

Commentary

Carbon capture and utilization: More than hiding CO₂ for some time

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Context

Energy offers comfort and economic development for those who have access to it. It enables a high quality of life and, if properly managed, makes humans healthy, prosperous, and free. In fact, it enables our access to clean water and abundant food, as well. However, energy choices are inherently about underlying trade-offs, as energy done the wrong way can inhibit economic growth, impinge on the environment, and undermine security as highlighted by the Russian war in Ukraine. To limit global

temperature increase to maximum 1.5°C above the pre-industrial level as agreed in the Paris Agreement, carbon neutrality should be reached by 2050. Reaching that goal implies that by 2050, no net carbon emissions should occur anymore and that all carbon emitted into the air will have to be compensated by CO₂ sinks, either natural or artificial. As argued previously (Mertens et al.¹), the prioritization for action is as follows:

1. First and foremost, we must (continue to) increase the energy efficiency of all our activities and processes and thus consume less energy. Energy efficiency remains a priority. Even though it is often considered that the low-hanging fruit of energy efficiency has been harvested, especially there remains tremendous improvement margin for it.
2. We should increase the share of renewable electricity production and use it to electrify as many processes as possible. This effort must go far beyond electrical transportation. It should include building heating and cooling, as well as many industrial processes and seawater desalination.
3. For processes where high energy density is crucial or for the chemical industry where hydrocarbons are needed as a feedstock or for the storage of energy over longer

time periods, the need for molecules will remain important. Hydrogen production is the most obvious e-molecule since it can be synthesized from renewable electricity and water, either locally or anywhere in the world where cheap renewable electricity and

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water are available.² As discussed in detail in Mertens et al. (2020),¹ due to its low volumetric energy density and the challenges related to its storage and transport, using this green hydrogen in combination with CO₂ or N₂ and convert it to high-energy-dense molecules (e.g., methane, methanol, ammonia, jet fuel, etc.) will be crucial for long-distance marine and aviation transportation, high-temperature heat in the industry, chemicals, long-distance transport of renewable energy, and long-term energy storage.

On our path to carbon neutrality, energy efficiency and electrification remain of utmost importance, and it is why we refer to them as number 1 and 2 in the action prioritization list above. However, it is clear that there is a need for sustainable molecules for applications that require high energy density, e.g., shipping, aviation, high-temperature processes, feedstock for chemistry, high-temperature heat, among others, or for the transport and storage of renewable energy over longer distances and time periods. These sustainable molecules include several types: biofuels based on wastes and residues (such as biomethane, bioethanol, biodiesel, etc.) and electricity-based e-fuels (such as hydrogen or hydrogen-derived molecules made from electricity). Biofuels are useful drop-in alternatives but are limited on a global scale because of competition with land use for food. Green hydrogen, that is, hydrogen made from water electrolysis powered by renewable electricity, is a prominent e-molecule that captures a lot of headlines and the attention of policymakers but is challenging to transport and store. Moreover, the use of hydrogen as a replacement for fossil fuels sets large challenges in terms of equipment revamping and technology developments.

The production of these e-molecules will require huge amounts of renewable energy, particularly to produce green

hydrogen. Many regions, like western Europe with limited access to renewable energy relative to the anticipated overall energy demand, may remain dependent on imports³ from countries where access to low-cost and abundant renewable resources is feasible. High-energy-density e-molecules turn out to be efficient energy carriers over long distances (e.g., methanol, ammonia, methane, jet fuel, etc.). Another advantage of e-fuels made from hydrogen is that they can be easily used as a drop-in fuel into the existing energy infrastructure, with an ultimate aim to maximize the value of the existing assets and minimize total cost. Consequently, this infrastructure will be carrying renewable molecules instead of fossil ones. However, when available and technically feasible, direct electrification options are typically lower in cost and higher in overall efficiency, which cannot be compensated by prolongation of existing infrastructure use.^{4,5}

International Energy Agency's (IEA) Energy Technology Perspectives (ETP) 2020⁶ report estimates that 38% of the emission reduction that is needed will come from making our electricity fully renewable. This potential improvement is not sufficient. Another 40% of the effort will have to come from reducing emissions from industrial processes, and the IEA concludes that "CCUS" (carbon capture utilization and storage) will play a major role in this part. It has to be emphasized that CCUS is a misleading term, as the impact and business cases for CCU and CCS are fundamentally different, and grouping both disjunct approaches does not reflect the reality of these two approaches.^{7,8} IEA is not the only one as reports from the German Energy Agency,³ LUT University,⁴ Stanford University,⁹ and others drew similar conclusions that fuels will be a necessary part of a swift, affordable, and reliable trajectory to net-zero carbon emissions. In the [supplemental information](#) section A, the case study for Belgium is

given as example to highlight that molecules will be needed to reach carbon neutrality.

Apart from renewable electricity, a source of carbon, hydrogen, oxygen, or nitrogen is also required to fabricate synthesized molecules such as ammonia (NH₃), methane (CH₄), methanol (CH₃OH), dimethyl ether (CH₃OCH₃), or formic acid (HCOOH). These sources are usually water or the atmosphere. Carbon capture from point sources is a mature technology to separate CO₂ from flue gases. Cryogenic air separation is a mature electrified process to separate O₂ and N₂ from the air. Direct air capture (DAC) is an emerging technology to concentrate CO₂ from the air.¹⁰ DAC has many opportunities and challenges that will be further discussed in the paper.

There exist several myths and beliefs around the topic of e-molecules, and this paper aims at demystifying some of them.

Myth 1: We must decarbonize to achieve our climate goal

As explained above as part of the third pathway toward carbon neutrality, meeting the climate goals will imply the use of lots of carbon.¹ Therefore, the bad connotation that carbon and CO₂ receive today needs to be reversed, and carbon and CO₂ should be seen as a resource. Many companies have announced their ambitions in terms of "decarbonization" while it would be better and more correct to announce ambitions in terms of "defossilization" or in terms of "carbon neutrality" since carbon will remain crucial in our society. In the future, no (fossil) carbon should be added to the atmosphere, but using carbon in a circular way is a matter of physical needs and will be required to meet the climate ambitions.

Figure 1 shows that CO₂ is a versatile feedstock for many processes, and a wide variety of technologies exist at a range of technological maturity from

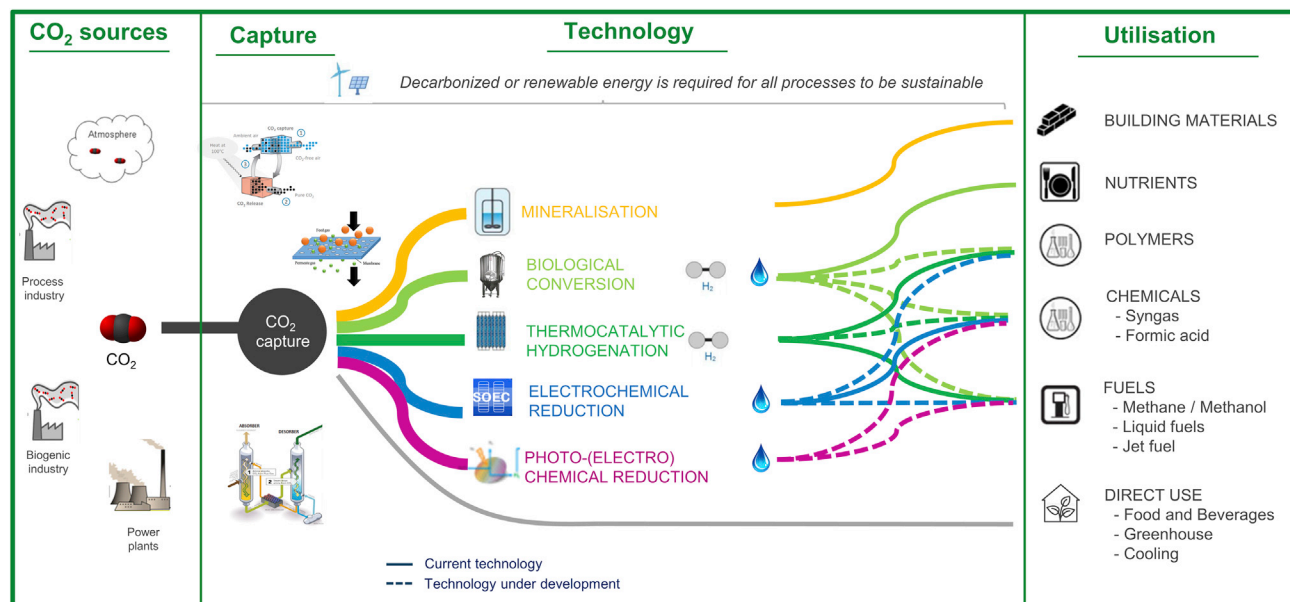


Figure 1. Different chemical and biological pathways exist to produce a wide variety of CO₂-based e-molecules, which can serve as building materials, fuels, chemicals, nutrients, or direct use

lab experiments, small pilots, or demonstrations to commercial-off-the-shelf (COTS) options. IEA's analysis indicates that 75% of the required emission reductions to reach the carbon neutrality ambition will have to come from a whole host of technologies that are not yet mature.⁶ This does not mean that they must be invented from scratch but rather that they will need to be quickly scaled up from benchtop technologies in laboratories to pilots, then demonstrators, and finally into the market of real industrial processes. This is true for many CCU technologies that remain to be industrialized, particularly biology-based technologies.

Mineral carbonation (Figure 1) refers to the conversion of alkaline materials such as magnesium or calcium oxides with CO₂ to produce solid carbonates. CO₂-curing of cement into concrete is a mineralization technology whereby CO₂ partially replaces water (0.02–3 wt %) for the hardening of concrete through a process called carbonation.

The biological conversion depicted in Figure 1 consists of the use of autotro-

phic microorganisms that can fix and reduce CO₂ into biomass and products. Due to the thermodynamic stability of CO₂, extra energy is needed and can be provided either as light or another reducing agent such as hydrogen, for example.

Thermal catalytic hydrogenation of CO₂/CO occurs at high temperatures and pressures using metal/metal-oxide-based catalysts. Two main pathways also exist here, i.e., by direct or indirect hydrogenation (production of syngas via reverse water gas shift).

The electrochemical reduction of CO₂ refers to the direct reduction of CO₂/CO in using electricity in an electrolyzer configuration (similar to a water electrolyzer for H₂ production). Two main types of electrolyzer technologies exist: low (<100°C) versus high (700°C–850°C) temperature ones.

In photo-electrochemical reduction, solar light irradiation is directly used as an energy source to convert CO₂ into selective gaseous and liquid products under mild reaction conditions. This is

often referred to as “artificial photosynthesis” because it mimics nature’s energy cycle to some extent. The semiconductor material is excited by the photons of energy equal to or greater than the band gap energy producing the electrons and holes at conduction and valence band, respectively. These charge carriers initiate and finalize the final products depending upon the redox reactions. Photoelectrochemical reduction of CO₂ (PEC) integrates the benefits of both electrocatalytic and photocatalytic conversion approaches. It can be implemented using four reactor configurations: photoanode/dark cathode, dark anode/photocathode, photoanode/photocathode, and hybrid PEC-solar-cell tandem. Solar chemistry may be the most appropriate terminology to describe these closely related solar-to-chemical energy conversion processes.

Mineralization and thermal catalytic hydrogenation processes are most mature today, and (large) demos exist and even more are under construction. Biological conversion and electrochemical reduction of CO₂ is today leaving

the lab phase (technology readiness level [TRL] between 5 and 8), while photo-electric chemical reduction, artificial photosynthesis, and solar chemistry (TRL between 2 and 5) are still at an earlier stage and studied at research centers. All these different technologies aim at valorizing CO₂ and using it as a resource and will be required to meet our climate ambitions, so the term decarbonization is misleading and erroneous, and we should better talk about defossilization.

Fact 1: CCU always requires large amounts of (renewable) energy

CO₂ has a very low Gibbs free energy; it has a high thermodynamic stability and high degree of oxidation, which means energy inputs and catalysts are needed to convert CO₂ into fuels/chemicals such as formic acid, CO, methane, and methanol. This stability, which makes it hard to convert CO₂ into a fuel, is also what makes it a long-lived atmospheric constituent once it has been emitted. Due to the further electrification of our mobility and industry wherever feasible, an increasing amount of electricity will be required. On top, even more electricity will be needed to serve as a basis to make hydrogen and other derived e-molecules. This renewable electricity is not consistently available everywhere or at an acceptable cost, and therefore moving renewable energy over longer distances will be necessary to succeed in the energy transition. That energy can be moved in the form of electricity or molecules. High-voltage direct current (HVDC) electricity transmission lines will be a part of the solution, but as distance or complexity of terrain increases, other transport modes, namely molecules via pipelines or shipping, could become more competitive,¹¹ particularly if the molecules are used directly as fuel or feedstock. Converting the electricity into an energy carrier such as hydrogen, ammonia, or synthetic hydrocarbons can help facilitate the transport of renewable energy over long distances.

Today, even more innovative solutions such as liquid organic or inorganic hydrogen carriers as well as metal fuels are emerging, and it is likely that these technologies will co-exist and serve to transport energy over (long) distances.

One important exception is the reaction by which CO₂ goes to carbonates (i.e., the mineralization pathway explained above). This pathway is exothermic and thus releases energy. All reactions can use catalysts to speed up the kinetics, but this is particularly useful for the mineralization reaction, which under natural conditions takes years/decades. Although this mineralization reaction is indeed exothermic, today we have no knowledge of applications that recover this heat and use it for a nearby application. Early demonstrations at geothermal fields in Iceland take place underground and thus the heat generation is not convenient to harness. All mineralization processes, however, need (renewable) energy to get access to raw materials for carbonation with CO₂, transport of these materials, grinding of these materials to make them fine enough for reacting with CO₂, and pumps, injectors, or other flow control devices for ensuring reaction. So even for mineralization processes, today renewable energy is required despite their exothermicity.

Myth 2: CCU just delays CO₂ emissions and therefore—even if deployed at a large scale—will not help fight climate change

CCU is a powerful tool to gradually shift current industries from a linear system that relies on hydrocarbon extraction to a circular industrial environment where CCU, powered by renewable electricity is used to valorize and displace hard-to-abate emissions.¹² Figure 2 suggests a near-future CO₂ emission reduction of 50% for the case of fossil CO₂ use and a 100% reduction in the case of atmospheric or biogenic CO₂ being used in the long-term. However, lock-in effects should be avoided

as practically all fossil CO₂ sources have to be phased in order to meet ambitious climate targets. Figure 2 also shows that CCU should not use CO₂ from sources where the low-carbon energy could have been employed more directly but only from hard-to-abate emissions.

For the case of e-fuels (or other synthesized fuels), the source and destination of the CO₂ will determine whether net-zero (or even net-negative) emissions can be reached. To reach the ultimate objective of carbon negativity, the CO₂ has to be biogenic (i.e., from biomass) or come from DAC and then sequestered permanently, while the upstream and downstream greenhouse gas (GHG) emissions for all processes involved are smaller than the amount of GHGs removed. The synthesized e-molecule avoids the need for a fossil alternative and thus has prevented this molecule from being extracted from the underground.¹² So, if low-carbon energy inputs are used, CCU can reduce or eliminate GHG emissions in absolute terms, which means the statement that CCU is just a delay of the CO₂ emissions is not correct. Nevertheless, CCU should not be employed to extend the lifetime of avoidable fossil CO₂ sources and avoid lock-in effects. Thus, the role of CCU as climate mitigation solution needs to be determined by full life cycle analysis in a systemic way, also accounting for alternative strategies.

The emission reduction related to CCU e-fuels will, in reality, be lower than 100% (biogenic CO₂) and 50% (fossil CO₂) due to GHG emissions associated with the carbon capture and e-fuel production process. A worked-out example in supplemental information section B demonstrates that emissions savings can reach 88% to 90% for the case of e-methane production from biogenic CO₂ and green hydrogen made from wind power. These savings will reduce by around half in the case of fossil CO₂ being used. The CO₂

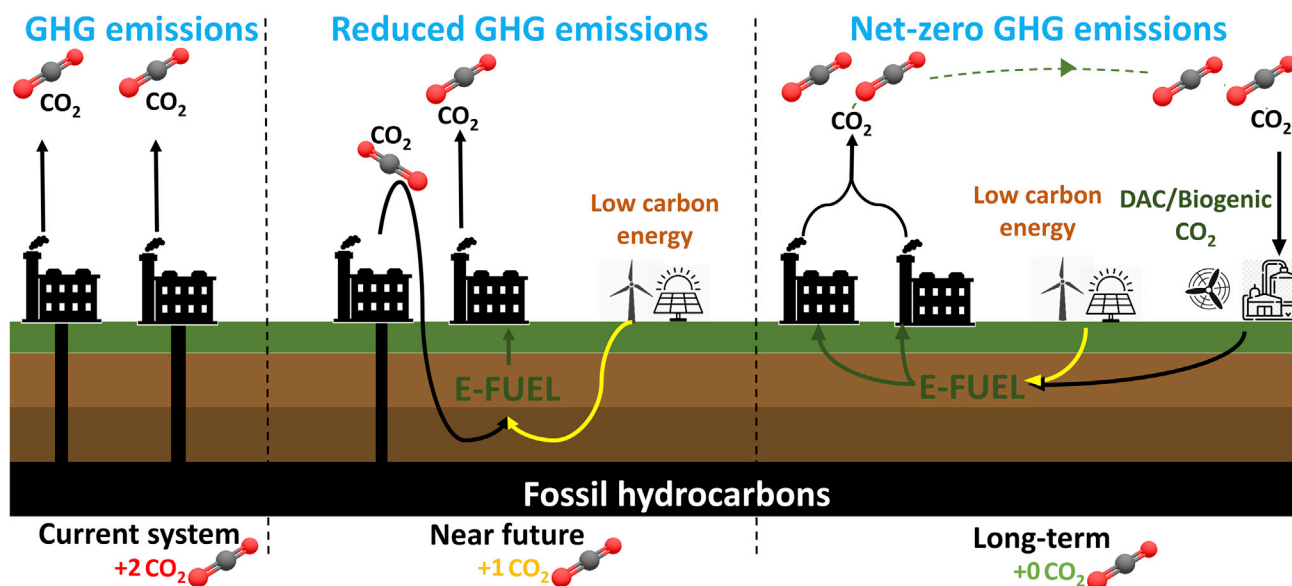


Figure 2. CCU using low-carbon energy is not just a delay in CO₂ emissions but can result in up to 50% emission reduction even when fossil CO₂ is reused

The long-term objective is complete carbon circularity, which implies the need for biogenic or DAC CO₂ as a source, or even carbon negativity, which in addition would require permanent carbon storage (not shown).

emissions related to the power production dominate the final value of the emissions reduction, and the analysis shows that producing e-fuels from fossil-based electricity generation makes no sense at all. Overall, in contrast to what is commonly expressed, CCU using fossil CO₂ from hard-to-abate fossil sources (and low-carbon electricity!) can potentially reduce emissions and therefore may make sense for initiating the industry transition and developing the supply chain for life cycle carbon management.

Moreover, myth 2 on the delay of CO₂ emission reduction in CCU also plays an important role in the perception and acceptance of CCU by society. Although the overall level of knowledge about CCU technology is low¹³—only a maximum of 10% of the population report a high level of subjective knowledge about CCU—the perceived lack of sustainability of CCU is one major barrier to the acceptance of CCU by the population.¹⁴ This is based on the social perception that CCU is only a pretext for "dirty industries" to continue emitting CO₂ and that it would cannibalize investments in the development of other more sustainable technologies.

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Fact 2: Direct air carbon capture and utilization (DACCU) using renewable energy allows full circularity of CO₂ and water

CO₂ can be removed from ambient air through chemical processes, typically cyclic processes. Capturing CO₂ from air is technically feasible and has been applied for decades to maintain safe levels of CO₂ in submarines and spaceships as well as in many processes for air liquefaction. Large-scale DAC processes started to emerge in 2010. Since the CO₂ mixing ratio in the air is so low (about 420 ppm in 2022), the only feasible techniques today involve ab(d)sorption/desorption (with minimal to no air pre-treatment). All currently available processes of air capture use absorption or adsorption on collector surfaces (filters or thin film membrane); the sorbent can be a solid or a liquid. Air can be mechanically driven (fans) or driven by natural flow. Two major commercial DAC processes are currently available: high temperature using an aqueous solution and low tem-

perature using a solid sorbent. The challenge related to these technologies is the large footprint both in energy requirement as well as in required land to install these large devices (although small when compared to the land needed for large scale photovoltaic plants for example). However, significant work is being done on better and cheaper contactors as well as the integration of waste heat for the case of low-temperature DAC.¹⁰

e-molecules are generally produced through CO₂ hydrogenation as explained earlier. Figure 3 highlights that water and heat can be recovered from the hydrogenation reactor to be used in the electrolysis and DAC process. Moreover, DAC systems cannot only capture CO₂ but allow capturing water at the same time. The question comes down to whether we can produce e-fuels and be perfectly circular both in terms of water and heat.

As mentioned earlier, clean fresh water is required for the electrolysis to produce green e-hydrogen needed for hydrogenation of the CO₂. The analysis

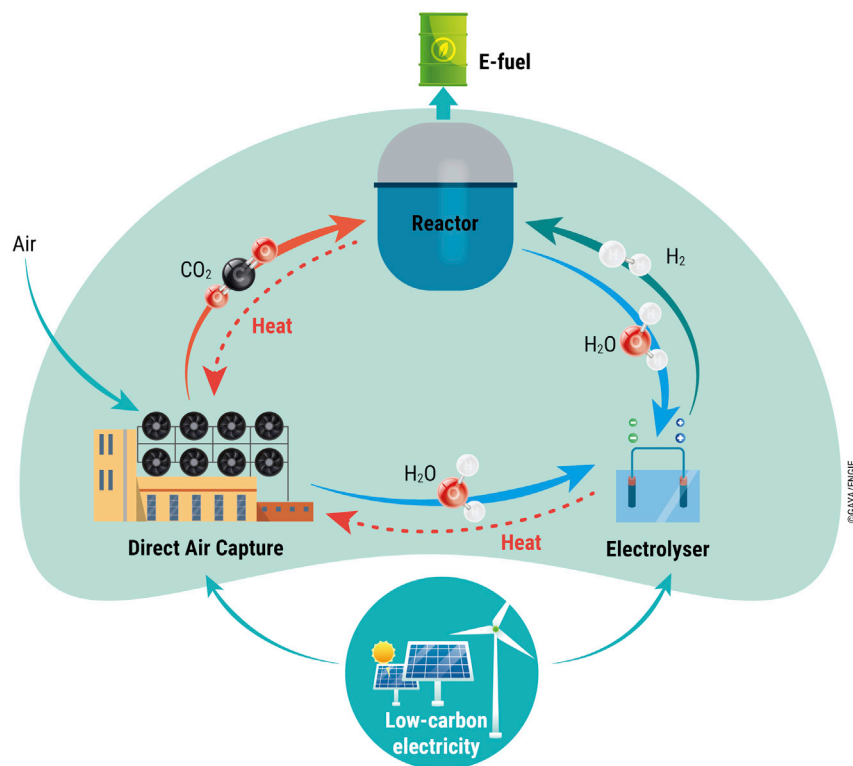


Figure 3. DACCU allows full integration of heat and water, leading to a system with renewable electricity as only input and e-hydrocarbons as output

presented in the [supplemental information](#) section C shows that the water produced during e-fuel production does not suffice to run the electrolyzer, but if complemented with water capture using DAC, sufficient water is available for the production of the e-fuel. Particularly in arid areas, this is very relevant since access to clean water will be an appealing co-benefit from the pathway to a power-to-X economy. In contrast, the heat produced in the e-fuel synthesis cannot completely cover the heat demand for DAC and depends on the targeted molecule: available heat is estimated to 24% for e-methanol synthesis, 81% for e-methane, and 124% for Fischer-Tropsch (FT) e-kerosene synthesis. However, if we include the heat produced by the electrolyzers in case of hydrogen production, more than enough heat is available. The challenge is that the utilization of this low-temperature heat (at 65°C) from the electrolysis will require an upgrading

to slightly higher temperatures (at 80°C–100°C), which may be achieved by mixing with higher temperature waste heat from the synthesis process. Conclusively, we can state that a DAC-e-fuel system has the potential to be self-sufficient in water (as long as process water can be recovered) and that the heat produced in the process can cover the heat demand from DAC but may need some upgrading of low-temperature heat from the water electrolysis.

Myth 3: e-molecules are and will remain too expensive until at least 2035

Many current CCU projects reveal that an economic positive business case allowing production of materials or e-fuels that can compete with their fossil alternative is difficult today. Knowing that the average natural gas prices for non-household consumers in the first half of 2021 in Europe was around

€30 per MWh and only around €15 per MWh for large-scale liquified natural gas (LNG), it is clear that on that basis, e-methane cannot compete with natural gas without other incentives or taxes. In the autumn of 2021, the price of natural gas has increased to historically high values in the range of €80–€100 per MWh and even higher during the Russian war in Ukraine in spring and summer of 2022 (peak >€300 per MWh). This may bring the economic feasibility of e-fuels forward, and it therefore makes more sense to compare this cost to the price of biomethane today in Europe, which is around €95 per MWh. For kerosene, assuming a biofuel alternative cost price of around €180 per MWh, the business case for e-kerosene may be achieved much sooner.

The concept of “social cost” has been mainly adopted to electricity generation¹⁵ and aims to determine which types of costs are relevant from a societal point of view when comparing generation technologies. Plant-level, system, and external costs related to environmental pollution are the main categories of this social cost. The “social cost of carbon” (SCC) is a more recent interesting concept for informing the public policy response to climate change. It represents the marginal damages of a unit of CO₂. The value of the SCC provides information for the valuation of carbon damages associated with climate mitigation public projects and policies. Estimating the damages associated with the marginal carbon emission is a complex exercise, and results have a high uncertainty. However, all studies agree that the social cost of CO₂ after 2030 will be several hundreds of euros per tonne. Even more recently, the concept of “the mortality cost of carbon” was published,¹⁶ which estimates the number of deaths caused by the emissions of one additional metric ton of CO₂ and the costs associated with it. It is estimated that the lifetime CO₂ emissions of 3.5

average Americans causes one excess death globally in expectation between 2020 and 2100. Although all these concepts are the result of models with huge uncertainties, considering this order of magnitude of costs related to CO₂ emissions, e-molecules replacing fossil fuels will become cost or rather value competitive.

Fact 3: CCU allows leveraging of existing infrastructure, making the energy transition less disruptive

As discussed before, hydrogen is challenging to transport and store and requires new infrastructure to be built, implying lots of capital expenditure as well as social acceptance issue. To some extent, hydrogen can be blended in methane pipelines, and several pilots have demonstrated the feasibility of up to 20 vol % of hydrogen without requiring any modification to the gas pipeline network or many of the downstream applications (e.g., GRYHD project in Dunkerque, France). However, for 100% hydrogen or for long-distance transport or long-term storage, other molecules such as ammonia, methanol, methane, and kerosene jet fuel are much more suited and, additionally, infrastructure today is in place and could be used to transport, store, and use these e-fuels without any modifications. Given the high costs related to new infrastructure and the social opposition that usually comes along with it, one could think about continuing to use oil and gas pipelines but also LNG terminals and tankers to transport e-methane over long distances or oil tankers to transport liquid e-fuels. Moreover, existing thermal catalytic facilities, such as the FT synthesis plants could also be leveraged for the production of e-fuels from CO₂ and H₂. For the chemical industry, CCU could provide the basic platform chemicals via methane and methanol such that the remaining chemical industry could run almost unaltered.¹² These characteristics of CCU products not only allow leverage of the existing infrastructure,

giving a significant cost advantage over new hydrogen transport and storage infrastructure and allowing for a faster and cheaper move toward carbon neutrality, but in fact can make the energy transition less disruptive and increase its social acceptance.

As discussed before, CCU will imply the massive rollout of renewable electricity generation, and this may make most sense in more remote (sunny) areas or offshore. Special attention must be given to leaks of gaseous e-fuels such as hydrogen and methane, which requires further clarification and regulation.¹⁷ Both have a global warming potential higher than CO₂, and thus any emissions during production, transport, and storage must be reduced to an absolute minimum.

Conclusions

e-molecules made from renewable energy will be crucial in the energy transition toward carbon neutrality, in particular for long-term energy storage, long-distance energy transport, and for processes that are hard to electrify in industry or long-distance marine and aviation transportation. This paper clarifies some issues that are matter of public debate.

Criticism of CCU by its opponents is often based on the false assumption that it will only delay CO₂ emissions. This concern also exists at the level of public opinion and influences the general socio-political acceptance of CCU. CCU, even when using CO₂ from fossil point sources, makes sense and can reduce up to 50% of the CO₂ emissions if renewable energy is used. However, renewable energy should first be used where it can reduce GHG emissions more efficiently such as in heating and mobility, and lock-in effects have to be avoided as practically all fossil CO₂ sources have to be phased on our trajectory to follow the 1.5°C target of the Paris Agreement. Using biogenic or CO₂ sourced by DAC allows CCU to

be circular in terms of carbon emissions and thus support carbon neutrality. In future DACCU for e-hydrocarbons will allow us to be not only circular in CO₂ but also in water. Moreover, heat from synthesis processes, such as methanation and FT, is available for DAC, and thus also in terms of energy integration, DACCU is highly synergetic. In any case, a full life cycle assessment of the CCU process is always required to understand the real environmental benefits and possible issues, far beyond just climate change but taking the energy-water-food nexus into account.

Today, incentives and/or taxes are required for most e-molecule production to bridge the gap with their fossil alternative, but concepts such as the SCC reveal that in future, this will change. It is true that e-molecules will require huge amounts of renewable energy, in particular to produce hydrogen. Therefore, their production in huge quantities will not be possible in parts of the world where access to cheap and abundant renewable energy is not feasible. Import of renewable energy may be required to meet the energy demand in these areas and e-molecules turn out to be efficient energy carriers over long distances (e.g., methanol, ammonia, methane, kerosene jet fuel). Concepts like the SCC or even the mortality cost of carbon are gaining traction and show that if we take the damage of climate change fully into account, CCU will be cost-effective. This discussion has recently also gained importance in the EU as a result of the huge floodings in Belgium, Germany, and Austria as well as the recent forest fires in Greece where billions of euros of damage was caused as a result of climate change. Ultimately, DACCU has the potential to make a significant contribution to combating climate change if, on the one hand, the link to existing infrastructure, and on the other hand, the use of renewable energies and the complete circularity of CO₂ and water are implemented. Besides technically innovative

and economically feasible solutions, environmental, political, and social parameters should always be included into future developments of CCU.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.joule.2023.01.005>.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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