homepage: 'Indeed, the chemical sector is about to face the biggest transformation in its history, changing how it produces and what it produces in less than 30 years. And we need to do this while remaining globally competitive so that we could continue supplying to important EU value chains, including clean tech […].'[51]

CCE will necessarily represent a strategic technology for the change. Hubs will have not to be 'cathedrals in the desert' (of which we have large evidence from the past) but the beating heart of change and the 'star that shows the way'. Noteworthily, if the real content of the CCE will be implemented, each region will have its own source of carbon that will, ultimately, be collected from the atmosphere (H_2O and CO_2) and transformed into necessary products according to a variety of value chains and local economies and CIns. Therefore, mapping regional CIns and matching them with the new strategic production technology will represent the first crucial step for preparing the change. Integration with local alternative sources of carbon (waste or grown) will produce the best operational conditions and greatest value. In principle, each Hub will have its own character, mission, and target and will produce results immediately usable from the regional CIn but can also be exported to other environments. Hubs will represent the operational integration of science and technology developers (universities, start-ups and professionals) with problem-solving organisations (social parties) and products providers (industries).

The concept of Hub has been discussed with some of the interested parties in JTF regions: the Italian region Apulia with AdI and Czechia (Federations of Chemical Industries). In both cases (even if quite different environments) the concept of Hub has been accepted with much enthusiasm for the change it may promote and the innovation it may sustain. The application of the hub concept in Taranto is detailed in the Annex. Even if AdI is not a CIn, nevertheless the transition from coal to green hydrogen will imply the development of new opportunities (availability of green energy and green hydrogen) that may be useful to other regional activities. Apulia is an interesting area as it already has a plastic recycling centre and a residual biomass utilisation centre (see Annex) that may generate new synergies.

5.4.1 Reorienting workers

Workers in the mining sector will need to be educated in new professions, matching personal attitudes, regional resources and new strategic developments, which will require a serious assessment of opportunities, options, and best practices. This is another positive contribution that will be brought in by HUBs, as a site for gathering intelligence and tactics developers, scientific and technical experts, and educators. Re-orientation will consider the new job market for the best valorisation of the existing competence. To this end, both AdI and the Czech CIn are pioneers in worker's re-education.

5.4.2 Reskilling workers

In a world that is fast evolving from the technological point of view, changing jobs requires a profound re-orientation of workers and the need to learn new concepts and new practical applications. This is not so easy and requires training with experts in education methodologies that may drive people to acquire new knowledge and new operational practices. If such reskilling occurs in a Hub where it is possible to touch with hands-up-scaling technologies, discuss new principles and acquire new concepts will facilitate the shift to innovation with respect to training exclusively based on theory or on practice. The Hub will be a 'nest for changing', a multiplicator of occasions and opportunities for people

[51] https://transition-pathway.cefic.org/ (last accessed on December 5, 2023).

who will be in the condition of changing work: the Hub will facilitate the entrance of workers in the world of innovation and into the future of technology. Both AdI and Czech CIn have ongoing activities in such direction.

5.4.3 Education of young and middle-aged people to innovation and CCE

A problem that will be faced is intergenerational integration which will be a real issue, considering that people to be re-oriented will belong most likely to two active age classes: young people (up to 40 years) and middle-aged people (40–55 years). Seniors (55+ years) will need consideration for the shorter time of activity in front of them. Both young and middle-aged people will need an adequate educational programme to be driven to understand and master innovation and its aspects. Again, the Hub will allow to put them in contact and produce a synergistic grow of both classes, with a reciprocal stimulus and transfer of knowledge.

5.4.4 Filling the gap between schools, universities and industry

The Hub will integrate educational programmes at different levels (high schools, universities, post-university courses, dedicated programmes for the formation of technical staff and managers) integrating basic, advanced, and applied technical concepts. Such integration will even produce a different educational environment, overcoming the present separation that keeps apart the actors who play key roles in education and those who play key role in the production world, in the real life. This will produce great benefits for the entire society.

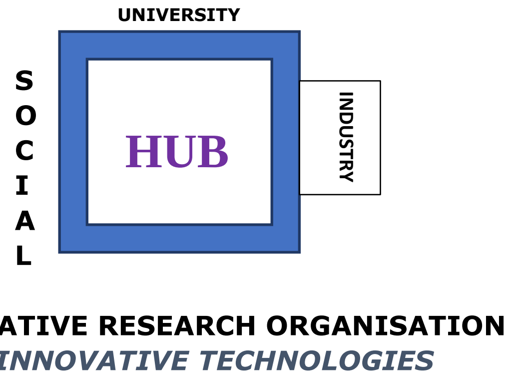
5.4.5 New EU Masters (Interregional Masters) for preparing new professions requested by the new CIn

Hubs will be the ideal site to deliver knowledge to innovation. They will merge all the competence necessary for building new knowledge. The presence of universities will allow to design and implement new courses aimed at building the new integrated knowledge. Formed people will receive a specific title, like a Master in the specific topic that will certify the new skill and their potential employment in the new productive activities that will replace the dismissed ones. This programme will gather direct and indirect former workers that need to find a new job. Their formation to the new regional production activity will avoid migration and the potential disassembling of families. The new educational programme will also produce a grow of culture in the specific region with global benefit. The authors of this document have experience of a successful ongoing EU Joint Master's Degree in Biorefinery (Project n. 610515 EPP-1-2019-1-FR-EPPKA1-JMD-MOB) that gathers students from emerging countries. We propose to aggregate interests and competence in JTF regions for launching an EU Master (for young workers of JTF regions) on 'Technology Innovation and Defossilisation of the CIn' on which we are ready to engage.

6. The creation of Hubs in JTF regions for multi-partnership

As mentioned above, Hubs in JTF regions should be built on four pillars: Social parties, universities, industries, and innovative RTOs (Figure 14). They will be driven by an internal unit for planning innovative technologies and coordinating the change and up-scale. An example of how a Hub should be built is reproduced in the Annex for the area of Taranto, Apulia Region, Italy where significant indirect effects will be felt due to the decreasing of use of fossil-C.

Figure 14: The four pillars for building a Hub



Taranto is in one of the major steel-making industries: stopping coal use will cause serious problems to the over 10 000 direct workers and 4 000 indirect workers. Replacing coal with other energy vectors is mandatory for continuing (or even expanding, as in the plans of AdI) the production in sustainable conditions, with a lower environmental impact and safer working conditions, producing less harm to the population of the area that is the most affected by cancer in Italy.

The Annex provides a picture of the present and future in the Taranto area and how a Hub would help change and support a new economy based on CCE. Even if steel production is not a CIn, nevertheless the transition from C-based fuels to green energy will build in the settlement several facilities that can be relevant to support chemical production nearby. AdI is selected for the presence of facilities functional to the development and support of innovation in the Chemical and Biotech Industry of the Region, which are not far away from Taranto. Noteworthily, the Association of Chemical Industry of the Czech Republic has expressed a strong interest to develop an analogous initiative for their Country. Analogous schemes could be built for other areas, knowing the local conditions, and planning new economic activities according to the local resource availability.

The Hub will facilitate the following:

6.1 Proving new synthetic procedures based on recycled carbon

Starting right now an integrated approach to coal substitution would allow the growth of innovative technologies that can be developed to the application level while lowering the intensity of coal use. The large-scale captured-CO_2 conversion requires in the short term the availability of large volumes of green H_2. In the long term, a different technology can be used based on co-processing of CO_2 powered by solar energy. A variety of approaches will be possible, such as:

1. co-electrolysis of CO_2 and water to C_2 and C_n energy-rich products;
2. photochemical co-processing of CO_2 and water;
3. photoelectrochemical co-processing of CO_2 and water, and;
4. photo-bio-electrochemical co-processing of CO_2 and water.

The state of the art of the various approaches is described in reference 10. Such approaches are all possible in the Taranto area which will be close to the Hydrogen-Hub for the Apulia Region. Taranto is also a sun-rich area and will be a suitable place for photochemical technologies, using marine water in co-processing of CO_2.

6.2 Up-scaling of new inventions

The Hub is the ideal place where innovative technologies can be up scaled to the application level. The existing integrated competence and expertise present in the Hub will be a guarantee for the up-scaling of innovative technologies from TRL three to four up to TRL six to seven. The existing stainless-steel plants will provide materials for building the new plants. The competence of the induct of the stainless plant will allow for the building of new plants for the innovative technologies to the pilot level. This will be true for the Hub located in Taranto. Such activities will reinforce the local economies and will employ new workers or re-employ workers that have lost their jobs, making profit of their competence and new knowledge acquired during the training periods.

6.3 Building-up demonstrators

Demonstrators (TRL 8–9) will be built within the Hub for the selected options to make applicable to production scale the new technologies. This final step will even include new collaborations with external competence, favouring, if it will be the case, inter-exchanges with large industries or/and other relevant Hubs in the EU-27. Demonstrators should be ready in time to produce raw materials that may substitute coal in productive processes. In this way a smooth shift from coal to other energy vectors will be possible. Carbon-based energy vectors with respect to hydrogen present several advantages such as: lower economic efforts (CAPEX and OPEX) in building new infrastructures as old ones can be used or easily adapted; lower demand of special materials; use of existing infrastructure for storage and utilisation; lower risks and higher safety.

6.4 Economic assessment of options

Various putative options will be assessed through building scenarios and modelling using advanced assessment methodologies. LCA, environmental LCA and social LCA will be used to assess new synthetic methodologies by using the new skills built within the Hub. The options that will pass such assessment will be scaled up to demo level and be brought to production, assuring that will not cause harm to people and will be sustainable and environmentally friendly. Such methodologies will be used even for deciding about the best use for streams of waste, based on their specifications and quality. The hub will drive the change and guarantee that the correct choices are made to change the life of regions for the better, without loss of work-power and improving the knowledge of people.

7. The system approach

7.1 Clustering of industries for an easy internal waste circulation

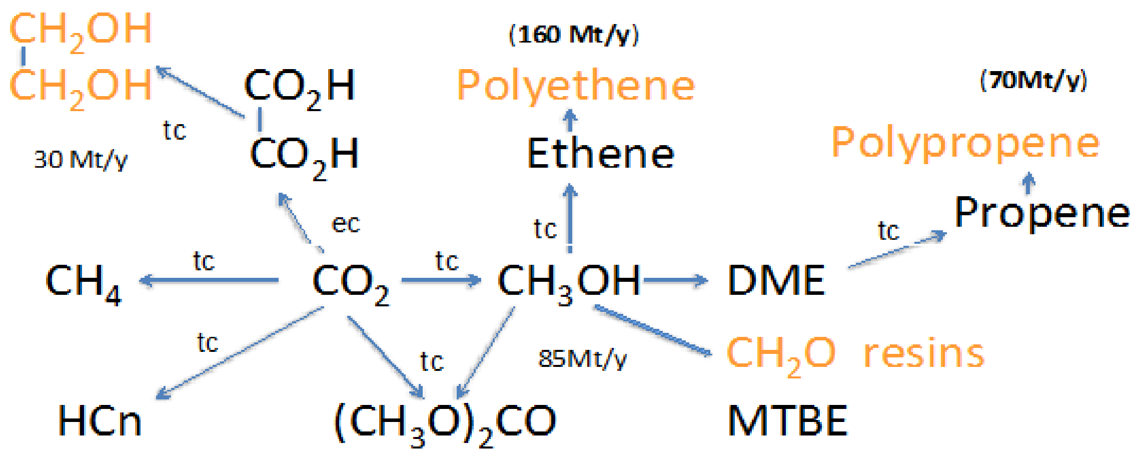
The key principle to be adopted in building new production sites is the 'clustering of productive activities'. In this way, the integrated site will allow an easy circulation of waste. As a matter of fact, in the circular economy view, waste of a production process may be raw materials for another process. Waste can be gaseous streams, liquids or solids: all may find application in new processes in a circularity approach. Streams containing carbon will be used for new productive activities, based on their specification, quality and best use identified using assessment methodologies.

Therefore, 'clustering processes and operations' will favour the efficient use of materials and even wastes, with many benefits for the environment and our society. Here, some key elements will be discussed to clarify the frame in which such an option can really contribute to recycling carbon and reducing CO_2 emissions. Most likely, the existing industrial organisation will be revolutionised in future to generate better options of a cascade utilisation of goods and residues. Industrial processes dispersed in separated sites rise the problem of transportation of specialty residues. In general, effluents and solid residues of an industrial process cannot be freely transported on the road but can circulate within an industrial site. In a circular economy frame, effluents and residues can become 'secondary raw materials' for another process. The clustering of processes and diverse activities will play a key role to optimise the utilisation of raw materials and minimise waste production and CO_2 emission. We have always believed that CO_2 is a renewable carbon; it can be recovered and cycled incessantly, as nature has always done.[52,53] Clustering of processes is, thus, a strategic approach to the efficient use of resources and valorisation of 'waste' streams.

7.2 Value chain approach for an easier use of secondary raw materials

The value chain approach integrated with the clustering of productive activities will allow us to get the best value out of the new industrial production organisation. Two value chains are reported in Figures 15 and 16 that show how CO_2 can be converted into chemicals, fuels and materials (Figure 15) and how CO_2 and waste H_2 can be used for making useful products (Figure 16).

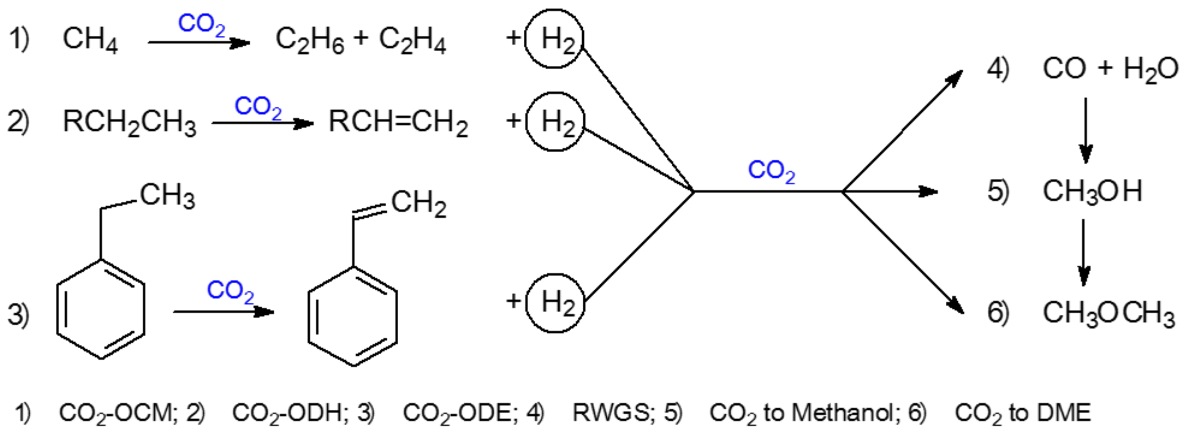
Figure 15: A summary of CH_3OH-centred value chains for CO_2 utilisation (tc=thermal catalysis; ec=electro catalysis). Figures in parentheses give the actual market of products made using fossil-C. In the future, they could be made from CO_2).



Approaching the conversion of CO_2 via 'value chains', more than single reactions, will give a new system perspective to CCU. Figure 15 is an example of integration of processes to produce chemicals and fuels. It shows how it is possible to connect processes for going from a putative waste (CO_2) to a variety of chemicals, materials, and fuels. If such processes are present on the same site a great advantage is produced in chain development in terms of economy of transport and storage.

[52] M. Aresta, G. Forti Eds., Carbon Dioxide as a Source of Carbon: Biochemical and Chemical Uses, 1987, Nato Science Series C.
[53] M. Aresta, I. Karimi, S. Kawi, An Economy based on CO_2 and Water, 2019, Springer Verlag.

Figure 16: Utilisation of CO_2 as dehydrogenating agent and the use of produced H_2 for CO_2



Another example is given in Figure 16 which shows how hydrogen can be managed in a process system: if processes are clustered, 'residual' H_2 can be more easily cycled into a new process for CO_2 reduction opening to a range of opportunities. However, Figure 15 shows that CO_2 (combined or not with oxygen) can be used as dehydrogenating agent (Figure 15, left part, reactions 1–3) towards aliphatic hydrocarbons (CO_2 is a mild oxidant), namely in the coupling of methane or dehydrogenation of propane to propene or ethylbenzene to styrene, a process that is finding industrial exploitation with some demo-plants in South Korea and China. Such process brings to the production of single C-C or double C=C bonds and hydrogen that could be used for the reduction of CO_2 to useful products, either chemicals or fuels. Several other examples of value chains can be built according to local interests and resource availability.

7.3 Production of fuels through CCE

The production of fuels is the sector that will use large volumes of CO_2 (Gt scale). The market of chemicals is some 16 times smaller than that of fuels. As for today, some 210 Mt/y_{CO2} are used in the CIn, as reported above (plus >30 Mt/y in technological applications). It must be emphasised that chemicals may have more complex structures than fuels (that usually are linear/branched hydrocarbons) and processes on stream for their synthesis are multistep, energy-consuming, and waste-producing: the use of CO_2 may reduce the carbon footprint of a process by avoiding up to two to three times the amount of CO_2 fixed. This has been demonstrated by LCA studies.[54,55] A more direct process may avoid organic waste with respect to a multistep: reducing the production of organic waste means saving CO_2 emissions as most organic wastes are burned often without real utilisation of the heat produced. As we have already discussed, the conversion of CO_2 into energy products requires energy and hydrogen, both not originating from fossil-C.

However, only if perennial energy sources are used to power the process and hydrogen is derived from water it makes sense to convert CO_2 into energy products that may find elected application in sectors such as avio-, navy-, heavy road-transport where electric motors (directly or indirectly) powered by solar energy cannot be conveniently used. Noteworthily, it would make sense to implement such CO_2-hydrogenation reactions even today if excess-hydrogen is used. In fact, flared-H_2 amounts at ca. 8 Gm^3/y, as it

[54] M. Rosental, T. Fröhlich, A. Liebich, Frontiers in Climate, 2020, 2, 586199.
[55] C. Moretti, Science of The Total Environment, 2023, 854, 158694.

represents an average of 5.54 % of the total flared gases (150–179 Gm^3) which cause the emission of over 450 Mt/y_{CO2}.[56] However, the production of large-scale fuels from CO_2 requires non-fossil-H_2, such as low-cost PV-H_2 or H_2 that would be flared. Only under the latter conditions the conversion of CO_2 into Cn hydrocarbons or olefins may become an economically and energetically viable option.

Such a concept will be a driving force in future and process integration within the CIn and of the CIns with other sectors (utilisation of biomass, biotechnology) will be the winning option. Carbon-circular economy and bioeconomy are strongly complementary and, if integrated, can multiply the positive effects, balancing some externalities.[57] On the other hand, CO_2 is at the basis of both, and the integration can reinforce the weak points of one with the strong points of the other. Notably, nature has not maximised energy efficiency (there is plenty of solar energy) towards a single product but towards the production of useful chemicals to support life; while the CIn has the attitude to maximise selectivity and energy efficiency (of fossil-C, a not infinite resource) towards a single product. Will science and technology will be able to merge these two powers for finding the solution to the needs of our society? We believe they can.

8. Interlinkages with other Actions

Action 13 will collaborate with other Actions (mainly 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, but not only) and stakeholders (large industries, social parties, RTOs, universities, start-ups, SMEs, among others) so to have a 360° view on the problems that will affect JTF regions as consequence of defossilisation and identify most appropriate integrated solutions and best practices.

- Interacting with Action 16 will allow to bridge the CO_2 conversion to the production and best use of hydrogen, including necessary infrastructures. Such interaction will answer the question whether the use of H_2 for cycling carbon is a suitable option.
- Action 14 will provide views on a different case of CCU, the utilisation of CO_2 for making long-life materials such as cement or inorganic carbonates.
- Action 12 will provide a list of Good Practices (and Bad Practices as well, that will show what is not worth to do).
- The interaction with Action 10 and 9 will allow to have an ample view on the social impact and on consequences on employment of defossilisation.
- Action 8 will permit interaction with sectoral and inter-sectoral stakeholders.
- Actions 5, 6 and 7 will provide useful information and integration with socio-economic observatories, stakeholders and territorial socio-economic observatories which will be deeply implicated in Action 13.

9. Acknowledgements

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[56] E.A. Emam, Petroleum & Coal, 2015, 57(5), 532-555.
[57] M. Aresta, A. Dibenedetto F. Dumeignil, Biorefineries, De Gruyter 2021.

Annex

The Hub on Transition to Innovative Technologies for CCE.

With the key collaboration of:
- AdI;
- Apulia Region;
- CO2CZ;
- Association of Chemical Industries (Czechia);
- CO2Value Europe.

Location: Acciaierie d'Italia, Taranto, Apulia, Italy.

1. Why and where

AdI is a steel production plant that is now the first largest in the EU with an annual production of over 4.5 Mt/y steel (as per 2021) and the potential and intention to grow to >10 Mt/y if all units are switched on. AdI is undergoing a large conversion from coal to green energy and has on the way a wise transition programme, driven by a visionary mission and strong will. The conversion includes a shift from coal to green electricity/green H_2 for powering plants and use as a reductant of ores, respectively.

Such a shift requires large infrastructures, such as:
- eolic offshore platform and PV field for green electricity production;
- in situ large H_2-production unit;
- CO_2 capture unit.

To this end AdI has already implemented the following complementary infrastructures:
- **large laboratory** for analyses and research (set in a new dedicated building; well-conceived for hosting chemical labs and equipment for structural studies and material tests; already equipped with several key instruments; that can be enlarged by building a new floor);
- **technical academy** (already operating for the formation of new skills and devoted to educating young hired people and reorienting workers/dealers).

AdI already supports projects for the CCE:
- CO_2 utilisation technologies under screen, from reactive to non-reactive;
- Projects on CO_2 utilisation.

AdI has already ongoing networking activities with social parties and RTOs to push innovation:
- networking with academia and RTOs, already ongoing, with several projects (even EU projects) under development;
- networking with social parties (ongoing);
- rigorous quality check of materials and special products (auto-control under ATTIRA programme).

AdI owns large extensions of land that can be used for installing a PV field. Moreover, with Taranto City an offshore wind park is planned. AdI owns buildings that can be reshaped, and plants are easy to be retrofitted/converted to new uses.

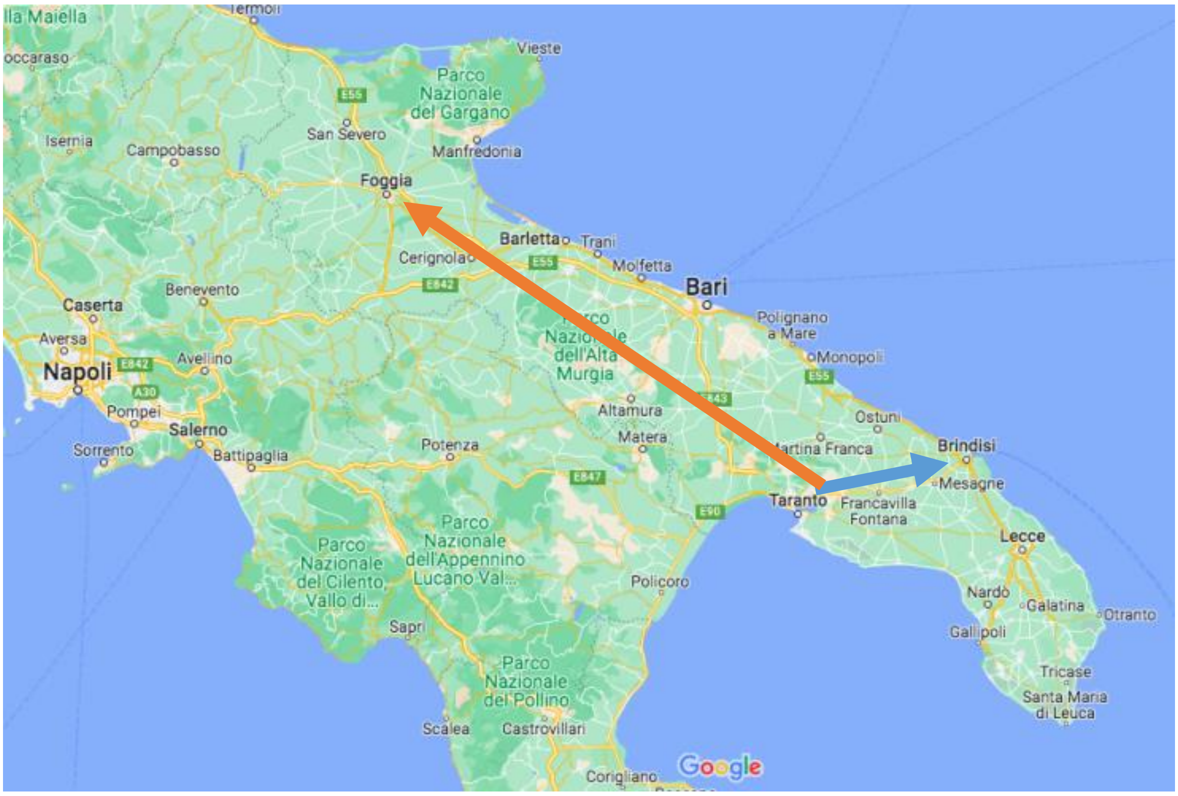
2. The AdI commitment: an evident engagement and a knowledgeable attitude to deploy through the Hub on CCE

AdI is strongly committed to change, with an effective transition from fossil-C to green energy, implementing the European Green Deal, as demonstrated by the number of projects that have been directly funded, all aimed at finding new solutions not based on coal or fossil-C in general*.* The AdI programme matches that of Action 13 and other Actions of the JTP WGs. Such commitment means that placing a Hub on CCE here will continue the company policy and positively impact the entire territory, accelerating the ongoing transition plan.

AdI has over 10 000 direct workers and some 4 000 workers of the induct in the region. It plans to expand the production from actual 4.5 Mt/y steel to over 10 Mt/y. The overall capacity of the four installed units, two of them are working now, is over 11.5 Mt/y of steel. In the past, over 20 000 workers were employed by AdI.

The existing facilities with the already planned ones represent a strong basis on which to build the Hub. It will serve not only the local asset of the company but will also represent an opportunity for the change in neighbouring areas and the entire Apulia Region.

Figure 17: Location of the hub



- **Brindisi**, 80 km away from Taranto, is a chemistry industrial area where polymer plants, plastic recycling, soda-chloro plants and others are still operating or have been just dismissed and are an opportunity to take. Brindisi hosts the largest Italian power plant based on fossil fuels that makes of Apulia (a region with a vocation to green energies: biomass, solar and wind) an overproducer of energy.
- **Foggia** (200 km away from Taranto) is the centre for waste biomass valorisation. Troia (FG) hosts the experimental plant funded by the EU Project STORE&GO for

the methanation of CO_2 with green hydrogen. HYSYTECH, partner of the project, has built there the plant for biogas upgrading to bio-methane (BIO-LNG).

Therefore, in the Hub all options to substitute fossil-C would be merged: biomass, plastic recycling (with demonstration plants in neighbouring areas) and CO_2 conversion.

Figure 18: Preliminary plan for the Hub