The Energy Transition: A Paradigm Shift from Emissions to Resources with CO_2 as a Critical Resource Among Others

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Keywords

Energy transition, Carbon Capture and Utilisation, Hydrogen, Renewable Fuels, Renewable energy, Materials criticality, Mining, Mineral processing

Abstract

Scientific evidence underscores the urgent need to reduce CO_2 emissions by over 90% to achieve climate goals. Key strategies include enhancing energy efficiency, expanding renewable electricity production, and recognizing the importance of molecules. While hydrogen is pivotal as an e-molecule, challenges persist in its storage and transportation. Transforming hydrogen into hydrocarbons using CO_2 is a rational approach, especially for energy-intensive tasks like shipping, aviation, and long-term energy storage/transport. CO_2 is set to become a crucial asset in the shift toward sustainable energy. However, achieving carbon neutrality also involves addressing critical raw material (CRM) supply chain challenges. Strategies like material efficiency and substitutivity are short-term solutions, but we must also consider environmental and social consequences in material lifecycle activities, including mining operations.

1. Context

There is ample scientific evidence (*IPPC, 2023*) that to reach our climate ambitions, the first and foremost focus should be on the reduction of our current CO_2 emissions (± 40 Gtonnes today) by more than 90 %. In February 2024, the European Commission presented its assessment for a 2040 climate target for the EU and thereby recommended reducing the EU's net greenhouse gas emissions by 90% by 2040 relative to 1990. To reach full carbon neutrality by 2050, some atmospheric CO_2 will need to be captured and stored. So-called Negative Emissions Technologies (NET's) will be required to compensate for those last few Gtonnes of yearly CO_2 emissions. There is a growing consensus on the pathways toward 90+ % emission reduction, whereby the order is important (*Mertens et al., 2023*):

1. First, we must (continue to) increase the energy efficiency of all activities and processes while providing the energy services for an increasing world population. Energy efficiency implies efficient end use, but also efficient conversion of primary energy to energy services. Energy efficiency remains a priority.
2. The share of renewable electricity production must be increased to directly electrify as many processes and applications as possible. This effort must go far beyond electrical transportation to include building heating and cooling, as well as many industrial and agricultural processes and water management, treatment, and irrigation to cope with droughts, including seawater desalination. The transmission accompanying the “electrification first” paradigm necessitates a strong, complementary focus on grid development, investment, and roll-out.
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 and will require innovative solutions to feedstocks and production.

On our path to carbon neutrality, energy efficiency and electrification remain of utmost importance, and it is why we order them as number 1 and 2 in the above priority list. Recently, studies have pointed to the supplementary challenges given the huge amounts of critical raw materials renewable energy and transmission technologies require as compared to fossil-based ones. This not only holds for the technologies related to electrification using renewables (wind power, solar photovoltaics, batteries, …) but also for the sustainable molecules needed where direct electrification cannot do the job (electrolysers, hydrogen production, transport and storage, catalysts for CO_2 methanation or ammonia production, …). We refer to this challenge as 'From Emissions to Resources' (*Mertens et al., 2024*) since the journey towards carbon neutrality through the reduction of greenhouse gas emissions must tackle the growing resource challenge of critical raw materials (CRMs). There is little scientific doubt that the geological reserves of materials are sufficient to meet estimated future demand (*Wang et al., 2023*) with a set of actions (*Breyer et al., 2022*). This demand comes with an increase in emissions related to this material production, but is limited in magnitude when compared to the continued use of fossil-fuel based energy technologies (*Wang et al., 2023*). Tangential to these opportunities, geopolitical tensions impose stress on global materials supply chains.

Hydrogen has long been considered the most prominent e-molecule in the third pathway since it can be synthesised from renewable electricity and water, anywhere in the world where cheap renewable electricity and water are available. However, as argued in this chapter, due to its low volumetric energy density and the challenges related to its storage and transport, converting green hydrogen produced under those proximity conditions in combination with CO_2 (or N_2) into high energy dense molecules (e.g. methane, methanol, ammonia, jet fuel, …) will be critical to the success of the molecular pathway. This is particularly true 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.

We will highlight that to succeed in the energy transition we must (i) consider CO_2 as a resource and not only as THE problem and (ii) accelerate the development of solutions to reduce supply chain vulnerabilities of resources, particularly the ones related to raw materials.

2. From Emissions to resources: CO_2 as a critical resource?

To get access to sustainable molecules, various options exist: biofuels based on wastes and residues (such as biomethane, bioethanol, biodiesel, …) 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 has captured the attention of policymakers.

2.1 CO_2 makes it easier to store and transport hydrogen

Figure 1 summarizes the volumetric challenges by illustrating the volumes needed to store or transport 10 kWh of energy using different energy vectors (*Mertens et al., 2020*): battery electricity, hydrogen (liquid or under pressure), liquid ammonia (NH_3), LNG (liquefied natural gas), and petrol (representing a wide variety of hydrocarbons). Table 1 complements this figure by complementing the volumetric energy density with the gravimetric energy density or specific energy of the different energy vectors.

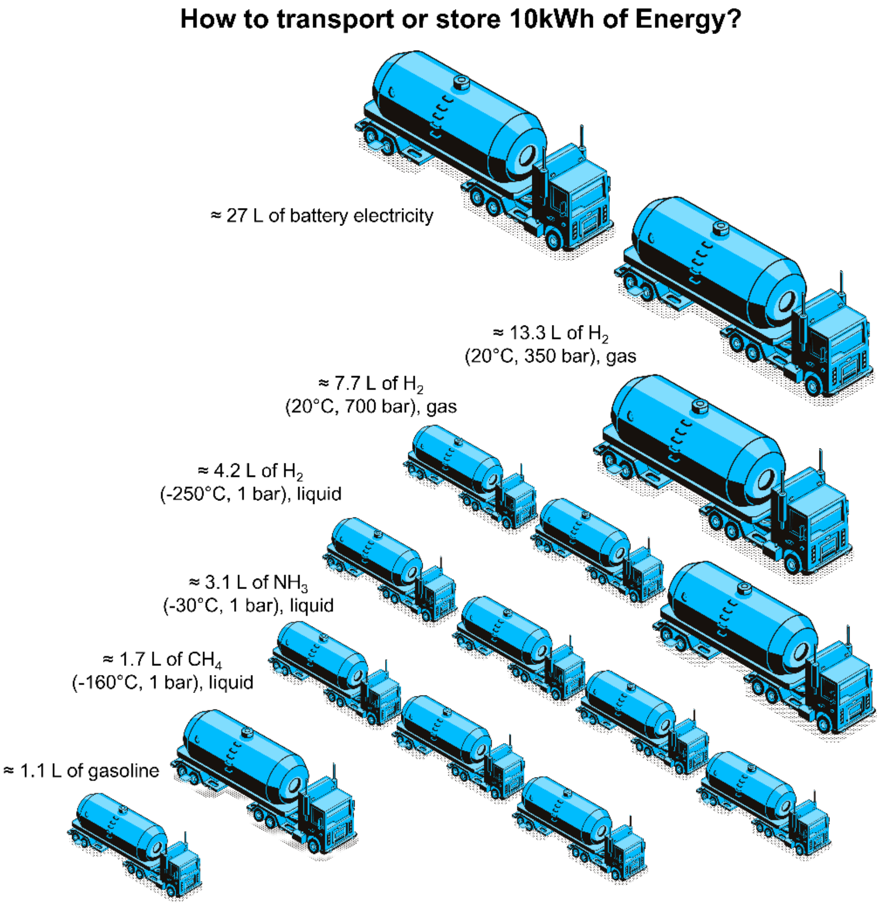

Figure 1 Transport or storage volume of 10 kWh of energy using different energy carriers.

The higher the energy density values listed in Table 1, the more useful a carrier becomes as an energy service supplier. They become easier, and hence more convenient, to store and transport. Current battery technologies are not as energy dense as typical "molecules". Battery storage of large amounts of energy implies enormous volumes and weights, making electricity very hard to transport over long distances (e.g., between continents) or store over long time periods.

Table 1. Specific energy and energy density of energy carriers.

Energy Carrier	Specific Energy kWh kg^{-1}	Energy Density kWh L^{-1}
Li-ion Battery electricity (average value)	0.3	0.5
Methanol	5.5	4.3
Methane (1 atm, 15 °C)	15.4	0.01
Liquified Natural Gas (LNG) (at −160 °C)	14.9	6.2
Liquid NH_3	5.2	3.2
Jet Fuel	11.9	9.7
Hydrogen liquid (LHV)	33.3	2.4
Hydrogen at 1 atm @ 15.5 °C (LHV)	33.3	0.003
Hydrogen at 690 atm @ 15.5 °C (LHV)	33.3	1.2
Gasoline	12.9	9.5

Under normal conditions, the volumetric density of hydrogen is extremely low, requiring enormous volumes for storage and flows in pipes. Increasing pressure up to 700 bar can relieve these problems somewhat, but it remains one-eighth the density of gasoline, which lowers its transportation utility drastically. While the low boiling temperature of hydrogen (−255 °C) makes its liquefaction energy intensive compared to LNG (liquefied natural gas). The low boiling temperature of hydrogen and reactivity also creates non-trivial challenges for the materials used in containments, pumps, and compressors (*Yin and Yu, 2019*).

But hydrogen is the building block for other molecules—the so-called hydrogen carriers such as methane (CH_4), ammonia (NH_3), methanol (CH_3OH), and formic acid (CH_2O_2)—that could be used for chemicals, energy storage, and energy transport. Hydrogen therefore holds great promises as a fuel and chemical feedstock—but not necessarily as an energy carrier. However, the need for energy transport will remain important in the energy transition and it will imply moving (renewable) energy from places where it is abundant and cheap (e.g., with high solar irradiation) to areas where demand is high (e.g., highly populated areas and industrial clusters). The Middle East, Chili, Australia, and others are considered potential sources of significant solar electricity. It is evident that electricity is not an option to bring renewable energy from Australia to North America or Europe. To bring energy to Europe from locations with excess renewable energy, two possibilities exist: HVDC electrical transport or chemical energy, i.e., molecules. Many authors look to hydrogen when considering molecule-based energy transport. However, it must be **analysed** whether this is, energy-wise, including the quality of energy, the best option.

When the hydrogen molecule route is chosen, electrolysis is used as a first step, to produce H_2 out of H_2O. The efficiency for electrolysis is assumed to be 70%. Cryogenic transport with ships is the most efficient way to bring the hydrogen to Europe. Due to the extremely low boiling temperature of hydrogen (−255 °C), its liquefaction is very energy demanding. Different values are found in the literature. We assume a value of 70% for this step. The energy use for transport is estimated at 10%, i.e., an efficiency of 90%. This efficiency includes the energy needed to bring the hydrogen by pipes to the coast where liquefaction takes place. The evaporation requires another 5% of energy leading to an overall efficiency of around 40%. Upon reaching the country of destination, it may be injected in the natural gas grid and delivered to the final consumer or alternatively and, where available, transport can be done using a hydrogen gas grid. A major challenge related to this hydrogen pathway apart from the low efficiency is the absence of existing infrastructure (i.e., liquefaction plants, gasification plants, pipeline networks) which implies huge costs that come on top of the large volumes of energy consumed in the transport process itself.

Therefore, the direct use of hydrogen at the production site is the preferred option. However, in many cases this will be a challenge since the production of hydrogen will mainly be in areas with abundant cheap renewable electricity that do not necessarily coincide with large industrial areas (with steel, cement, chemical, glass facilities, etc.) where enormous energy demands exist. In that case, just as we do today, energy will need to be transported over short and long distances and e-molecules produced from CO_2 and hydrogen make a lot of sense. Therefore, in a carbon neutral society, the need for CO_2 and hydrogen produced from carbon free resources will be massive to supply industrial heat, chemicals, and mobility while serving as a storage and transport medium for excess electricity generated in remote locations.

2.2 We should not decarbonise but de-fossilise

Therefore, the negative connotation that carbon and CO_2 receive needs to be reversed and carbon and CO_2 should be seen as a resource. Many companies have announced their ambitions in terms of 'decarbonisation' whilst it would be more relevant to state ambitions in terms of ‘defossilisation’ or ‘carbon neutrality’ since carbon will remain crucial in our society. No (fossil) carbon should be added to the atmosphere but using carbon in a circular way will be required to meet the climate ambitions.

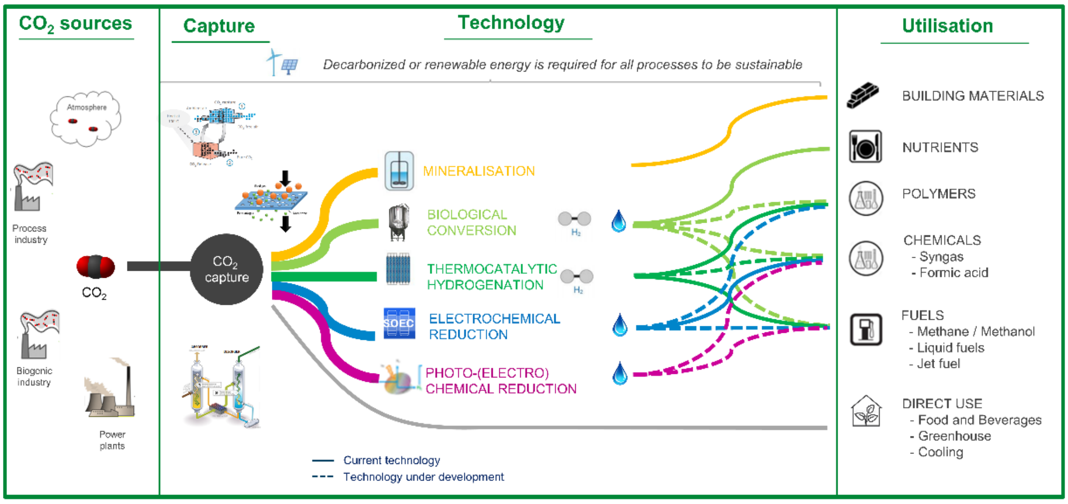

Figure 2 Different chemical and biological pathways exist to produce a wide variety of CO_2-based e-molecules, which can serve as building materials, fuels, chemicals, nutrients, or direct use

Figure 2 shows that CO_2 is a versatile feedstock. A wide variety of technologies exist with technological maturities ranging from lab experiments, small pilots or demonstrations to commercial-off-the-shelf (COTS) options. IEA indicates that 75% of the emission reductions to reach the carbon neutrality ambition will have to come from a host of technologies that are not yet mature (*IEA, 2020*). They must not be invented from scratch, but they will need to be scaled-up rapidly from laboratories to pilots, then demonstrators, and finally into the market of real industrial processes. This holds for many CCU technologies to be industrialised, especially bio-based technologies.

Mineral carbonation (Figure 2) refers to the conversion of alkaline materials such as magnesium or calcium oxides with CO_2 into solid carbonates. CO_2-curing of cement into concrete is a mineralisation technology whereby CO_2 partially replaces water (0.02 – 3 wt%) for the hardening of concrete through a process called carbonation. The biological conversion depicted in Figure 2 consists of the use of autotrophic microorganisms that can fix and reduce CO_2 into biomass and products.

Thermal catalytic hydrogenation of CO_2/CO occurs at high temperatures and pressures using metal / metal oxide-based catalysts. Two pathways exist i.e. by direct or indirect hydrogenation (production of syngas via Reverse Water Gas Shift). The electrochemical reduction of CO_2 refers to the direct reduction of CO_2/CO using electricity in an electrolyser configuration (similar to a water electrolyser for H_2 production), either at low (<100 °C) or high (700-850 °C) temperatures.

In Photo-Electrochemical reduction, solar light irradiation is directly used as energy source to convert CO_2 into selective gaseous and liquid products. This is referred to as “artificial photosynthesis” because it mimics nature’s energy cycle. Photo-Electrochemical reduction of CO_2 (PEC) integrates the benefits of both electrocatalytic and photocatalytic conversion. 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.

CO_2 has a very low Gibbs free energy, it has a high thermodynamic stability and high degree of oxidation, which means significant energy inputs and catalysts are needed to convert CO_2 into fuels/chemicals such as formic acid, CO, methane, and methanol. This stability, making it hard to convert CO_2 into a fuel, is also what makes it a long-lived atmospheric constituent once emitted. Due to electrification of 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.

One important exception is the reaction by which CO_2 is the mineralisation/carbonation pathway which is exothermic and thus releases energy. All reactions can use catalysts to speed up the kinetics, but this is particularly useful for the mineralisation reaction, which under natural conditions takes years/decades.

Mineralisation and thermal catalytic hydrogenation processes are quite mature, (large) demos exist and more are under construction. Biological conversion and electrochemical reduction of CO_2 is moving out of the lab (TRL 5-8) whilst photo-electric chemical reduction, artificial photosynthesis and solar chemistry (TRL 2-5) are at an earlier stage and under study. As these technologies aim at valorising CO_2 as a resource to meet our climate ambitions, the term decarbonisation is misleading and should better be turned into de-fossilisation.

2.3 CO_2 from industrial processes of from the air?

Figure 3 shows how CCU and CCS are part of the 90 % emissions reduction required to reach our climate goals. Carbon removal using Negative Emission Technologies is not treated in this chapter but consists of a set of (Technological or Nature based) solutions that take CO_2 out of the air and store it away, required to ‘compensate ‘ for the last 10 % emissions.

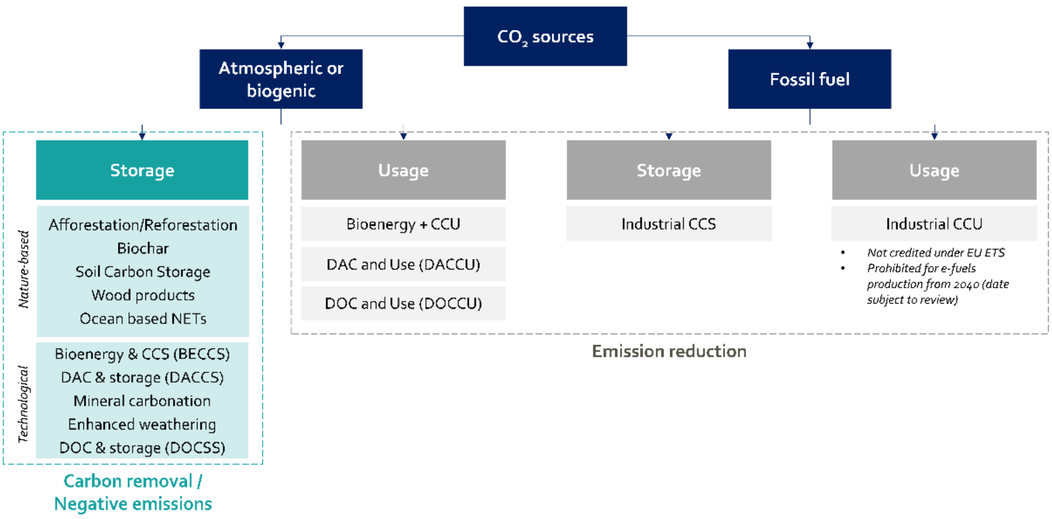

Figure 3 Two dimensions structure the technological landscape: biogenic versus fossil CO_2 and CO_2 storage versus use. CCS of fossil fuel based CO_2 and CCU both allow emission reduction whilst carbon removal or negative emissions can only be achieved through the storage of biogenic or atmospheric CO_2

CCU is a powerful tool to gradually shift industries from a linear system that relies on hydrocarbon extraction to a circular industrial environment where CCU, powered by renewable electricity is used to valorise and displace hard-to-abate emissions (*Kätelhön et al., 2019*). Figure 4 suggests a near-future CO_2 emission reduction of 50% for the case of fossil CO_2 use and a 100% reduction in case atmospheric or biogenic CO_2 is used in the long-term. However, lock-in effects should be avoided as practically all fossil CO_2 sources have to be phased out. CCU should only be used with hard-to-abate emissions.

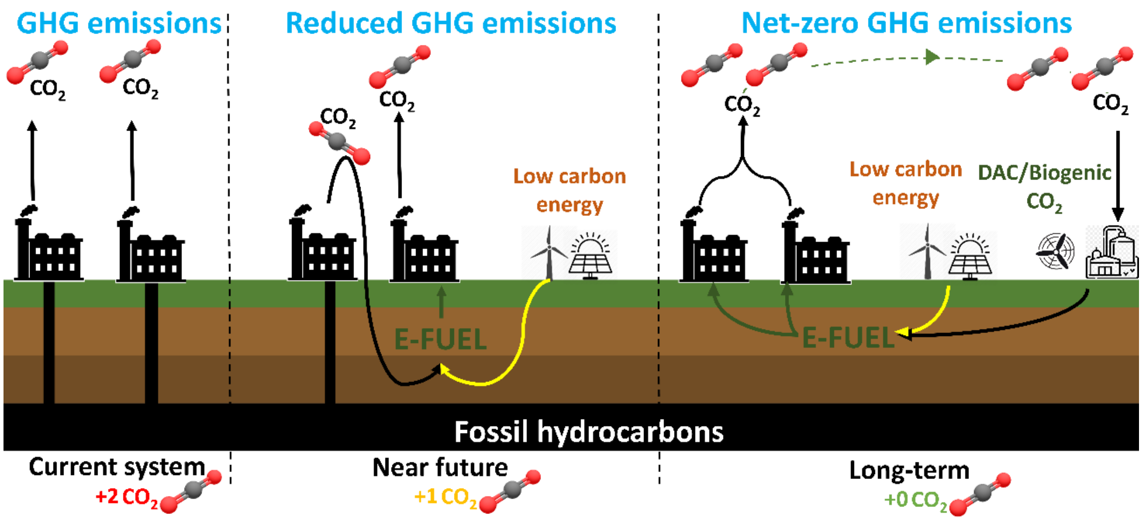

Figure 4 CCU using low-carbon energy is not just a delay in CO_2 emissions but can result in up to 50% emission reduction even when fossil CO_2 is Reused

For e-fuels (or other synthesised fuels), the source and destination of the CO_2 will determine whether net-zero (or even net-negative) emissions can be reached. To reach the ultimate objective of carbon negativity, the CO_2 must be biogenic (i.e. from biomass) or come from DAC and then sequestered permanently (see figure 3). The synthesised e-molecule avoids the need for a fossil alternative and thus prevents this molecule from being extracted (*Kätelhön et al., 2019*). 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 CO_2 emissions is not correct. Nevertheless, CCU should not be employed to extend the lifetime of avoidable fossil CO_2 sources and avoid lock-in effects.

The emission reduction related to CCU e-fuels will be lower than 100% (biogenic CO_2) and 50% (fossil CO_2) due to greenhouse gas emissions of the Carbon Capture and e-fuel production process. An example in *Mertens et al., 2023* demonstrates that emissions savings can reach 88 to 90% for the case of e-methane production from biogenic CO_2 and green hydrogen made from wind power. Overall, in contrast to what is commonly expressed, CCU using fossil CO_2 from hard-to-abate fossil sources (and low-carbon electricity!) can reduce emissions and may make sense for initiating the industry transition and developing the supply chain for lifecycle carbon management.

Although the overall level of knowledge about CCU technology is low (*Arning et al., 2021*), the perceived lack of sustainability of CCU is one major barrier to its acceptance (*Arning et al., 2020*). This, though, is based on the social perception that CCU is a pretext for "dirty industries" to continue emitting CO_2 and that it would cannibalise investments in the development of other more sustainable technologies.

3. From Emissions to resources: increasing need for raw materials

On our journey towards carbon neutrality through the reduction of greenhouse gas emissions, we must tackle the growing resource challenge related to critical raw materials (CRMs). Although there is no geological shortage as such, having access to these materials in a ‘sustainable’ way is crucial to succeed in the energy transition.

'Sustainable' is not only related to having enough materials available but also refers to further improving the environmental and social impacts of mining and material lifecycle activities (e.g., mining, refining, recycling, …) (*Farjana et al., 2019*). As new mining locations are being explored, lower metal grade ores are considered which increases the need for energy, water and chemicals and thus the environmental impact of mining activities (*Global Resources Outlook, 2019*). Clean energy technologies and sustainable raw materials thus become very much dependent on each other. Finally, more attention should be given to the social impact of mining activities, especially the labour conditions and human health impact (*Sovacool et al., 2020*) .

The IEA, 2022 alerts to a mismatch between the amount of materials (in particular Li, Co, and Cu) required to meet climate ambitions and the amount of these metals that are today available from operating mines even when complemented with mines that are today under construction. A review of historical lead times for nickel mine development over the last three decades, based on 67 mines, indicates that the time elapsed between the start of the exploration campaign and the beginning of commercial production has significantly increased with the median shifting from 8 to 12 years *(Heijlen et al., 2021*). It is clear that this cannot be solved by the development of new, land-based mines alone. Finally, the concentration of mining activities in a few countries is not the only concern: materials refining and processing them into components for clean energy technologies is dominated by China. Despite having sufficient supply on a planetary scale, synchronizing materials supply and demand coupled to strategic autonomy raises frictions that require complementary solution pathways.

An extensive literature exists on the challenges related to the availability of critical raw materials for renewable energies (*Lundaev et al. ,2023*). But, only few studies report on the portfolio of mitigation options that could overcome these challenges. *Mertens et al., 2024* attempt to fill this gap whereby they focus on four renewable energy technologies (both for electrification and molecules): solar photovoltaics (PV), wind turbines, Li-ion batteries for large-scale electricity storage, and water electrolysers. Four mitigation pathways are proposed to reduce supply chain vulnerability on critical raw materials and to increase the likelihood of achieving our climate ambitions: (i) material intensity reduction and hence material efficiency increase, (ii) substitutivity, (iii) recycling and eco-design for recyclability and (iv) re-localization. Here, we focus only on the first two, i.e. the material efficiency and substitutivity pathways since they seem most promising in the short run.

Even though recycling should ultimately dominate the CRM supply chain, we can expect recycling to scale up steadily but gradually over the next 15 years given the supply – demand frictions of recyclable, used product. Until then, clean energy assets will mainly be built from ‘primary’ raw materials. The rather slow pace at which recycling is kicking in, is mainly driven by the availability of sufficient end-of-life clean energy assets and longer product life cycles than originally foreseen (e.g., longer lifetimes of PV assets, second life of EV batteries for stationary storage applications, …). Moreover, the recycling process technologies have not yet reached their dominant design phase. Competing technologies for Li-ion battery recycling exist, combining shredding to black mass or not, hydrometallurgy and pyrolysis, pyrometallurgy, … while battery metal compositions have different degrees of recyclability (e.g., LFP versus NMC). Their environmental impact and economic value must be assessed while investments must be made ahead of the battery recycling curve (*Adhikari et al., 2023*).

The last pathway, namely re-localization, intends to bring the production of clean energy technologies closer to where they are deployed. Mining, but even more so, the refining and manufacturing activities of materials and components for clean energy technologies is mostly dominated by China. Recently, the US and EU have designed policies to reduce this dependence on one country. In the EU, the Critical Raw Material Act (CRMA) aims at securing the supply of critical raw materials, mitigating risks to Europe's strategic dependencies while boosting its autonomy, by promoting refining, processing and recycling whilst the Net Zero Industry Act (NZIA) should boost the manufacturing capacity of technologies to support the clean energy transition and to release extremely low, zero or even negative greenhouse gas emissions. In the US, the Inflation Reduction Act (IRA) offers funding, programs, and incentives to accelerate the transition to a clean energy economy.

3.1 Material efficiency: can we do the same with less material?

Figure 5 presents the expected efficiency gains computed by the European Commission (*European Commission, 2020*) for a selected number of CRM that play an important role in the manufacturing processes of the four clean energy technologies highlighted in this chapter. Reductions of material use (expressed in ton per GW of manufactured asset) between 65-95% are expected between now and 2050. This reduction is substantial and is mainly driven by scale effects and understood efficiency improvements (i.e., doing the same with less material), no disruptive technology changes are required. As pressures on CRM availability and cost increase, the efficiency gains expected today are possibly underestimated. Though, as shown in the right column of Figure 5, comparing these reductions to the enormous amounts of material required to meet the energy transition ambitions (*IEA, 2022*), shows that material efficiency alone will not solve the challenge. Moreover, the IEA estimations of the global installed capacity presented in figure 5 may be an underestimation with a factor 4 or 5, for example for PV (*Haegel et al., 2023*). However, a lot is to be expected from material efficiency and it will be an important lever in solving the supply chain challenge of CRM, while it cannot be the sole answer to the challenge.

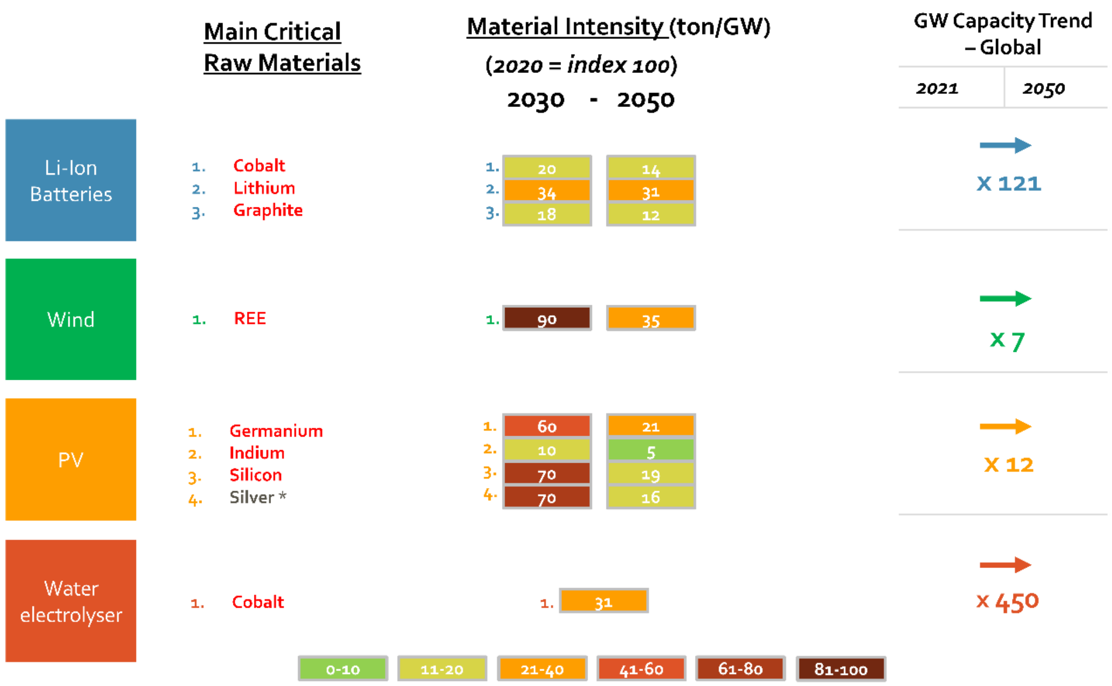

Figure 5 Material efficiency for a selection of CRM between 2020 and 2050 (2040 in case of electrolysers) expressed in tons of material used per GW of manufactured asset (European Commission, 2020) compared to the foreseen increase in installed capacity required to meet our climate ambitions (IEA, 2022). (The asterisk (*) indicates that silver is not listed as CRM in the 2023 list of EU CRM (European Commission 2023) but is still included due to its important role and related cost in the production of silicon-based PV panels)

3.2 Substitutivity: can we replace the critical material with an earth abundant material or switch technology?

Substituting one critical material for another, earth abundant material is increasingly considered to reduce material supply chain issues. A famous example is TESLA switching from nickel, manganese, and cobalt (NMC) based Li-ion batteries towards lithium, iron, and phosphate (LFP) based Li-ion batteries stressing the absence of cobalt as CRM. The European criticality methodology takes substitution of a material for another more earth abundant material into account. The correction factor is a function of the loss in material efficiency this may cause (i.e., lower energy density of LFP batteries versus NMC batteries). Another example of material substitution is the research to replace silver with copper or aluminium in silicon-based PV (*Haegel et al., 2023*). For wind turbines, the CRM challenge is related to the Rare Earth Elements in permanent magnet-based wind turbines.

Instead of material substitution, we can think of switching to an alternative (and usually less mature) technology providing the same or similar energy services. Figure 6 presents a qualitative analysis for various alternatives to the four mature clean energy technologies considered in this chapter where we estimate the vulnerability of the critical material supply chains and their 'scalability'. A technology is considered 'scalable' if we estimate that it can substantially grow by 2035 and could become a major complement or substitute to the incumbent mature technology. Technologies in the upper right corner of the figure present alternative technologies that are both scalable and are less vulnerable to the CRM supply chain challenges. It is interesting that the four technologies found in this top right corner are alternatives for large-scale stationary electricity storage using Li-ion batteries. This implies that in case supply chain issues for batteries would arise, alternative technologies exist that could be scaled up rather fast and which are less vulnerable to CRM issues. For the well-developed silicon-based PV, perovskites can be rather scalable if we can solve their stability, though still a lot of CRM are required. For organic PV, we expect far less CRM challenges but question their scalability according to the above definition. However, the two possible substitutions are rather theoretical as the silver case is considered as no major challenge (*Haegel et al., 2023*). As for water electrolysis to produce hydrogen, most alternative technologies are not CRM sensitive but not one technology is evaluated as scalable. However, for alkaline water electrolysis no material limitation has been reported. Finally, airborne wind requires far less materials than traditional wind turbines, but its scalability is evaluated too low to be a valid alternative technology. Wind turbines using no Rare Earth Elements are well established and can be scaled, even the potentially limited copper could be substituted with aluminum. For ocean energy that could complement or replace both wind turbines and solar PV, technologies are quite diverse and require CRMs whilst none of them are today scalable. A breakthrough is needed for ocean energy to play a significant role in the energy transition.

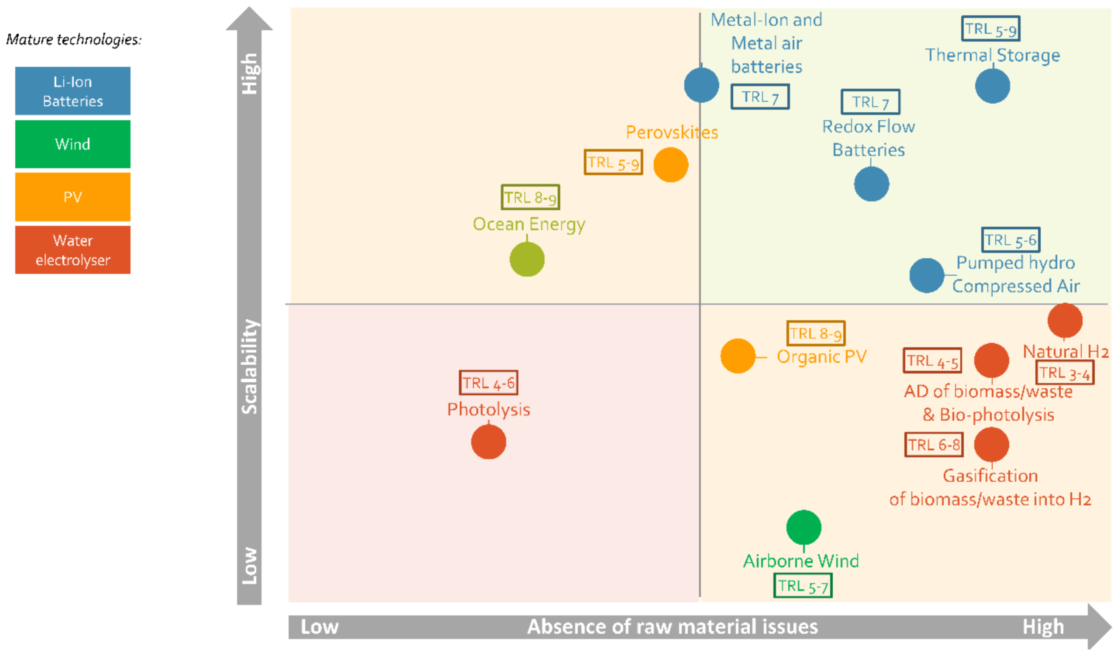

Figure 6 Qualitative evaluation of scalability and CRM vulnerability of alternatives to the mature technologies considered in this study (stationary storage using Li-ion batteries, silicon-based PV, wind turbines and water electrolysis).

Increased research and innovation are required to cope with supply-demand mismatches in CRMs. We should not only raise awareness on the supply chain risks. There is enough literature doing that today. But more important, we should spread the message that complementary pathways to mitigate this risk exist and we should accelerate their development.

4. Conclusion

Scientific evidence suggests that to achieve climate goals, CO_2 emissions must be reduced by over 90%. The consensus on this reduction prioritizes increasing energy efficiency, expanding renewable electricity production, and maintaining the need for molecules in high-energy-density processes. Hydrogen is a key e-molecule but suffers from storage and transport challenges. Converting it to high-energy-density hydrocarbons using CO_2 makes a lot of sense. This is especially true for applications requiring high energy density, such as shipping, aviation, high-temperature processes, and feedstock for chemistry. CO_2 will therefore be a critical resource in the energy transition.

This transition to carbon neutrality presents a challenge due to the use and demand for critical raw materials (CRMs) in renewable energy technologies. Material efficiency and substitutivity are presented as two short term mitigations to reduce our supply chain vulnerability. However, on top of the materials' availability challenge, when striving for carbon neutrality, we must address the environmental and social impacts of material lifecycle activities. This includes improving the environmental footprint of mining activities and reducing their water and chemical requirements.

Every step taken towards carbon neutrality is a step towards a sustainable and resilient future. We must continue to innovate, adapt, and join forces to turn this vision into reality.

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