CCS reality check

Risks and Priorities

EEB
European Environmental Bureau

eeb.org

We are Europe's largest network of environmental citizens' organisations. We bring together 185 civil society organisations from 41 countries. Together, we work for a better future where people and nature thrive together.

The EEB is an International non-profit association /
Association internationale sans but lucratif (AISBL).
EC register for interest representatives:
Identification number 06798511314-27
BCE identification number: 0415.814.848
RPM Tribunal de l'entreprise francophone de Bruxelles

Published: May 2025
Lead Author: Riccardo Nigro
Responsible Editor: Christian Schaible
Contact: sustainableindustry@eeb.org
Graphic Design: Mathieu Sabathé

European Environmental Bureau (EEB)
Rue des Deux Eglises 14-16
1000 Brussels, Belgium
+32 (0)2 289 1090
eeb@eeb.org
eeb.org
meta.eeb.org

With the support of:

With the support of the LIFE Programme of the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor CINEA can be held responsible for them.

CCS reality check
Key takeaways

1. Industrial transformation towards climate neutrality can happen with a marginal use of **Carbon Capture and Storage (CCS)** if any, though this requires a range of other measures to be in place. A **strong mix** of circular economy and demand-side practices, energy and material efficiency, behavioural changes, material (including feedstocks) substitution and a shift towards electricity-based industrial processes could even remove the need for any CCS.

2. Investments and policies should start today to unleash the potential of electrification for the coming decades. **Direct electrification technologies**, expected to be available by 2035, could meet 90% of the energy demand not yet electrified by European industry[1]. Technologies readily available today, such as **heat pumps** and **electric arc furnaces**, could cover over 60% of this demand. Instead, fossil fuels account for about 75% of the energy consumed by industrial process heating.

3. **So far, CCS has not played any role to help the decarbonisation** of carbon-intensive activities. On the contrary, presently the main role of CCS is to facilitate the extraction of fossil fuels. Moreover, CCS cannot address CO_2 emissions along value chains, such as **fugitive methane emissions** due to the extraction of fossil fuels.

4. CCS is expensive and is **not expected to become significantly cheaper** in the future. According to researchers at the University of Oxford[2], it would be prudent to assume that CCS will continue to be as expensive as it is today, particularly when not associated with the extraction of fossil fuels, which so far has been the only way to justify a business case for CCS projects without public funds. Any financial support should come from private investors, strict enforcement of the **polluter-pays principle** and **extended producer responsibility** for the impacts generated by pollution.

5. Costs associated with widespread CCS use would be extremely high and could **divert funding from more mature and cost-effective solutions**. According to the Institute for Energy Economics and Financial Analysis (IEEFA)[3], Europe's current project pipeline could cost as much as **520 billion €** and require **140 billion € of government support** to capture and store only a fraction of longer-term targets. Public investment at this scale would draw scarce public money from much more effective decarbonisation solutions.

6. Carbon-intensive sectors such as **steel and cement**, which used to be considered "hard-to-abate", **can be considered "fast-to-abate"** due to rapid advances in fossil-free production processes, improved recycling and circular processes, as well as market-ready low-carbon substitutes able to sideline carbon-intensive traditional products. Similarly, **transport and low-temperature heating** can be decarbonised without the use of CCS.

7. **CO2 is not a commodity, but a dangerous pollutant that must be treated as such**. If CCS is deployed, permanent CO_2 storage must always be the preferred option over use, unless CO_2 can be bound in products for a period of several centuries.

[1] Fraunhofer ISI (2024): Direct electrification of industrial process heat. An assessment of technologies, potentials and prospects for the EU. Study on behalf of Agora Industry.
[2] Bacilieri, A., Black, R., & Way, R. (2023). Assessing the relative costs of high-CCS and low-CCS pathways to 1.5 degrees. Oxford Smith School Working Paper 23-08
[3] IEEFA, 2024, Carbon capture and storage: Europe's climate gamble

CCS reality check
Realities, Risks and Priorities

CONTENTS

1 The limits of CCS

a Unfulfilled promises always linked to the fossil fuels industry

The track record of CCS achievements in the last decades tells a story of undelivered promises. Already in 1991, CCS was depicted[4] "as a promising solution for the near term" and, in any case, as an "interim priority". So far it has not played any role to help the decarbonisation of carbon-intensive activities. On the contrary, presently the main role of CCS is to facilitate the extraction of fossil fuels.

At the end of 2023, only 41 CCS projects were operational globally [5] . Of these, 15 operational projects were linked to the extraction of fossil gas[6] , while 29 used the captured CO_2 to facilitate the extraction of oil through a process called Enhanced Oil Recovery (EOR) [7]. To date, only 6 projects are active in Europe; the two largest ones (Snøwhit and Sleipner in Norway) facilitate the processing of fossil gas. In other words, today operational CCS projects are financially intertwined with the fossil fuels industry, which is essential to justify the financial viability and profitability of such projects. This creates a perverse mechanism where CCS does not contribute to fix the climate crisis through emission reduction at the source, such as stopping fossil fuel extraction, but rather incentivises more CO_2 emissions.

It is not clear whether there is a business case independent from the revenues of the fossil fuels industry. In the EU, even high carbon prices have not provided enough financial incentives to invest in CCS; the power sector is rather investing in renewables, a cheaper and more profitable option.

[4] Nebojša Nakićenović, Aviott John, CO_2 reduction and removal: Measures for the next century
[5] Global CCS Institute, 2023 Global Status of CCS
[6] To produce marketable natural gas when the extracted raw gas contains too much CO 2 .
[7] Enhanced oil recovery is the extraction of crude oil that cannot be extracted otherwise through the injection of gases, including CO 2 . EOR enhances the oil production rate from fields that have passed their maximum output rate. Beyond allowing the extraction of additional oil, EOR projects results in significant re-emission of CO 2 into the atmosphere, as enhanced oil recovery injection sites can have CO 2 retention rates below 30%.

b CCS deployment is slow and not in line with the mid-term climate targets of the European Union

At a moment when the world is already experiencing temperatures exceeding the 1,5°C threshold set in the Paris Agreement[8], the potential contribution of CCS is clearly minor and would divert financial resources from other more effective, cheaper and readily available decarbonisation solutions, such as electrification, material and energy efficiency, enhanced circular economy strategies, other process innovations and low-carbon substitutes. In the EU, the CO_2 emissions of the more carbon-intensive sectors except combustion of fuels (refining of mineral oil, production of cement clinker and production of pig iron and steel) alone amount to around 300M tonnes of CO_2 per year[9]. Even if the EU manages to implement the target of 50 million tonnes of injection capacity per year foreseen in the Net-Zero Industry Act (NZIA), this will only happen from 2030 onwards and that will only address 17% of the CO_2 emissions of those three sectors.

According to the Haut Conseil pour le Climat[10], an independent expert body in charge of assessing public activities regarding climate action in France, the goal of France to capture 4 to 8 Mt of CO_2 per year "looks ambitious" though it would only represent between 13% and 26% of the CO_2 emissions from the aforementioned sectors.

c CCS is the least efficient and one of the most expensive climate mitigation options

According to researchers from the University of Oxford[11], neither the CCS industry nor the International Energy Agency (IEA) have ever systematically assessed costs linked to CCS deployment. The literature only provides approximations. These show variations in cost estimates for the same CCS project by up to 65%. Further uncertainties arise when considering storage and storage maintenance, for which there is limited real-world experience. The study shows that, in general, the costs of CCS are usually underestimated, while technological progress is overestimated.
The evidence gathered by the researchers also suggests that the learning effect, which usually brings the cost of technologies down, is unlikely to happen for CCS, mainly because its equipment consists of mature engineering components such as steel pipes and gas pumps.

A report by the EU Joint Research Centre (JRC)[12] highlights that costs vary a lot, anywhere between 13€ and 103€ per tonne of CO_2 depending on the industry and CO_2 concentration. Transport and storage costs can also vary significantly depending on distance, volume, geographical location and storage conditions. The French Agence de d'Environnement et de la Maîtrise de l'Énergie (ADEME) estimated that capture and storage costs for the French industry vary between 69€ and 143€ per tonne of CO_2 eq[13].

[8] According to the EU's Copernicus program, "we have also just experienced a 12-month period of more than 1.5°C above the pre-industrial reference period. Rapid reductions in greenhouse gas emissions are the only way to stop global temperatures increasing".
[9] European Environment Agency, EU Emissions Trading System (ETS) data viewer (2023 data)
[10] Haut Conseil pour le Climat, 2023, Avis sur la stratégie de capture du carbone, son utilisation et son stockage (CCUS)
[11] Bacilieri, A., Black, R., & Way, R. (2023). Assessing the relative costs of high-CCS and low-CCS pathways to 1.5 degrees. Oxford Smith School Working Paper 23-08.
[12] EU Joint Research Centre, 2023, Carbon Capture, Utilisation and Storage in the European Union
[13] ADEME, 2020, Le Captage et Stockage géologique du CO2 (CSC) en France

At the EU level, industrial operators active in the cement sector[14] estimate that the costs associated with widespread CCS deployment are very high. Using the cement sector as an example, only connecting the more than 200 clinker producers in the EU to a transnational CCS network would require a financial effort of billions of euros; only operationalising the NZIA injection capacity target (50M tonnes by 2030) would require up to 10,5 billion €[15], while IEEFA estimated in 520 billion € the cost of the current EU's project pipeline[16] . If such a financial commitment would come from the public purse, CCS would divert scarce public resources from much more mature, readily available and effective decarbonisation solutions.

Moreover, more CCS means higher costs for renewable energy. The Oxford study mentioned above shows an important side-effect linked to a large and unfocused deployment of CCS. Decarbonisation pathways foreseeing a high use of CCS will cause higher prices of renewable energy technologies (solar and wind) and electrolysers than low-CCS pathways.

The reason for this is that, as low-CCS pathways deploy more solar, wind and electrolysers, the cost of these technologies comes down faster. As well as creating cheap and early emissions reductions, faster deployment of renewable energy and electrolysers makes even more substitution of fossil fuel technologies possible at lower cost than in high-CCS pathways. This effect is likely to be found also for energy storage. On the other hand, high-CCS pathways foresee a higher use of fossil fuels, consequently slowing down the deployment of renewable energy sources and electrolysers and, as a result, reducing their learning effect and increasing their costs.

In a nutshell, high-CCS pathways would carry the risk of perpetuating the use of fossil fuels, with all the associated risks and impacts, including detrimental business case for renewables.

d CCS performances in terms of actual capture rates are always overestimated

In general, it is usually assumed that CCS can capture 85-90% of the CO_2 released after combustion, leaving unsolved the problem of dealing with the 15-10% of emissions that CCS cannot capture. According to a Senior Research Engineer at the Massachusetts Institute of Technology (MIT), achieving capture rates above 90% is more expensive: the closer a CCS system gets to 100% capture efficiency, the harder and more expensive it becomes[17].

[14] Ecocem's answer to the Industrial Carbon Management strategy
[15] European Commission Staff Working Document: Investment needs assessment and funding availabilities to strengthen EU's Net-Zero technology manufacturing capacity
[16] IEEFA, 2024, Carbon capture and storage: Europe's climate gamble
[17] MIT Climate Portal: How efficient is carbon capture and storage?

According to a study released by IEEFA[18] analysing the actual capture rate of 16 existing CCS projects, no existing project has consistently captured more than 80% of CO_2 (see figure 1). The average capture rate of such projects is around 49%, with some only at 10-17%. For certain specific applications such as ammonia and methanol production, capturerates can be higher due to the purity of the CO_2 stream.

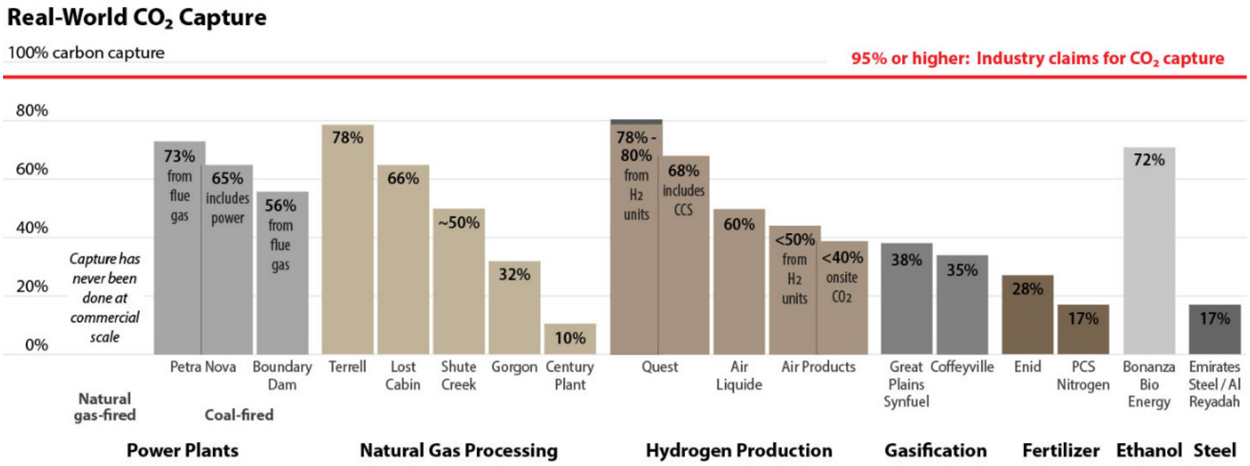


Figure 1 - Source IEEFA

An analysis by ARIA[19] on the Al Reyadah CCS project in the United Arab Emirates has found that it could capture only 13,6% of the CO_2 emitted by the steel mill it serves, with additional GHG emissions occurring up and downstream. The fact that the CO_2 captured is used for Enhanced Oil Recovery (EOR, see footnote 5) further compromises the climate performance of Al Reyadah.

An additional issue arises as industrial facilities usually have various points of emissions, some of which might be too difficult to address due to too low CO_2 concentration in the waste gas. In fact, the lower the CO_2 concentrations, the higher the costs and the amount of energy required by a CCS facility. In a medium-sized blast furnace steel plant, for instance, such a limitation would imply that only 73% of its total CO_2 emissions would be captured, resulting in the release of about 2,5 Mt of CO_2 per year[20] into the atmosphere.

More transparency is needed to fully understand the actual achievable capture rate of CCS and whether those rates are kept sufficiently stable on the long term. In general, minimum capture rates should be kept stable in the >95% range to ensure that CCS projects provide the highest climate benefits.

[18] IEEFA, https://ieefa.org/ccs
[19] ARIA, 2023, The shaky foundation of the UAE's carbon capture strategy
[20] Agora Industry, 2024, Low-carbon technologies for the global steel transformation

e CCS impacts on pollution (air, water, waste)

The use of CCS can have an indirect positive impact on air pollution. According to a study released by the Clean Air Task Force (CATF) focused on four large industrial facilities in the US[21], the use of CCS nearly eliminated the emissions of sulphur dioxide (SO_2), reduced particulate emissions by 90% and abated nitrogen oxides (NO_x) emissions by 2% in cement plants and 33-73% in refineries. This happens because, to work properly, CCS equipment must process a flue gas stream without SO_2 and particulate matter, which must be removed. Nevertheless, when it comes to NOx emissions from refineries, the use of CCS is less efficient than dedicated NO_x abatement techniques such as Selective Catalytic Reduction (SCR).

In any case, the use of pollution abatement techniques is required by EU legislation regardless of the use of CCS. Moreover, many other air pollutants are not captured by CCS equipment and include CO, organic gases, mercury and other heavy metals, black carbon, and other aerosol components[22]. Many of such pollutants will simply continue to be emitted, regardless of the presence of CCS equipment. For instance, in waste incinerators the use of CCS will address CO_2 emissions but will not reduce other persistent organic pollutants such as dioxin or furan[23].

Additionally, by promoting processes based on combustion, the use of CCS increases upstream GHG emissions and environmental damages (e.g. methane emissions due to coal mining[24]) due to the extraction of fossil fuels.

Finally, CCS increases the pressure on water resources for the cooling of fumes and amine scrubbing. An estimated volume of at least 1,71 m^3 of water per tonne of captured CO_2 is required for coal power plants, 2,59 m^3 for gas power plants and 4m^3 for direct air capture techniques (amine scrubbing[25]). Another study by Lorenzo Rosa et al. (2021) refers to water withdrawal rates going from 0,74 to 575 m^2 for water/tonne of CO_2 captured[26]. According to the IPCC[27], water withdrawals for CCS are 25–200% higher than plants without CCS due to energy penalty and cooling duties, which also impacts biodiversity. In case of water scarcity, it is possible that CCS equipment must be even switched off.

CCS requires, for most technique options, the use of solvents (amine process) that generate toxic waste and require energy for regeneration. According to the Haut Conseil pour le Climat, an estimated solvents consumption of 1,85 kg is required for 1 tonne of captured CO_2. The most common solvent used is monoethanolamine (MEA) or methyldiethanolamine (MDEA), other solvents used are a blend of Piperazine/amino-methyl-propanol.

[21] Clean Air Task Force, 2023, Air Pollutant Reductions from Carbon Capture
[22] Mark Z. Jacobson, The health and climate impacts of carbon capture and direct air capture, Energy Environ. Sci., 2019, 12, 3567
[23] European Environment Agency, Persistent organic pollutant emissions
[24] Coking coal, used in steel production, is an important source of methane emissions.
[25] Haut Conseil pour le Climat, 2023, Avis sur la stratégie de capture du carbone, son utilisation et son stockage (CCUS)
[26] Lorenzo Rosa et al., 2021, The water footprint of carbon capture and storage technologies
[27] IPCC, 2022, Sixth Assessment Report

f Environmental and social risks associated with CCS

When the captured CO_2 is injected to increase the extraction of oil in EOR projects, up to 70% of the injected CO_2 is released back into the atmosphere[28] . But even when the idea is to pick storage basins to deposit CO_2 indefinitely, the actual CO_2 retention ability over prolonged periods is unpredictable.

According to a study by IEEFA[29] on the literature describing the well-established Sleipner and Snøhvit projects in Norway, neither the performance nor the integrity of storage sites can be guaranteed, whether ex ante or over time. The literature review indicates that:

- Both projects have seen unexpected behaviours of the stored CO_2 that might have led to leakages.
- Extensive studies are required at site-level; the learning effect is small due to the unique geology of each site.
- Monitoring programs would need to continue for the whole lifespan of the project, which usually means decades, to assure the permanent sequestration of CO_2 long after storage sites' closure. Not only is the earth's geology dynamic and the long-term impacts of artificial storage are unpredictable, but also each stage of the lifecycle of carbon storage projects carries different risks that should be monitored.
- Contingency plans should be prepared and budgeted for, meaning that the necessary equipment, finance and personnel must remain available for decades.

The two running Norwegian projects (with a combined storage capacity of only 1,7 Mtpa of CO_2) are dramatically smaller than the ones proposed at the EU level (280 to 450 Mtpa by 2050 according to the EU Industrial Carbon Management strategy[30]). Given that the EU storage targets would require multiple times the capacity of the Sleipner and Snøhvit projects, it is uncertain whether it would be possible to deliver such storage capacity with the level of safety required to store big amounts of CO_2 for centuries. Given these premises, it is far from clear whether CCS can be scaled safely and efficiently and where the economic resources for such a long-term commitment will come from.

When it comes to risks to human health in case of leakages, they depend on CO_2 concentrations and duration of exposure, as well as on local weather, geographic conditions and personal predisposition. Also, risks change according to the stage where it happens (transport, injection, storage). Potential effects range from intoxication, asphyxiation, headaches, dizziness, muscle twitching, confusion and unconsciousness. Such effects are difficult to predict; nevertheless, for safety reasons a 400-metre danger zone around the point of leakages should be defined to promptly address them.

When it comes to risks to the marine environment in case of leakages, they depend on the amount of CO_2 released. In cases of temporary leakages (e.g. a pipeline rupture) significant biochemical impacts due to pH changes can be expected in marine biodiversity. In case of continuous leakage such harmful effects would be more severe[31].

[28] Thomas Longden, Fiona J. Beck, Frank Jotzo, Richard Andrews, Mousami Prasad – 'Clean' hydrogen? – Comparing the emissions and costs of fossil fuel versus renewable electricity-based hydrogen, Applied Energy, Vol. 306, Part B, 2022.
[29] IEEFA, 2023, Norway's Sleipner and Snøhvit CCS: Industry models or cautionary tales?
[30] European Commission, Towards an ambitious Industrial Carbon Management for the EU (COM/2024/62)
[31] Öko-Institut e.V., 2024, Securing the Underground: Managing the risks of carbon storage through effective policy design

Finally, it is important to note that the purity of CO_2 plays a key role in preventing leakages; a CO 2 flux that is not adequately purified through the removal of substances like SO x or even water vapour would corrode the CO_2 transport and injection machinery, leading to higher risks of leakages. For instance, the only CCS project in Europe that is due to start operating in 2025, Norway's Northern Lights, demands that liquefied CO_2 delivered for permanent storage be 99,81% pure and contain no more than 10 parts per million (ppm) of SO_x and 30ppm of water, amongst other tight limits[32] .

g The energy penalty issue

CCS requires additional energy to capture, compress, and transport the CO_2 that leads to a general increase of emissions. This additional amount of energy used to operate CCS is called energy penalty and varies depending on the specific technology and application. According to the IPCC, it is generally in the range of 13-44%, leading to additional emissions and increased costs.

Moreover, the energy penalty reduces the net efficiency of the installations using CCS by 6-13% depending on the type of plant: for instance, recent analysis suggests that CCS reduces the efficiency of a combined cycle gas turbine (CCGT) plant by between 7 and 11% (implying an increased fuel burn of 17–22% compared to a plant without CCS) and between 9 and 10% for super-critical coal plants[33].

Even if this additional energy is produced with renewables, it is arguable whether its best use is to run a CCS facility instead of using it to directly electrify other processes. Also, CCS causes other GHG emissions along fossil fuels value chains (e.g. methane due to mining) and so, paradoxically, such renewable energy would increase GHG emissions elsewhere. In the cases where CCS is needed, such energy penalty must be accounted for and covered through additional and dedicated renewable energy provided by the company benefitting from CCS.

[32] https://norlights.com/

[33] Lyons, M., P. Durrant and K. Kochhar (2021), Reaching Zero with Renewables: Capturing Carbon, International Renewable Energy Agency, Abu Dhabi.

2 The role of CCS in different scenarios

a PAC Scenario

The PAC Scenario project[34] (Paris Agreement Compatible Scenarios for Energy Infrastructure) provides an energy scenario for Europe compatible with the Paris Agreement. The scenario is intended to ensure that we are planning and building the infrastructure necessary for a future renewables-based energy system.

It also considers industrial emissions. Different scenarios have been built to show how the industrial sector could go towards net zero through the deployment of various levers, ranging from technological ones (e.g. fuel and technology switches, energy and material efficiency, CCS, use of hydrogen, etc.), behavioural ones (e.g. longer life of appliances, substitution rates, rate of use of recycled materials, etc.) and economic ones (e.g. level of imports and exports).

The project has produced three scenarios with respectively 85%, 90% and 95% GHG net emissions reduction by 2040. Each scenario specifies the amount of residual emissions (in $MtCO_2$ eq) in 2050 for many industrial sectors and the expected use of CCS (table below).

	Steel residual emissions	Cement residual emissions	Chemicals residual emissions[35]	Other sectors residual emissions[36]	Use of CCS
S1: -85% by 2040	37,04	36,3	27,56	62,09	-23,28
S2: -90% by 2040	22,68	28,01	22,03	38,3	-18,63
S3: -95% by 2040	15,02	21,42	18,18	39,96	0

Table 1: CO2 emissions in different sectors according to the three PAC scenarios (figures in MtCO 2 eq.)

What the PAC scenarios show is that there are pathways leading to net zero by 2050 with a much more limited use of CCS, with scenario S3 completely avoiding the use of carbon capture and storage. Given the possibilities highlighted by the PAC scenarios, the target set by the European Commission in its Industrial Carbon Management Strategy looks exaggerated and carries the risk to focus too many resources on this technology. The injection capacity target set by the Net-Zero Industry Act (50 Mt) looks more realistic, even though it is still higher than what the PAC scenarios show is possible.

[34] https://www.pac-scenarios.eu/
[35] It sums ammonia production, olefin production and other productions
[36] It includes aluminium, ceramic, food processing, glass, lime, non-ferrous, paper, wood industries

b CLEVER Scenario

The CLEVER (a Collaborative Low Energy Vision for the European Region) scenario[37] aims at promoting an ambitious yet realistic decarbonisation pathway for Europe. The scenario presents a pathway that reconciles the long-term climate and sustainability imperatives with the short-term energy security constraints and practical feasibility of such a transformation.

CLEVER evaluates the potential of energy demand reduction (sufficiency and efficiency) and renewable energy development at the national and European level, aiming at reaching carbon neutrality at the European level by 2050 at the very latest, together with a 100% renewable mix.

In its final report[38] , CLEVER shows that sufficiency and circularity can be at the basis for decarbonisation of the EU industrial sector, whereby electrification should play a crucial role and hydrogen use should be targeted to steelmaking and production of ammonia and olefins. In such a scenario the reduction of consumption of materials plays a key role, allowing to reduce the EU industry final energy consumption by 37% and to avoid the use of CCS.

Using the steel sector as an example, 11,2% (63 TWh) of the reduction of the final energy consumption is obtained through sufficiency strategies (e.g. fewer new constructions and reduced demand of cars), 20,6% (116 TWh) through circularity measures (increased use of scrap-based steel, requiring 4-6 times less energy than the iron ore-based route), 15,6% (88 TWh) through energy efficiency and technological substitution. In such a scenario, the use of resources and feedstocks (e.g. hydrogen) is reduced, making the decarbonisation of the sector more feasible.

c LIFE Scenario

The LIFE scenario is included in the Impact Assessment Report[39] accompanying the European Commission's Communication setting a 2040 intermediate emissions target on the path to climate neutrality by 2050 (so-called EU 2040 climate target)[40]. The Impact Assessment is based on three possible scenarios that reach climate neutrality by 2050 but with different 2040 intermediate goals[41].

In addition to these scenarios, an alternative option is provided (LIFE scenario) that assumes a shift in behavioural patterns towards more sustainable lifestyles, a more circular economy and more reliance on the sharing economy.

The LIFE scenario goes beyond the purely supply-side focus of S1, S2 and S3 and addresses the demand-side, foreseeing lower needs for raw materials and primary production of materials and, consequently, lower need for CCS. S2 and S3 scenarios foresee a need for CCS for industrial processes between 123 and 137 MtCO_2 per year in 2040; similar amounts are foreseen in 2050. Considering the LIFE approach, the need for CCS is reduced to about 110 MtCO 2 per year in 2050, out of which approximately 10 MtCO_2 for metal production, about 25 MtCO_2 for the chemical industry and the rest to produce mineral products (e.g. cement).

[37] https://clever-energy-scenario.eu/
[38] CLEVER, 2023, Climate neutrality, Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables
[39] European Commission, SWD/2024/63 final
[40] Such target includes also the use of CCS and carbon removals to complement the reduction of emissions.
[41] S1: emission trends in line with the Fit-for 55 energy trends – S2: emissions reduction of at least 85% by 2040 – S3: emissions reduction of at least 90% by 2040

This scenario essentially recognises the fact that steelmaking can be decarbonised without the use of CCS, while supporting the idea that carbon capture will play a key role in bringing down CO_2 emissions from the cement industry. Moreover, the Impact Assessment includes a complementary analysis investigating the impact of a selected group of deeper circular economy actions[42] able to reduce up to 10% more emissions than the standard scenario. However, this complementary analysis fails to adequately recognise the potential of low-clinker cements, which can cut the process emissions of the sector by 50-60% (see chapter 4.c).

d Summary of the three scenarios

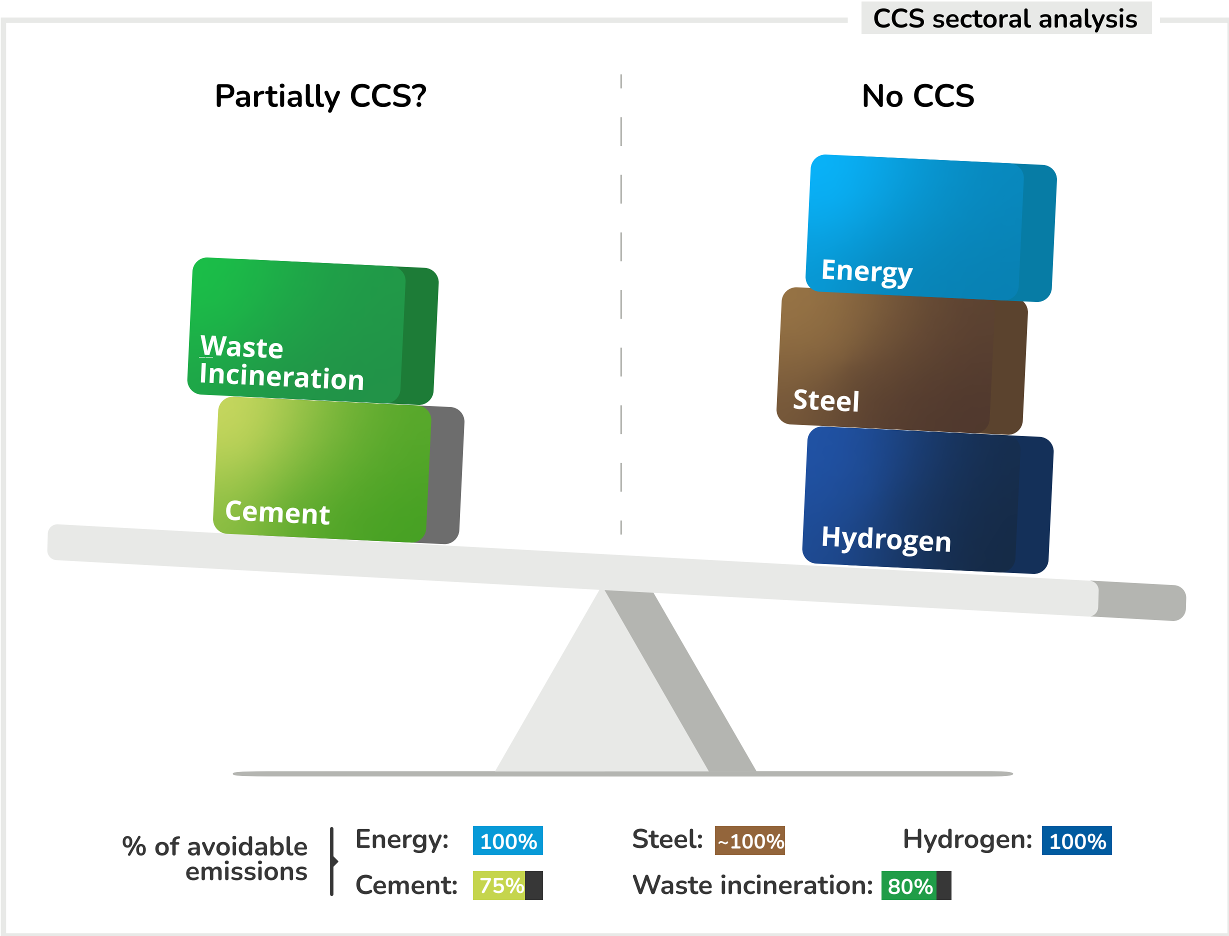
The scenarios above suggest that the decarbonisation of carbon-intensive sectors can happen with a very limited role for CCS, if any. For such scenarios to deliver the suggested cut in GHG emissions, they require the prioritisation of measures aimed at increasing the level of circularity and efficiency of the use of materials and at accompanying the shift of behavioural patterns toward more sustainable habits. This approach would not only allow to reduce reliance on CCS but also lower the need for renewable electricity and hydrogen, as well as raw materials, delivering a more resilient and autonomous EU economy.

Regrettably, in proposing an EU 2040 climate target the European Commission did not consider the LIFE scenario, nor the complementary analysis on circularity, nor more ambitious proposals such as the PAC and CLEVER scenarios; instead, it decided to bet too heavily on a broad use of CCS and carbon removals, unrealistic future hydrogen production and growing pressure on the environment to get the raw materials needed for the transition.

Ideally, the target included in the Net-Zero Industry Act looks reasonable to cover possible shortcomings in the implementation of circularity, efficiency and electrification strategies.

[42] For steelmaking, such actions include reduced exports of scrap and end-of-life cars, better sorting of scraps to prevent downcycling, lifetime extension of cars and machinery, reuse of 6% of structural steel in buildings, design for building disassembling (also for cement), lightweighting of steel-intensive products, reduce overspecification up to 41% (also for cement). For cement, use of 20% of recycled cement in buildings, use of innovative binders (up to 10%), life extension of buildings, use of low-clinker cements (0,7 clinker/cement ratio).

3 Focus on specific sectors



a Power generation

Given the mentioned shortcomings related to costs and alternative cheaper and more effective decarbonisation solutions, under no circumstances should CCS be used for power generation. Here the priority must be to deploy non-combustion-based renewable electricity as quickly as possible and phase fossil fuels out by 2030. When it comes to the specific case of bioenergy with CCS (BECCS), not only is its deployment clearly constrained by the availability of biomass, but the production of biomass for this specific purpose would raise major concerns regarding land grab, biodiversity, water use and food security. BECCS would only transfer biogenic carbon to geological formations; large-scale deployment of BECCS would drive unsustainable levels of land-use change and biomass use that are incompatible with the objectives to increase carbon sequestration in soils and vegetation, biodiversity conservation, and would hinder ecosystem restoration[43].

[43] See the EEB recommendations for carbon removals

b Steel Production

The combination of circular practices, material and energy efficiency strategies, a higher use of scrap, the roll-out of Electric Arc Furnaces (EAF) and Direct Reduced Iron reactors (DRI-EAF) with renewable hydrogen allows to reduce the sector's CO_2 emissions to nearly zero without CCS.

CCS is clearly insufficient to decarbonise the classic iron-ore steel production route based on the use of coal in blast furnaces – basic oxygen furnaces (BF-BOF). According to Agora Industry[44] , considering a BF-BOF steel plant equipped with CCS at its three main CO_2 emission sources[45] and assuming an ambitious 90% CO_2 capture rate (this may be optimistic, see figure 1) at the three points of emission, only 73% of the steel site's total CO_2 emissions can be captured. Other remaining emission points characterised by low CO_2 concentrations would be too expensive and energy-intensive to address with CCS. This would mean that, for a medium-sized plant producing 5 Mt of crude steel per year, a CCS retrofit would still result in around 2,5 Mt of CO_2 per year released in the atmosphere. Such huge emissions would severely impact the possibility of achieving national and global climate targets and put these plants in a position to quickly become stranded assets.

On the contrary, the DRI-EAF route is very flexible, since it can operate with fossil gas (NG) and renewable hydrogen. Given that in the next years the availability of renewable hydrogen will be limited, it might be more likely that operators will make an initial use of fossil gas (NG-DRI-EAF route), which should be conditional to a clear and mandatory decarbonisation roadmap with dissuasive penalties to ensure that the uptake of renewable hydrogen (H_2-DRI-EAF route) is promoted, including through Power Purchasing Agreements, where the operator commits to supports its availability.

An alternative path foresees the use of CCS in the NG-DRI route, since the DRI emits a stream of relatively highly concentrated CO_2 ; even though this would reduce emissions by 89% compared to the BF-BOF route, it would leave a high amount of residual emissions (onsite and upstream) and would be always subject to the actual capture rate of the CCS facility (see the aforementioned Al Reyadah project as a reference).

Technology	CO 2 emission reduction (including upstream emissions)	Residual emissions (tCO_2 per t of crude steel)
BF-BOF with CCS	-73%	0.64
NG-DRI-EAF	-55%	n.a.
NG-DRI-EAF with CCS	-89%	0.31
Renewable H2-DRI-EAF	-100%	0.01
Scrap-EAF	-100%	0.01

[44] Agora Industry, Wuppertal Institute and Lund University (2024): Low-carbon technologies for the global steel transformation. A guide to the most effective ways to cut emissions in steelmaking.
[45] The coke oven, the hot-blast stoves and the onsite power plant, since they have relatively high CO2 concentrations.

C Cement Production

The sector is characterised by an important amount of process CO_2 emissions due to clinker production[46] , the key constituent of cement. While CCS is commonly promoted as the main solution to decarbonise cement production, other effective and readily deployable solutions are available but often overlooked.

Circularity (e.g. reuse or repair of concrete) can play a role in reducing emissions[47]. Eventhough the relative potential is lower than for other products like steel, the volume of available cement is so high that the absolute potential is still worth factoring in. Recycling of Portland cement is possible and creates the first zero-emissions alternative to existing cement production[48].

According to the Alliance for Low-Carbon Cement and Concrete (ALCCC)[49], clinker and cement substitution can play a much bigger role in reducing GHG emissions than it does today. Existing and commercially available solutions can be scaled up at near zero costs, and when done successfully, cut the cement industry's footprint by 50%. The potential for abatement is even higher given that other technologies with high Technology Readiness Levels are in full development, showing great potential to further bring down clinker use in cement due to more complex mixing designs or even substitute it altogether (e.g. cement-free concrete mixes).

While the LIFE Scenario considers a 70% clinker-to-cement ratio as an ambitious target to increase emissions reductions, a study by The New Climate Institute and the Environmental Coalition on Standards[50] modelled different mitigation scenarios where the clinker-to-cement ratio in Europe reaches 60%, 50%, or even 40% by 2050. The study shows a significantpotential for CO_2 reduction, with annual emission savings of up to 52% in the most optimal scenario. More recent insights and research show that it is possible to go faster and further in clinker reduction in Europe, with the possibility of reaching a 40% ratio by 2030 and a 25% ratio by 2035[51].

The implementation of other non-CCS decarbonisation strategies will further allow to bring emissions down:

- Increasing material efficiency by reducing overspecification in building construction without compromising safety would allow to reduce the use of cement by 40% (see note 36).
- Increasing the energy efficiency of dry kilns by 13%
- Increasing the electrification of kilns by 70% by 2050[52].
- Increasing the lifetime of buildings through deep renovations instead of building new constructions.

CCS might have a role to play in cement production by capturing residual CO_2 emissions, but it would be only a complementary role. At the EU level, by reducing overspecifications by 40%, emissions can be brought down to 56 $MtCO_2$ eq. annually[53]. With ambitious clinker-to-cement ratios this figure can be brought down to 28 Mt. Improving energy efficiency can lower it further, while electrification would significantly reduce CO_2 in the first place by preventing combustion of fossil fuels. This approximate calculation is consistent with what is envisaged by the PAC scenario, which in its more ambitious pathways consider a range from 0 to 23 $MtCO_2$ eq./year to be captured with CCS in all sectors.

[46] ~50% of CO2 emissions come from the calcination process, a chemical reaction removing CO_2 from raw materials i.e. limestone and giving clinker as a result. Further 40% of emissions is caused by the need for high temperatures to start calcination reaction.
[47] P Gowler et al., Circular economy and reuse: guidance for designers
[48] Dunant, C.F., Joseph, S., Prajapati, R. et al. Electric recycling of Portland cement at scale. Nature 629, 1055–1061 (2024). https://doi.org/10.1038/s41586-024-07338-8
[49] ALCCC, 2023, Fast-tracking cement decarbonisation
[50] New Climate Institute and ECOS, 2023, Clinker Substitution in the EU Cement Sector
[51] Horizon Europe, Data to Enable Transformation and Optimisation for Concrete Sustainability
[52] PAC Scenario
[53] The calculations of this paragraph are rough and based on the 2023 emissions of the sector (93 Mt CO_2eq.), as per the European Environment Agency EU ETS data viewer.

Also, a key role is played by the actual capture rate; Heidelberg Materials is developing the world's first CCS facility in the cement industry in Brevik, Norway, which will be able to capture only 50% of the CO_2 emitted by the plant[54]; such a capture rate is clearly insufficient to bring down emissions in a way that is consistent with climate neutrality by 2050.

All things considered, the decarbonisation roadmap promoted by Cembureau[55] foreseeing the use of CCUS (Carbon Capture, Usage and Storage)[56] to capture 50 Mt of CO_2 per year by 2040 and 62 Mt by 2050 looks exaggerated and risky, since it relies too much on an unproven, unprofitable and unsafe technology (see chapter 2) that, to date, is still very far from ensuring such a high amount of capacity.

d Hydrogen Production

Using CCS to produce hydrogen from fossil fuels does not mean that CO_2 emissions are reduced to zero, particularly if upstream and fugitive emissions due to fossil fuels extraction and transport (e.g. methane emissions) are considered.

According to an analysis by the Carbon Tracker Initiative focusing on the UK[57], fugitive emissions from fossil gas extraction are uncertain and often underreported; independent studies suggest that emissions from liquified fossil gas from the US could be 80% to 150% higher than what is reported by the UK's North Sea Transition Authority. On average, fossil gas imports have a carbon intensity five or more times greater than natural gas from the North Sea.

When assessing CCS projects, typically a capture rate of 90% is assumed; actually, as seen above, capture rates are rarely transparent and often far from 90%. When it comes to hydrogen production, in 2023 there were seven operational facilities in the world operating with CCS. Out of them, six use the captured CO_2 for enhanced oil recovery[58]. The only facility that sequesters captured CO_2 is the Quest plant in Canada, which reported for 2020 an average capture rate of only 76,8%[59].

[54] https://www.heidelbergmaterials.com/en/sustainability/we-decarbonize-the-construction-industry/ccus
[55] Cembureau, 2024, From ambition to deployment
[56] Cembureau's roadmap mentions CCUS, meaning that part of the captured CO2 will be used for other applications, potentially resulting in part of the captured CO2 released in the atmosphere after a few months or years (depending on the application).
[57] Carbon Tracker Initiative, 2024, Kind of Blue: The real climate impact of Blue Hydrogen and Gas-CCS
[58] Global CCS Institute, 2023 Global Status report
[59] https://open.alberta.ca/dataset/d5694c02-019d-4650-8b09-3b5a9afff181/resource/0064427f-6d73-4042-bd8c-cdf9921d9204/download/quest-co2-capture-ratio-performance.pdf

In contrast, producing hydrogen with electrolysis driven by renewable energy results in no GHG emissions. This should be the path to follow, which should also consider a targeted use of hydrogen for the applications providing the most climate-effective result (e.g. steelmaking) is paramount. Betting on fossil-based hydrogen production, even with CCS, would result in risk of stranded assets and lock-in to carbon-intensive processes.

e Waste incineration

The general rule to reduce emissions is to prevent waste and recycle. Emissions from the incineration of mixed municipal waste are therefore largely avoidable through either preventing waste in the first place or by recycling, following the waste management hierarchy.

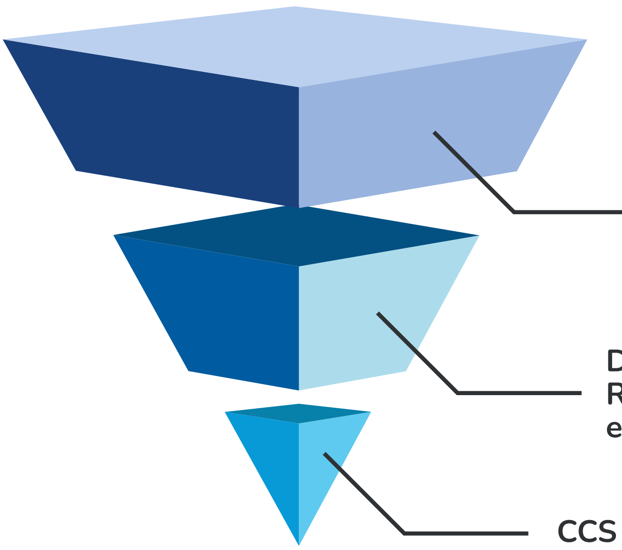
A further way to decrease the amount of mixed waste that must be incinerated is to sort it by using "leftover mixed waste sorting" techniques (LMWS). A combination of LMWS and CCS would result in higher recycling rates, higher levels of CO_2 emissions reduction and a much lower average cost per unit of CO_2 reduction than where CCS is deployed without LMWS (€63-84 per tonne of avoided CO_2 with LMWS against €122-143 with CCS)[60]. Therefore, all measures to prevent and recycle municipal waste must be applied before CCS can be considered for any residual emissions.

Moreover, attention needs to be paid to the systemic risks that CCS poses to a circular economy: further investments in incineration facilities may reinforce technological lock-in effects that lead to stagnating recycling rates and little incentive for waste prevention. Investments in new incineration facilities are deemed unsustainable according to the Taxonomy Regulation due to the harm they cause to achieving the goal of a circular economy.

When it comes to plastic production, according to a report by Systemiq[61], with circularity solutions the quantity of plastics that need to be incinerated or put in landfills could reach only 9% by 2050, with 78% of plastic waste that can be managed through elimination of unnecessary plastics, reuse and recycling. Such circularity scenario would reduce 80% of end-of-life plastic disposal and reduce CO_2 emissions by 65%.

[60] Zero Waste Europe, 2024, Materials or Gases? How to Capture Carbon
[61] Systemiq, 2022, Reshaping Plastics. The study focuses on plastics used in packaging, household goods, automotive, and construction

4 Alternatives to CCS



a Efficiency, sufficiency, circularity and demand reduction should be at the centre of industrial decarbonisation efforts

The implementation of circularity and efficiency strategies at sectoral level would automatically reduce the amount of CO_2 emitted into the atmosphere through an optimal use of resources[62], and thus a reduction of embedded emissions in those materials, while sparking new business models.

The Impact Assessment on the 2040 EU Climate Target reports a 20% GHG emission saving potential in the EU due to circular economy actions until 2050, which can go up to 25% in certain Member States. Nevertheless, this appears to be a conservative estimate; other studies point out that more ambitious savings can be reached through a decisive implementation of circular economy and demand-side reduction strategies. For instance, a report by Material Economics[63] states that a more circular economy can cut emissions from heavy industry (steel, cement, plastics and aluminium) by 56% by 2050 through higher re-circulation of materials (60% of potential emission savings), higher efficiency (19% of potential emission savings) and circular business models (21% of potential emission savings).

Similarly, according to a study by Agora Industrie and Systemiq[64] focused on Germany, climate targets can be achieved faster, cheaper, and with less energy consumption through circular economy than scenarios that only consider the decarbonisation of primary production. With a combination of decarbonised primary production and circular economy measures in the energy-intensive value chains of steel, cement, and plastics, cumulative GHG emissions can be reduced by 25% by 2045, transformation costs by 45% and energy consumption by 20%.

[62] Efficiency strategies are conditioned by the so-called rebound effect (Jevons paradox). Nevertheless, such a paradox exists whatever the strategy used to save energy, materials, etc.
[63] Material Economics, The circular economy, a powerful force for climate mitigation
[64] Agora Industrie & Systemiq, 2023, Resilienter Klimaschutz durch eine zirkuläre Wirtschaft

Waste management strategies have a high potential to reduce emissions from carbon-intensive sectors, as well as an approach to product design that should prioritise reuse and preserving the value of materials after recycling. Municipal waste management recycling rates are surging throughout the EU: the average EU recycling rate is 48,7%, with peaks of 67,8% in Germany and 60,8% in Slovenia[65].

These trends together with the legal obligations that will increasingly lower the amount of waste going to landfills (e.g. EU-wide target of 65% recycling rate by 2035) will likely make CCS facilities stranded assets.

Moreover, further improvements are possible in terms of recycling. Even in Member States with highly developed waste management systems, such as Germany, the non-sorted waste collected from households contains almost 67,5% recyclable materials. Recycling this waste could save between 10,2 and 28 Mt CO_2 eq. per year, which represents up to 25% of the total 2020 EU waste sector emissions[66].

CCS could play a limited role to capture CO_2 from the incineration of hazardous waste; but even for such use the principle of prevention and recycling should apply first. In general, the use of CCS in the waste incineration sector would likely become

b Unleash the potential of direct and indirect electrification

The replacement of combustion processes through electrification using renewable electricity is a powerful but still untapped way to quickly reduce CO 2 (and other pollutant) emissions without relying on CCS.

According to a study by Fraunhofer ISI on behalf of Agora Industry[67], direct electrification technologies expected to be available by 2035 could meet 90% of the energy demand not yet electrified by European industry, including high-heat processes. Technologies readily available today, such as heat pumps and electric arc furnaces, could already deliver more than 60% of this demand. Instead, today process heating is still supplied by fossil gas (35%), coal (27%) and other fossil fuels; overall, fossil fuels account for about 75% of the energy consumed by process heating.

When it comes to cement production, its electrification potential is only partial and lies in the electrification of heat production, which could be feasible by 2030. Recycling of Portland cement with an all-electric process is possible and can be operated as co-production with steel recycling or for the exclusive production of cement using an EAF with a small untapped pool of molten steel[68]. Unavoidable CO 2 emissions due to the calcination process can be tackled with other strategies, as shown in chapter 4.c. What is important to underline is that a possible use of CCS in the sector should not disincentivise the electrification of its energy demand.

[65] Circular Economy Monitor Flanders, 2021 data
[66] Zero Waste Europe, Join position paper on mandatory implementation of CCS in municipal waste incinerators
[67] Fraunhofer ISI (2024): Direct electrification of industrial process heat. An assessment of technologies, potentials and future prospects for the EU. Study on behalf of Agora Industry.
[68] Dunant, C.F., Joseph, S., Prajapati, R. et al. Electric recycling of Portland cement at scale. Nature 629, 1055–1061 (2024). https://doi.org/10.1038/s41586-024-07338-8

When it comes to steelmaking, total direct and indirect electrification through the DRI with renewable hydrogen route allows reducing GHG emissions by 99,6% compared to the BF-BOF route[69]. This potential can be achieved in the next decade with the right investment decisions today.

For other industrial sectors[70], the technical potential for direct electrification is huge, reaching 90% of the total energy demand.

C A marginal role for CCS

The two paragraphs above give an idea that the emissions that could justifiably be declared as "unavoidable" are marginal and could be prevented by implementing strategies targeting the demand-side and innovative substitution technologies.

It is often said that unavoidable emissions are associated with "hard-to-abate" sectors, but such a definition is misleading because it does not consider the different kinds of emissions within an industrial process (e.g. from combustion or from chemical reactions), the potential of circular economy and efficiency practices, nor the technological developments of these sectors and the internalisation of external costs of inaction.

For instance, steelmaking is often referred as "hard-to-abate", but the sector is evolving: according to Agora Industry and the Wuppertal Institute steel production meets the requirements to be a "fast-to-abate" sector due to availability of new technologies, minor impact on the costs of final products made with green steel, the possibility to use zero-carbon electricity, and the potential for a quick transition (early 2040s)[71].

Nevertheless, if CCS is needed for limited specific situations, its use should be regulated to target only genuinely unavoidable CO_2 emissions and not distract from the uptake of the above-mentioned decarbonisation paths.

[69] Agora Industry, Wuppertal Institute and Lund University (2024): Low-carbon technologies for the global steel transformation. A guide to the most effective ways to cut emissions in steelmaking.
[70] Beyond iron & steel and cement, the report considers chemicals and petrochemicals, non-ferrous metals, non-metallic minerals, food & beverages, paper, pulp and printing, other non-energy-intensive sectors.
[71] Agora Industry & Wuppertal Institute, 2023, 15 insights on the global steel transformation

5 Policy recommendations

The 2024-2029 legislative cycle will focus on industrial policies and decarbonisation, notably through the **Clean Industrial Deal**, the proposed **MFF Competitiveness Fund**, the implementation of the **Industrial Carbon Management Strategy**, the **Electrification Action Plan**, the **Steel and Metals Action Plan** and associated measures. These should consider the following policy recommendation stemming from the analysis of relevant literature:

1. **EU funding should not support CCS where more cost-effective, reliable, and efficient decarbonisation routes exist**. For example, the Innovation Fund and Trans-European Networks for Energy should not be used for carbon capture related projects where alternative mitigation options exist.

2. **Industrial decarbonisation policies must prioritise circularity, sufficiency, efficiency and demand-side measures**, which are often more effective and cheaper. The contribution of CCS must be clarified such that it does not undermine these priorities.

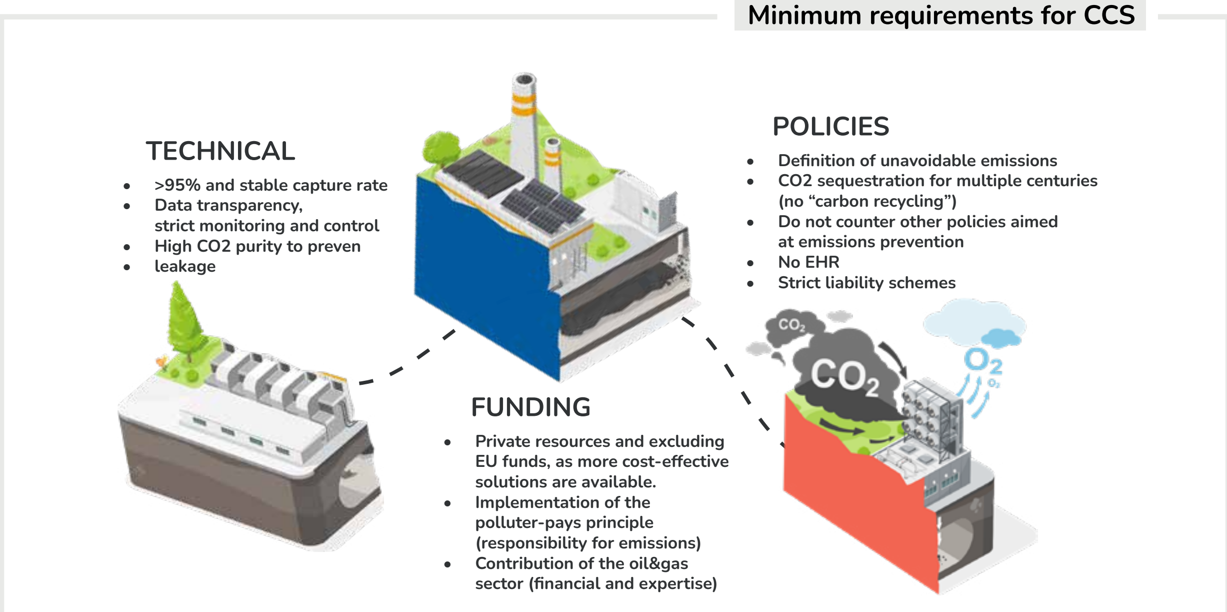
3. **Electrification powered by renewables is key for decarbonisation**. Barriers to direct and indirect electrification, whether technical, financial, or organisational, must be removed. Support must continue for **renewable electricity generation**, **storage** and **grids**, as key enablers of electrification. The final goal must be to achieve a fully renewable energy system, with non-combustion industrial processes and efficient resource use.

The above three steps should be carefully assessed through a **Life-Cycle Cost Analysis (LCA)** methodology within the project scoping phase.

While it is possible to meet the climate mitigation goals with close-to-negligible use of CCS, it is useful to articulate recommendations on strict conditions for the potential use of CCS, for example, by the private sector:

4. **Any CCS costs should be covered by private funds** or resources generated through rigorous enforcement of the polluter-pays principle, as well as extended producer responsibility of emitters.

Minimum requirements for CCS



5. **CCS might only play a complementary role to address CO_2 emissions that cannot be abated via other means**. Such "unavoidable emissions" cannot be abated through the above-mentioned strategies or through any other technical means.

6. **Under no circumstances should the use of CCS support the extraction or use of fossil fuels**. This implies that CO_2 sequestration must be reliable for multiple centuries, also when embedded in products. CO_2 must not be used for Enhanced Hydrocarbon Recovery.

7. **CCS must not conflict with other environmental policies**, such as pollution and waste prevention at the source.

8. **CCS infrastructure must be safe**, with monitoring and contingency protocols in place for the long term to prevent any environmental and public health risk. CO_2 purity must be sufficient to prevent corrosion of pipelines and machineries, reducing the risk of incidents or leakages. Private operators must be liable for any accident and subject to penalties.

9. **Capture rates of each CCS project must be public, monitored, and enforceable** to avoid risk of false green claims. For any CCS projects, strict rules should be envisaged to ensure that at least **95% of CO_2 is captured and permanently stored**. If a project drops below this threshold, operations must cease until the capture rate is restored and operators must pay for the uncaptured emissions.

10. **The oil and gas industry must take responsibility for the climate change it has fuelled** and provide storage sites sustaining their long-term management at their expense. Even a limited use of CCS would require a copious amount of funds and expertise for the deployment of the necessary infrastructure and the long-term monitoring of the storage sites to address potential leakages. These responsibilities must be carried by the fossil fuel industry, in line with the polluter-pays principle, which, as highlighted by a recent report of the Euro-

EEB
European
Environmental
Bureau

[71] European Court of Auditors, Special Report 12/2021: The Polluter Pays Principle: Inconsistent application across EU environmental policies and actions