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Defining ‘abated’ fossil fuel and industrial process emissions

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ABSTRACT

There is scientific consensus that limiting warming in line with the Paris Agreement goals requires reaching net zero CO_2 emissions by mid-century and net negative emissions thereafter. Because of the entrenchment of current fossil fuel energy and feedstock demand estimated in almost all global modelled scenarios, ’abated’ fossil fuel and industrial process and product use (IPPU) CO_2 emissions, using carbon capture and storage (CCS) technologies to perform carbon management, are likely to be part of any transition. In addition to fossil fuel combustion, this will be primarily in cement & lime kilns, chemical production, and possibly waste incineration and iron and steel making, in processes producing maximally concentrated CO_2 waste streams. Abated fossil fuel and IPPU CO_2 emissions in the context of recent commitments, however, requires consideration of capture rates for fuel processing and end-use, permanence of storage, reduction of upstream production and end-use fugitive methane, and sufficient means to sequester residual emissions. Based on an assessment of evolving CCS technologies in existing sectors and jurisdictions, criteria are proposed for defining a benchmark for ’abated’ fossil fuel and IPPU emissions as where near 100 % GHG abatement is to be eventually achieved, with N_2O and fluorinated gases considered separately. This can be accomplished through: 1) CO_2 capture rates of more than or equal to 95 % of CO_2 emitted; 2) permanent storage of captured emissions; 3) reducing upstream and end-use fugitive methane emissions to <0.5 % and towards 0.2 % of gas production & an equivalent for coal; and 4) counterbalancing remaining emissions using permanent carbon dioxide removal. Application of these criteria to just steel and cement yields estimates of more than or equal to 1.37 Gt CO_2 per year reductions after all other reasonable and lower cost actions are taken. At the same time, we acknowledge the value of capture rates below 95 %, so as long they are designed to enable eventual full abatement through process learning. We also discuss commercialisation and deployment policy for CCS, highlighting the need to integrate these criteria into international climate agreements.

1. Introduction

Recent international climate negotiations have highlighted the need to phase out or transition away from fossil fuels to mitigate climate change. The COP28 UAE Consensus text, reaffirmed at COP29, emphasised "transitioning away from fossil fuels in energy systems, in a just, orderly and equitable manner, accelerating action in this critical decade, so as to achieve net zero by 2050 in keeping with the science" [1, 2]. This paper critically examines the alignment of these commitments with the underlying scientific literature, focusing on the nature and timing of net zero emissions in energy and industrial systems, what this means for the role of fossil fuels in transitioning these systems, and in

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particular the role and definition of 'abated' fossil fuel use and industrial process and product use (IPPU) emissions.

The scientific literature for the nature and timing of net-zero CO_2 and net-zero GHG emissions is well established. According to the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (AR6), in most global modelled mitigation pathways that limit warming to 1.5 °C (>50 %) with no or limited overshoot, all energy supply and demand, industrial processing and land use reaches net zero CO_2 emissions by early 2050s, and net-zero GHGs 20 years later [3], with energy supply and land use reaching net-zero earlier than the buildings, industry and transport sectors. Pathways that limit warming to 2 °C hit the same benchmarks roughly 20 years later.

As for the transition of energy systems and broader economy away from fossil fuels, the literature indicates a necessary shift towards phasing out overall fossil fuel consumption [4–8]. This is coupled with an increase in the use of low- and zero-carbon energy sources. Additionally, it involves a broad adoption of and switching to electricity across various end-use sectors (i.e. buildings, most personal transport and industry). Parallel to the phasing out of fossil fuels, the deployment of alternative energy carriers is necessary, especially in sectors where direct electrification poses challenges [9]. Furthermore, where fossil fuels will likely maintain a role, albeit a diminishing one, is in the industrial sector's transition [10,11], which did not receive due attention in the COP28 decision. Despite a significant shift towards cleaner energy sources, fossil fuels will continue to be utilised in this sector for a lengthy period depending on how long it takes to develop non-emitting alternatives and deploy them, albeit in a more controlled manner. The key lies in integrating fossil fuel combustion (or oxidation by other means) and IPPU emissions with abatement technologies to allow carbon management, i.e. carbon capture, utilisation and storage (CCU and CCS), in order to substantially reduce addition of CO_2 to the atmosphere, thus enabling continued operation while developing viable clean energy alternatives. These emissions are referred to as 'abated,' a label that signals such practices are in line with the actions required to achieve the Paris Agreement goals. However, it is crucial to distinguish between CCS practices that achieve 95 % or higher capture rates, which we argue in this paper qualify as abated and support Paris Agreement-aligned emissions reductions, and those with lower capture rates (which should be specified by their actual capture percentage, such as 50 %). Clear criteria for what constitutes abated emissions are essential for ensuring transparency about the level of emissions reduction being achieved. Lower capture rates than 95 % on some early projects are also valuable and should be expected, so long as they are designed to enable eventual full abatement, e.g., through process learning and cost declines.

A clear benchmark definition of abated emissions is needed to guide researchers, international climate negotiations, national policymakers, and firms making decisions for climate policy compliance with long term climate goals. For example, in the approval session of WGIII AR6 Summary for Policymakers (SPM) [8], a debate over the term 'unabated' took a centre stage in the negotiations [12], leading to the introduction of a definition as footnotes 54 and 36 in the SPM that clarifies the term:

> *Footnote 54 "In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life cycle; for example, capturing 90 % or more from power plants, or 50–80 % of fugitive methane emissions from energy supply. {Box 6.5, 11.3}" as well as footnote 36 "in this context, capture rates of new installations with CCS are assumed to be 90–95 %+ {11.3.5}. Capture rates for retrofit installations can be comparable, if plants are specifically designed for CCS retrofits {11.3.6}."*

This combined definition is incomplete for several reasons. Simply fitting CCS technology systems to facilities and processes emitting CO_2 does not automatically translate to effective 'abatement' of greenhouse gas emissions from fossil fuels and IPPU. If the criteria for 'abatement' remain vague or open to interpretation, it could inadvertently permit the continuation of substantial greenhouse gas emissions through several pathways. Capture rates of CO_2 could be lower than technically possible and economically effective for a given process, CCS equipment could be run intermittently, and the CO_2 might only be stored temporarily. Furthermore, the technical and economic limit to how close to 100 % capture can be achieved for different processes will also evolve. While 90 % capture is commonly used, Brandl et al., [13] indicate this may be a maximum capture rate only for very low concentration (~2 %) CO_2 flows and likely an artefact from outdated literature. Gas generation plants produce 3–5 % CO_2 concentration flows and coal plants 10–18 %; if the concentration is 30 % or more, common for many processes as we shall discuss, Brandl et al. argue up to 98 % capture is technically feasible. Finally, because geological methane releases are inherent to all coal, crude oil and gas extraction, continued use of fossil fuels in the context of the Paris Agreement requires criteria for maximum upstream, transport and end-use fugitive methane emissions reductions [9,10]. Since fugitive methane and anything <100 % CO_2 capture leave residual emissions to the atmosphere, carbon dioxide removal (CDR) from the atmosphere is also eventually required to compensate for the residual emissions [14,15]. In effect, abated fossil fuel and IPPU emissions will always require a mix of fugitive methane emissions abatement, CCS or CCU with effectively permanent storage duration, and permanent, verifiable, and additive CDR to reach towards 100 % mitigated life cycle GHG emissions. The absence of a practical set of benchmark criteria for all the above represents a significant gap in both the scientific literature and policy discussions surrounding 'abated' fossil fuels and industrial process emissions.

This paper aims to build on footnotes 54 and 36 of the AR6 WGIII SPM above and establish a robust benchmark definition of 'abated' fossil fuels and IPPU emissions that maximises emission reductions from activities labelled as 'abated', closing the potential gaps in interpretation and application that could compromise the integrity and success of global climate change mitigation goals. By proposing such criteria, this paper bridges the divide between technical possibilities and policy implementation, providing a benchmark goal for CCS orientated policy. Furthermore, our comprehensive review of CCS applications across different sectors offers a unique synthesis of current technological states and economic viabilities, contributing to both the academic discourse on emission reduction technologies and the practical policy-making process. We focus on establishing these criteria reflecting best-available technology and stringent climate conditions, rather than providing a fully operational implementation framework. Our intention is that they serve as benchmark guidance for fossil fuel and CCS policy. They can guide future work on operationalisation in modelling exercises, policy instruments, and industry decision-making.

The remainder of the paper is organised as follows. Section 2 provides a comprehensive review of CCS applications in different energy systems and industrial sectors, highlighting their current technological state and economic viability, showing where and to what degree abated fossil fuels and industrial processes emissions are possible. Section 3 provides a formulation for a robust set of benchmark criteria for distinguishing 'abated' from 'unabated' fossil fuels, with the aim to ensure better alignment of abatement efforts with the Paris Agreement's goals. Section 4 presents a synthesis of the projected scale of CCS applications in the future decarbonisation of the energy supply and industrial sectors, drawing insights from the top-down modelling literature and worked bottom-up examples from the steel and cement sectors. Section 5 reviews the role of policy and regulations in facilitating the adoption and implementation of CCS technologies at scale. Section 6 concludes.

2. In what sectors and to what degree is abatement through CCS possible?

Understanding the potential and limitations of CCS across various sectors is crucial to determining how close to 100 % abated fossil fuel and IPPU emissions along the supply chain can currently be achieved. There is a lack of data on state-of-the-art capture rates for CCS applications in the peer reviewed literature, which presents a challenge in evaluating their utility in meeting tighter global emission limits [16]. This section presents a structured review of CO_2 capture applications in various energy systems and industrial sectors, drawing on the IPCC AR6 industry and energy chapters [9,10], recent literature that distinguishes by process [13,17], the IEA CCUS database [18], as well as summary reviews of pilot projects and field applications [19], and segments these applications into four distinct tiers. The section's purpose is to show an up-to-date summary of where and to what degree abatement of fossil fuels with CCS may be possible.

Table 1 below presents CO_2 capture applications by sector and currently GHG-intensive processes. Given the requirement of eventual 100 % abatement and impossibility of achieving this with current CCS technologies, it is important to minimise the need for compensating CDR due to the energy requirements, costs, resource limitations and sustainability concerns associated with many CDR measures, such as direct air capture and storage (DACCS) and biomass combustion, capture and storage (BECCS) [20–22]. Table 1 therefore includes processes that are deemed eventually capable of achieving more than or equal to 95 % capture based on Brandl et al., [13] while illustrating their current technological and commercial readiness [14,23]. For each CO_2 capture application, the table includes detailed information on: potential CO_2 concentrations in waste gases, which affects the costs and technical complexities of capture, e.g. CCS is fully commercial with near pure streams of CO_2 today; the maximum achievable capture rates under incentivised conditions; notes on the status of the technology; and its formal Technology Readiness Level (TRL) according to the most recent literature source. TRL is measured on a scale from 1 to 9 that measures the maturity of a technology, from initial concept (TRL 1) to fully commercially developed and operationally proven (TRL 9). Note that

Table 1
CO_2 capture (CC) applications.

Sector	Process	Status of CC application [18]. unless otherwise stated	Potential CO_2 concentration in waste gas	Range of Max Capture Rate	TRL
Commercially viable applications for ≥95 % capture, low uncertainty					
Natural gas processing	Removal of CO_2 from raw formation gas	20+ projects operating or under construction	95–99 %	≥95 %	9+
Chemicals	Ethanol, methanol & other chemical production process CO_2	5 ethanol, 1 methanol, & 3 other chemicals and projects operating or under construction [11]	95–99 %	≥95 %	9+
Hydrogen production for refining, ammonia, and Direct Reduced Iron (DRI) steel making	Autothermal "blue" hydrogen & syngas (H2+CO) production from methane	Operating or under construction: 8 refineries or other fuel making; 5 fertiliser plants; 1 DRI facility (17 % capture).	95–99 % of CO2 associated with H_2 to make ammonia; CO_2 losses as fertilizer urea not included	≥95 %	9+
Technologically emerging applications, moderate uncertainty					
Cement and lime production, just calcination	Concentrated CO_2 calcination emissions (50–60 %) captured first and separately (e.g., LEILAC - Low Emissions Intensity Lime and Cement)	Pre-separation of limestone calcination emissions allows for a high purity CO2 stream and low-cost disposal. LEILAC 1 (2016) captured 25kt. LEILAC 2 to be operational ~2025, is to capture 100kt and be the standard sized operating unit [25, 26]	95 %	99 % of calcination emissions, which is 60 % of BAT (Best Available Technology) cement making	8
Cement and lime production, calcination and clinker making	Cement and lime kilns, precalciner and post combustion emissions captured together	50 % capture plant under construction in Brevik to be operational mid-2025, capture rate set by waste heat availability, & several 95 %+ capture facilities awaiting final investment decision (FID)	20 %, scrubbed flue gas	≥95 %	7
Power generation	Methane oxycombustion in supercritical CO_2	50 MW trial plant operating (NetPower), 350 MW plant under construction [27]	99 %	99 %	7–8
Developing applications, high uncertainty					
Waste Combustion	Waste-to-energy	One under construction, temporarily halted in Klemetrud, Norway	Unknown, and likely variable concentration and gas quality	Pilot tested at ≥90 %	6–7
Iron and steel production	Smelt reduction with CCS	HISARNA oxycombustion technology. Stalled [28]	80 %+ concentration	Pilot tested at 80–90 %	6–7
Power generation	Post-combustion gas-fired	Many planned, none under construction	3–4.5 %	≥95 %	6–7
Early-stage applications, very high uncertainty					
Pulp and paper	Tomlinson recovery boilers	No known projects at advanced planning stage [29,30]	8–15 % in theory, recovery boilers likely highly variable without separation	≥90 %	3
Power generation	Post-combustion coal fired	Two problematic trials (Boundary Dam & Petro Nova, restarted late 2023), 3 under construction, many planned with no FID [19]	10–18 %	≥95 %	4–6
Power generation	Post-combustion biomass-fired	One facility operating using wood pellets (UK/Drax), one small (180 kt/yr) in Fukuoka, Japan [31]	8–15 %, waste gas of highly variable quality %	≥90 %	4–6
Iron and steel	Coking, iron reduction (Blast furnace) and steel manufacturing (basic oxygen furnace) BFBOF	Course 30 & 50 projects most advanced, but are small pilots with slow progress. Existing BFBOFs can only be retrofit to <=50 % capture due to multiple exhaust points & varying gas quality [28]	CO = 21 %, CO_2 = 21 %	45–50 % retrofitted, ≥95 % if designed for CCS	5

technologies can stall at a given TRL, that progress is not linear, and effort and resource needs generally increase considerably with each step. There is a consistent development pattern for products to evolve from university labs (TRL 1–2) to smaller then larger staging firms (3–5), and for products with public good characteristics (like CCS) to require private-public partnerships and other support to traverse the TRL 6–7 "valley of death" before reaching the level where costs can be offset with early lead market revenues (TRL 8+) [24]. Furthermore, the rapidly evolving nature of CCS technologies means that the technological readiness assessment requires regular updates. This categorisation aids in identifying the most promising areas for CCS application, aligned with the broader goal of establishing criteria for the definition of abatement. The applications we present below are segmented into four distinct tiers, as follows:

- *Commercially viable applications*: This tier includes applications with a Technology Readiness Level (TRL) of 9+, where capturing more than or equal to 95 % of CO_2 is proven and technologically mature. These applications have high commercial readiness and are economically viable with appropriate incentives in place to cover the extra capital and operating costs. The uncertainty associated with these applications is low.
- *Technologically Emerging Applications*: This category consists of applications where current technological advancements suggest a high potential for capturing more than or equal to 95 % of CO_2 emissions, with TRLs of 7–8. These applications have low to medium commercial readiness and are potentially viable but require further development. They are in the pilot or demonstration stage, and the uncertainty associated with these applications is moderate.
- *Developing Applications*: This tier consists of applications that are actively being developed or there has been at some time active development and notable progress toward achieving more than or equal to 95 % capture rates, mainly TRL 6–7. However, these applications have low commercial readiness and are not yet economically viable. They are in the experimental stage, the uncertainty associated with their outcomes and timelines is high, or progress may have stalled.
- *Early-Stage Applications:* This category includes applications with a TRL of 3–6, where efforts towards achieving more than or equal to 95 % capture are in the early stages or progressing slowly. These applications have very low commercial readiness and face high development costs. The uncertainty associated with their technological feasibility and time frame for reaching higher capture rates is very high.

To summarise Table 1, CO_2 capture is only fully viable today where there are highly concentrated waste flows of CO_2, e.g., from formation gas cleaning, ethanol production, and autothermal hydrogen making (Tier 1: Commercially Viable Applications). This suggests efforts are needed to adapt and develop industrial and power processes to produce concentrated streams of CO_2 that do not require separation from nitrogen. Post-combustion CCS, however, may be critical for cement making (20 % CO_2 content) due to a lack of medium term alternatives for reaching more than a 50–75 % reduction in CO_2 (e.g., from material efficiency, cementitious material substitutes, and possibly calcination only CCS) in the sector [32] (Tier 2: Technologically Emerging Applications). Steel blast furnace gas also has a high combined CO_2 (21 %) and CO (21 %) content, making it also a feasible candidate for CCS if all the plant gases could be collected, cleaned and separated reliably, especially if oxycombustion is employed (e.g., in smelt reduction, Tier 2: Developing Applications), but current BFBOF plants are not designed for this (Tier 4: Early-Stage Applications).

For broad CCS use to be feasible, cooperation toward full commercialisation and cost reductions is required, especially for developing countries to use the technology. The critical need to make CCS work to negate limestone calcination emissions for cement and lime may provide the learning needed to master CCS in other practices such as waste incineration and coal and gas use for power generation and primary steel making. These practices are characterised by complex challenges in decarbonisation, particularly in Tier 4: Early-Stage Applications, where CCS faces significant implementation hurdles. Successfully overcoming these challenges is essential for meeting the Paris Agreement goals. It is crucial to recognise that the difficulties are due to the intrinsic nature of specific processes rather than from the sectors as a whole. Therefore, we propose a reframing that prioritises innovation and targeted efforts to address these process-specific challenges, encouraging strategic advancements in technology deployment across these sectors. This reframing is important as it allows for more targeted innovation and R&D efforts, enables more nuanced policymaking, guides strategic investment decisions for maximum impact, and encourages cross-sector collaboration on similar challenging processes.

3. Establishing criteria for differentiating 'abated' and 'unabated' fossil fuels

Building on our review of CO_2 applications across various sectors, we now turn to the critical task of establishing clear criteria for differentiating 'abated' from 'unabated' fossil fuels. This section proposes a set of criteria for abatement that maximises emission reductions to support the achievement of the Paris Agreement goals, addressing the gap in current policy discussions and scientific assessments. To be fully considered fully abated, fossil fuel use and industrial processes must result in zero net addition of GHG to the atmosphere. Therefore, abated fossil fuel use will always require a mix of fugitive methane emissions abatement, CCS and permanent, verifiable, and additive CDR to reach 100 % mitigated emissions across the supply chain. This is limited by evolving technical limits. In differentiating 'abated' from 'unabated' fossil fuels, we therefore make the argument for the following four criteria:

1. The CO_2 capture rate is greater than or equal to 95 %.
2. The captured CO_2 is transported to permanent geological storage, with adequate monitoring and verification.
3. The level of upstream fugitive methane emissions is <0.5 % and towards 0.2 % of gas production equivalent.
4. The remaining emissions from CO_2 capture rates of <100 % and upstream methane are compensated by CDR.

It is important to note that these criteria represent a robust conceptual benchmark based on the best currently available technologies and practices. By focusing on the key characteristics of abatement (e.g. $\geq$95 % CO_2 capture, stringent methane limits, permanent storage, and compensatory CDR) rather than prescribing fully developed operational tools or compliance frameworks, we provide a clear reference point for what 'abated' means in the context of achieving the Paris Agreement goals. As technologies improve and costs evolve, likely with early technologies achieving less than full abatement, regulatory criteria should be tightened over time, e.g. moving to higher capture rates as feasibility and economic evidence accumulate. The specific numeric thresholds offered here are anchored in current literature and experience but are not fixed limits; they may be revised as the technology matures and empirical data on capture rates, fugitive methane reductions, and CDR scalability becomes available.

3.1. CO_2 capture rates: greater than or equal to 95 %

As we demonstrated in Section 2 and Table 1 above, there are various applications of CO_2 capture technology across different energy systems and industrial sectors, where over 95 % CO_2 capture is technologically feasible and economically viable under current market conditions, with others in early-stage applications where progress toward 95 %+ capture is slow and uncertain. On the downstream combustion and process side, capture of concentrated flows of CO_2 can be done today for the cost of transport and compression, with enhanced oil recovery using CO_2 as a common application to generate revenues to reduce overall costs. As of writing, there were 40 facilities capturing 46 $MtCO_2$ per year [5]. However, in post-combustion processes, where CO_2 is a small portion of the waste flue gases, and there are other waste products (e.g., nitrous and sulphur oxides, particulate matter, carbon monoxide and heavy metals in the case of coal), capturing CO_2 is much more challenging and eventual commercial feasibility is uncertain [33]. In sectors like cement and lime kilns, however, CCS is the only medium-term solution for large, moderately concentrated (20 %) process emissions from limestone calcination, after all other strategies such as fuel switching, demand, material efficiency, cementitious material substitution, and potentially cement recycling are exhausted [19,34–36]. The only way to find out if low CO_2 concentration, waste flue gas CO_2 capture is fully commercialisable at a reasonable cost is to carry out a well-resourced and intensive campaign of full-scale iterative deployment on various key applications like cement plants. The high value of learning from serious experimentation indicates that CCS experiments designed to promote learning towards eventually capturing >95 % of emissions can help maximise efforts toward achieving the Paris Agreement goals.

Governmental policies have a crucial role to play in this endeavour, especially for cement and possibly waste incineration, but so do firms [37]. Even if it were successful, however, the eventual net cost and macroeconomic drag of applying greater than or equal to 95 % capture would need to be weighed by firms against the cost, availability, and environmental impact of alternative fuels and direct electrification if possible.

3.2. Transport and permanent storage of captured CO_2

The fate of captured CO_2 is also crucial, particularly the lifetime of storage, i.e., geological storage versus the use of CO_2 in short-lived products. The captured CO_2 must be stored underground permanently, as is normally done with oil field brines and hydrogen sulphide [38]. It is important to evaluate factors such as safety, storage capacity, and efficiency, ideally using deep saline aquifers and basalt formations for ensuring effective applications [39], as well as having measuring, monitoring and verification processes in place [40].

For CO_2 capture and utilisation (CCU), fossil fuels can only meet the proposed criteria for 'abated' if the energy use for the conversion processes is roughly CO_2-neutral, and the CO_2 is utilised in a product or as a service where it is permanently stored, e.g., in building materials [41]. CO_2 utilised (CCU) and re-released to atmosphere, e.g., as shipping or aviation fuel, would have its net lifecycle CO_2 impacts accounted for in national accounting systems.

3.3. Level of upstream fugitive methane emissions: <0.5 % and towards 0.2 % leakage of gas production equivalent

Methane emissions from the coal, oil, and gas sectors are a primary source of the energy supply sector's non-CO_2 GHG emissions, contributing approximately 18 % to total GHG emissions and 90 % of non-CO_2 emissions in this sector [9,42], with combustion N_2O forming the remainder. Practices contributing to reducing methane emissions include collection and utilisation of all gas and liquid products rather than flaring co-produced gas (i.e., the elimination of routine flaring), electrification of compressors and devices, monitoring of combustion completeness, and leak detection and repair programs. Clarke et al. [9] indicate that oil and gas fugitive methane can be reduced by 50 % at net-negative costs and 80 % at less than $50/tonne USD. In coal mines, where fugitive methane constitutes around 80 % of the sector's supply chain emissions and can vary from 0.77 to 18 m cubed per tonne coal product depending on depth and coal quality [43], transforming ventilation air methane to CO_2 & H_2O in underground mines and implementing pre-mining measures (i.e., pre-drilling & deposit shattering to release the methane, followed by collection and destruction) in open pit mines can achieve 50–75 % reductions at 1 % of total production cost [44,45]. These methods are already standard in certain regions and could serve as a blueprint for global standardisation this decade. Aligning with the IEA's aim to reduce methane leakage by 75 % by 2030 [46], some countries and subnational offshore and onshore jurisdictions like Norway, The Netherlands, the UK, Colorado, and British Columbia have demonstrated the feasibility of maintaining fugitive methane levels below 0.5 % and towards 0.2 % [47]. This is equivalent to −85 % to −95 % of current estimated US leakage of 3.0 % [48]. However, the practice is not common, normally an outcome of the need to reduce fire risk on offshore platforms.

3.4. Remaining supply chain GHG emissions are counterbalanced by CDR

The effectiveness of our criteria relies on large-scale implementation of CDR to counterbalance residual emissions from CO_2 capture and upstream fugitive methane to reach net-zero GHG emissions, therefore relying on CDR measures to achieve full technological and market readiness. Many low-carbon scenarios depend heavily on novel technological CDR, despite its uncertain feasibility, particularly for technologies like BECCS and direct air CO_2 capture and storage. Grant et al. (2021) found that accounting for CDR uncertainty requires an additional 10 $GtCO_2e$ reduction by 2030 compared to scenarios ignoring this uncertainty (see also Powis et al. [49]). Global distribution and capacity building, especially in developing regions, is essential for large-scale CDR deployment (Gidden et al., 2023). Holz et al. [50] indicate that all 1.5 °C mitigation pathways require increased near-term emission reductions, regardless of future CDR assumptions. These studies support the formulation of criteria for abated fossil fuels based on the deepest emission reduction that can be achieved, limiting the reliance on CDR.

As a final note to the criteria, we do not provide complete GHG coverage in our benchmark criteria. Combustion related N_2O, roughly 10 % of non-CO_2 energy related emissions, does not need to be neutralised like NO_x to prevent CCS solvent decomposition and must be removed using advanced scrubbers. Non-combustion based N_2O and fluorinated gases account for about half of IPPU emissions in global accounts, but the process changes for eliminating these are highly specific to sectors and unrelated to combustion, other carbon oxidation and bulk CO_2 releases and the use of CCS and CCU, and are therefore not considered here as well.

In summary, we argue 'abated' fossil fuels should meet four key criteria: CO_2 capture rates should meet or exceed 95 %; CO_2 storage should be effectively permanent; upstream fugitive methane emissions must be below 0.5 % and heading towards 0.2 %; and CDR measures can be reasonably assumed to cover residual emissions mitigation to net-zero GHG emissions by dates consistent with the Paris Agreement's climate goals.

4. CCS uptake in IAM projections and sector examples using 'abated' criteria

To explore the potential impact of our criteria, we first explore the scale of CCS uptake in the AR6 Scenario Database of top-down integrated assessment models projections (i.e. long-term mitigation scenarios) and then provide bottom-up sectoral examples for steel and cement using the abated criteria.

4.1. Projections of CCS uptake in the IPCC WGIII AR6 Scenario Database

This section synthesises the scale of projected CCS applications in future decarbonisation scenarios, based on integrated assessment modelling literature, aligned with Paris Agreement goals. Fig. 1 shows fossil coal and gas use with and without CCS in global scenarios from the AR6 Scenario Database [51]. Crude oil is omitted due to its dispersed combustion patterns, largely by small volume emitters, limiting CCS applicability, and at the same time its potential CCS uses are heavily

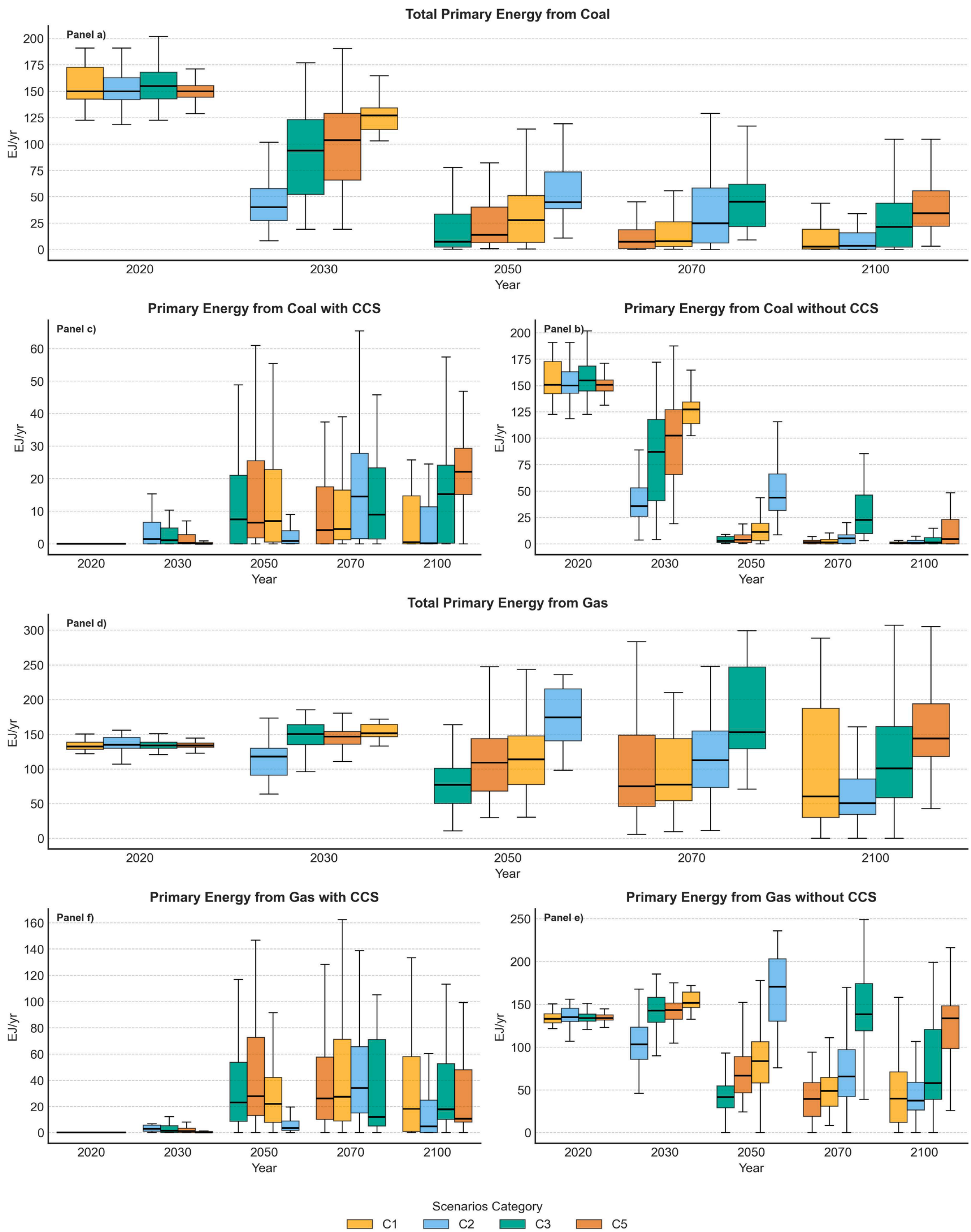

Fig. 1. Primary energy coal and gas use with and without CCS from the global modelled pathways submitted to the IPCC AR6 Scenarios Database. The top panel displays total primary energy from coal across scenarios. The second-row panels differentiate the energy from coal, with the left showing scenarios incorporating CCS and the right without CCS. The third and final row panels focus on gas, following the same approach for the first two rows. Note that the y-axes scale differs between the panels. Four scenario categories are presented: C1 (Limit warming to 1.5 °C with no or limited overshoot); C2 (Return to 1.5 °C after high overshoot); C3 (Limit warming to 2 °C) and C5 (Limit warming to 2.5 °C - aligned with pre-COP26 Nationally Determined Contributions - NDCs).

model-dependent and sector-specific [11,52,53].

Fig. 1 shows that for coal, usage starts primarily without CCS in the 2020s but shifts towards heavily CCS-enabled use in the latter half of the century, especially in more ambitious climate scenarios. Coal use without CCS is nearly eliminated in stricter scenarios by 2050. Natural gas follows a similar pattern, with non-CCS use dominating initially, then transitioning to CCS-enabled use mid-century. Both coal and gas see significant reductions in use by 2050 compared to 2019 levels, with more stringent mitigation scenarios showing greater reductions. In scenarios aligned with limiting warming to 1.5 °C (C1, check figure caption), unabated coal use is reduced by median values of 100 % (interquartile range of 95–100 %) by 2050. For gas, the reduction is over two-thirds 70 % (60–80 %) in most scenarios. The scenarios aligned with NDCs (C5) consistently show higher fossil fuel use compared to more ambitious climate target scenarios but still project substantial reductions. In C5 scenarios, unabated coal use is reduced by around median value of 95 % by 2050, while unabated gas use is reduced by around 60 %.

The IEA Net Zero by 2050 Scenario [54] shows an even stronger phase out of fossil fuels, with median reduction rates of 98 % for unabated coal, and 90 % for unabated gas in 2050 relative to 2022. The NGFS (Network for Greening the Financial System) Phase IV Net zero 2050 scenarios [7] also show strong levels of reductions, with median reduction rates for unabated coal of 87 % in 2050 relative to 2020, and for unabated gas of 73 %.

Each of these scenarios also uses varying levels of CDR measures in addition to CCS. Without access to commercialised CDR, the fossil fuel consumption values would be much lower. The scenarios in the AR6 Scenario Database mostly assume post-combustion CCS for coal and gas is commercialised and CDR is available at a large scale [55].

Looking at the future trajectory of CCS technologies deployment as assessed in the IPCC AR6 report and other global assessments above, our analysis reveals a trend towards increasing adoption of CCS in the energy supply and heavy industry sectors, especially in the latter half of the century. The projected phase out of unabated coal and substantial reduction in unabated gas use by 2050 in the various scenarios demonstrates a clear scientific consensus on phasing out unabated fossil fuels.

However, these projections hinge on the rapid scale-up and commercialisation of CCS technologies. The reduction rates discussed above are heavily contingent on optimistic assumptions about CCS uptake; notably, the IEA [5] has reported a rise in new projects announced since January 2022, with 50 facilities expected to capture 125 $MtCO_2$ per year by 2030. Yet, adding the current operating capacity of 46 $MtCO_2$ per year, 20 Mt under construction, 129 Mt at advanced development, and 188 Mt at the concept and feasibility stage, there remains a shortfall of 776 Mt to meet the IEA's projected CCS deployment of 1.16 $GtCO_2$ per year in 2030, essential for staying on course for global net-zero CO_2 emissions by 2050. Kazlou et al., [56] indicate perhaps 370–740 Mt CO_2 per year may be possible by 2030 based on deployment of existing similar technologies. The substantial gap between these sobering assessments and the needs of Paris compatible pathways emphasises the urgent need for the rapid commercialisation of CCS technologies, despite their significant costs.

4.2. Impact of using abated criteria in bottom-up steel and cement examples

Around 93 % of primary iron (used for 75 % of crude steel production, the rest being recycled) is currently reduced using metallurgical coal-driven blast-furnace basic oxygen furnaces (BFBOFs) [57]. The most recent generation of BFBOFs directly emit an average of 2.2 tonnes CO_2 per tonne iron reduced, with a wide variance depending on iron ore quality and scrap pre-charging. While metallurgical coal methane content can vary from near nil to over one tonne CO_2e per tonne crude steel made with a BFBOF, according to the IEA (IEA, 2022) the most common Australian metallurgical coal emits 5.4 kg methane per tonne coal, which translates to 0.28 tonnes CO_2e if 700 kg of coal is needed per tonne crude steel in a modern BFBOF and using the IPCC AR6 GWP 100 value of 29.8. Recently built Chinese BFBOF plants using Australian coal, the majority of the global fleet, are then likely emitting about 2.48 tonnes CO_2e per tonne crude steel.

CCS remains underdeveloped for BFBOF steel making and cannot be immediately deployed even if policy were stringent enough. A key intermediate strategy involves transitioning to fully commercial methane (syngas) driven direct reduced iron furnaces, followed by electric arc furnaces to make crude steel. When methane syngas is produced autothermally, the CO_2 purity is very high, enabling capture rates of ≥95 % using existing commercialised equipment.

Syngas DRI uses 278 cubic meters of methane per tonne iron reduced [58], assumed to be produced at 75 % efficiency once heat consumption is included in (i.e., requiring 371 cubic meters of energy and feedstock gas), becoming 0.70 tonnes CO_2 per tonne iron. If we assume 2 % upstream and transmission fugitive methane again using a GWP 100 value of 29.8 for methane 0.42 tonnes CO_2e is emitted per tonne iron reduced, for a total of 1.12 tonnes CO_2e per tonne iron, not including electricity for the electric arc furnace if run as an integrated DRI-EAF.

Applying our criteria sequentially demonstrates significant impact, as illustrated in Fig. 2, upper panel, below. Starting with unabated syngas DRI as the base iron reduction technology for new builds in a GHG constrained scenario:

- Enforcing ≤0.5 % upstream fugitive methane vs 2.0 % reduces DRI emissions from 1.12 to 0.81 tonnes CO_2e per tonne
- Implementing 50 % CO_2 capture from the DRI furnace further reduces emissions to 0.46 tonnes
- Achieving 95 % CO_2 capture brings emissions down to 0.15 tonnes, an 87 % overall reduction from the initial 1.13 tonnes.

At mid-century, if a quarter of global steel production (550 Mt of ~2200 Mt projected [59] shifted from unabated BFBOFs to abated DRI as defined above, the 0.97 tonnes per tonne reduction would yield a total global reduction of 534 Mt CO_2e per year — roughly equivalent to Canada's entire energy supply and demand emissions.

Moving to the case of cement, mid-century cement demand is estimated at 4.4 Gt per year [60], with significant uncertainty. Clinker production, cement's primary component, emits an average of 0.8 tonnes CO_2 per tonne produced [61]. These emissions vary regionally—from 0.6–0.7 tonnes in Brazil (using mainly biomass for heat) to 1.0 tonnes in countries primarily using coal, with approximately 0.5 tonnes consistently coming from limestone calcination process emissions.

Emissions reduction in cement production can follow a hierarchy of interventions [36]: 1) minimising concrete use to where compression and corrosion resistance is necessary; 2) full implementation of cement and concrete making best practices (e.g., optimised aggregate sizing, mixing & hydration); and 3) reducing the global clinker ratio from today's global average 0.63 [62] to 0.50 using low GHG substitutes that are both well established (e.g., blast furnace slag, fly ash, pozzolans, ground limestone) and newer (e.g., limestone calcined clay cements [63]). These measures combined could reduce clinker requirements—and thus the core source of emissions—by up to 60 % from today's 2.8 Gt of production of clinker by 2050. However, until alternative chemistries and binders gain widespread acceptance, CCS remains essential for eliminating residual heat and process CO_2 emissions from the 1.1 Gt of clinker production that would remain after aggressive application of all measures, with ~880 Mt per year of CO_2 emissions if unabated with current fuel mixes. With 50 % capture, this falls to 440 Mt, and with 95 % capture, merely 44 Mt per year, plus associated upstream fugitive coal and methane emissions. Check Fig. 2, lower panel.

In summary, after all other reasonable lower cost actions are taken, we estimate application of our criteria reduces emissions by ~534 Mt

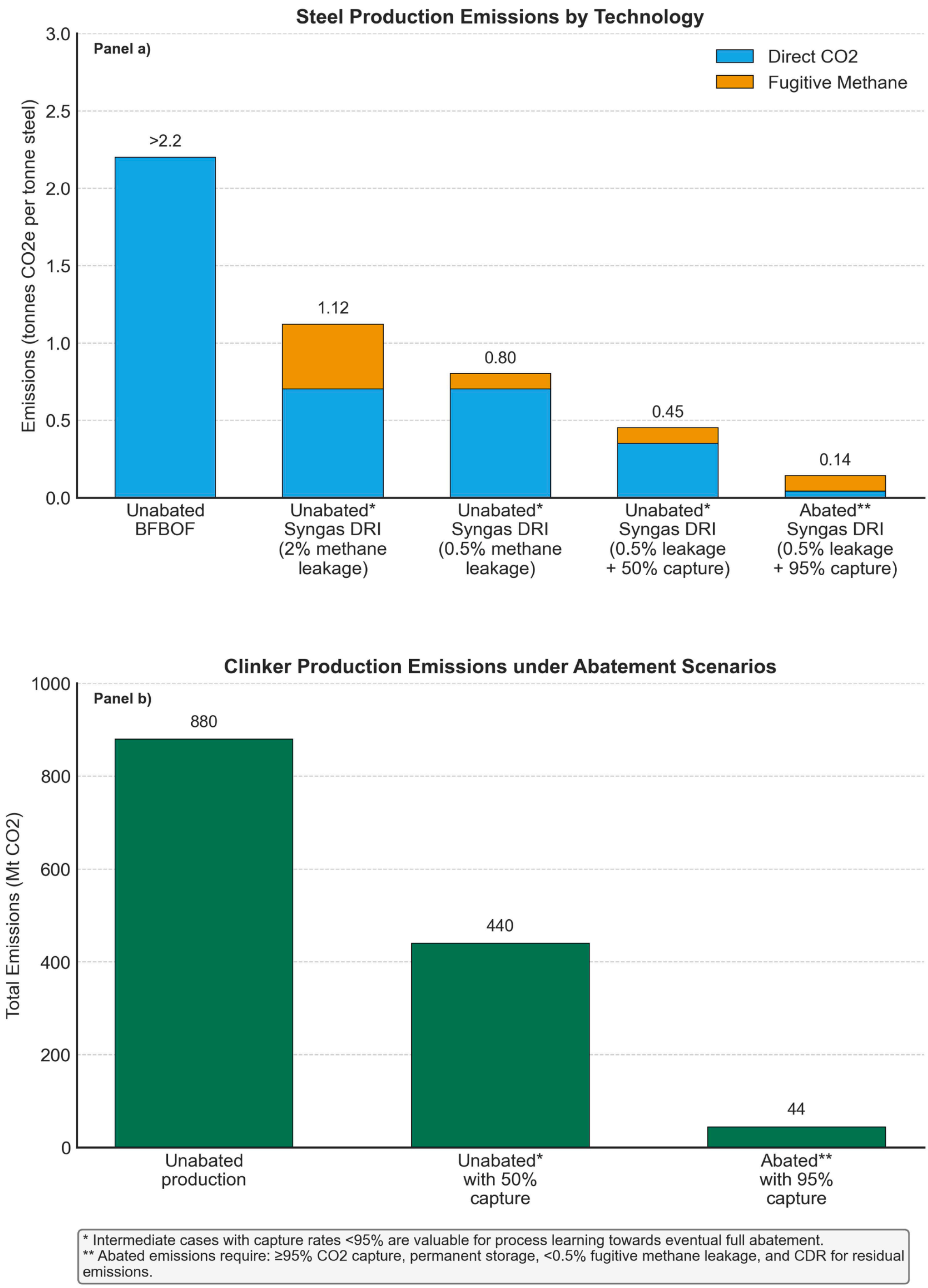

Fig. 2. Emissions reduction potential in industrial sectors through carbon capture and storage (CCS) and methane leakage control. Panel a) Steel Production Emissions by Technology shows emissions from conventional BFBOF compared with various syngas DRI configurations, not including EAF electricity emissions. Panel b) Clinker Production Emissions under Abatement Scenarios illustrates total annual CO_2 emissions from 1.1 Gt of clinker production mid-century after maximal clinker & cement use minimisation under different mitigation approaches. Together, these panels demonstrate that combining high capture rates with upstream methane leakage control can achieve up to 87 % emissions reduction in steel production starting from unabated syngas DRI (and >94 % starting from BFBOF), while cement emissions can be reduced by >95 % after application of all measures. Note that BFBOF emissions do not include additional varying fugitive methane from coal mining due to wide variation of estimates but are in all case higher than methane based DRI.

CO_2 per year in steel at mid-century, and ~836 Mt in cement, for a total of 1.37 Gt CO_2 per year.

5. Role of policy, regulation, and markets in fugitive regulation & CCS adoption

While the above criteria for abated fossil fuels and IPPU CO_2 emissions are technically feasible, greater than or equal to 95 % capture and functionally permanent storage has only been continuously achieved with concentrated CO_2 flows at a few projects, mainly formation gas cleaning and ethanol plants, where the CO_2 went into deep saline aquifers, and not for post-combustion. A step change in ambition, policy scope and stringency are required to meet these criteria in a way that maximise mitigation efforts in line with the Paris Agreement goals. This is also dependent on regional differences in technological capacity, economic conditions, and political will.

5.1. Fugitive regulation

Until recently, with the advent of drone and space-based methane monitoring, it was impossible to apply a per unit carbon price to fugitive methane and the default was intermittent monitoring to enforce a regulatory approach. Given these new capacities, some pricing might be possible, especially for super emitter events within willing jurisdictions, but for the foreseeable future the best course is likely to be duplication of best-in-class fugitive control regulation, as applied in the North Sea, British Columbia, Colorado or New Mexico, and application of underground and open pit coal bed methane destruction mandates where possible. At minimum, the IEA goal of −75 % by 2030 could be considered the guidepost for oil and gas fugitive methane controls (which brings most regions towards our criteria of <0.5 % and ideally 0.2 %). A standard of 1–3 tonnes methane per kilotonne sold coal by 2030 has been proposed, which is a 60–75 % reduction of methane emissions per unit of sold metallurgical coal from the level averaged over 2017–2019 [44,45].

5.2. Carbon capture

CCS is capital and operating cost intensive. For that reason it needs policy certainty and more than or equal to \$40/t CO_2e on all tonnes emitted for concentrated flow streams and more than or equal to \$80–150+/t CO_2e for diluted flows such as those produced with post-combustion of coal and natural gas [10,37]. Substantially higher prices are likely required with any sort of policy uncertainty [64,59]. Some processes already have concentrated flows of CO_2 (e.g., formation gas cleaning and ethanol fermentation), and could be mandated to use CCS, albeit with cost recovery mechanisms (e.g. production and/or investment tax credits, or the ability to include the cost in rate bases for regulated natural monolopy suppliers). To encourage investment in processes that produce concentrated CO_2 (e.g., autothermal hydrogen production, and oxycombustion more generally), and CCS more generally, production and investment tax credits (e.g., under the IRA [65]) or contracts for difference (e.g., under Germany's scheme [66] or the UK Offshore Wind scheme [67] can be used as inducements [68,69]. Carbon pricing could be applied where politically feasible but is unlikely to reach the \$80–150+/t CO_2 necessary for post-combustion CCS in most jurisdictions for the foreseeable future. Instead, tradable zero emissions materials standards modelled on the California Zero Emissions Vehicle standard could be used that simulate the effect of higher carbon prices on a sector by sector basis [59,70].

5.3. Transport, disposal and permanence monitoring

There are three main geological destinations for CO_2 injection: into depleted oil and gas reservoirs for enhanced oil and gas recovery (EOR) with adequate well sealing[71], deep saline layers, and basalt [72]. All three can be permanent, but EOR requires purposeful well management and intensive monitoring, at least for several years. The latter two require less management after the initial injection phase, as the CO_2 binds to the underlying geology. There is some debate, however, over the rate with which CO_2 can be injected into the ground, even if capture, transport and compression is available, subject to regional geological characteristics [73].

5.4. Incentivisation for CDR

Both Sweden and the UK have discussed auctions for government purchases of CDR credits, the EU has establish rules for CDR crediting in the EU ETS [74], and numerous cap and trade designs have been discussed for "negative caps" [75]. A "Carbon Takeback Obligation" (CTO) has also been proposed, where all net and residual emissions by firms must be compensated with purchased negative emissions via natural or novel CDR measures [76]. Finally, in a global version of the CTO, a global drawdown account to pay for CDR could be established, possibly funded by those nations with cumulative historical responsibility and capacity to pay, either based on emissions or cumulative GDP underpinned by fossil fuels [77]. Schenuit et al. [78] argue for five principles for developing these policies: 1) implement credible monitoring, reporting, and verification; 2) embed and phase in CDR policies into existing climate policy frameworks; 3) link deployment to a jurisdictional net-zero goal; 4) establish net-negative ready policy frameworks; and 5) strengthen international cooperation on research, demonstration and deployment.

The policy mechanisms and market incentives discussed above are crucial for realising the potential of CCS and CDR technologies and achieving the criteria for 'abated' fossil fuels proposed in this paper.

6. Conclusions

In this paper, our analysis highlights the necessity of distinguishing between 'abated' and 'unabated' fossil fuels and IPPU CO_2 emissions to maximise emission reductions and support the achievement of Paris Agreement temperature goals. In aiming to set robust standards for the term 'abated' based on best practices, we propose four benchmark criteria: 1. A CO_2 capture rate of more than or equal to 95 %, representing a critical threshold for achieving deep decarbonisation; 2. Transport and permanent storage of captured CO_2, as opposed to temporary storage where CO_2 eventually ends up in the atmosphere; 3. Limiting upstream fugitive methane emissions to below 0.5 %, with a target of achieving 0.2 %; 4. Counterbalancing residual emissions from <100 % CO_2 capture and upstream methane emissions using CDR, ensuring abated fossil fuels are net-zero GHG emissions, meaning no net addition of GHG to the atmosphere. This criterion relies on the critical assumption that CDR measures reach full technological and market readiness. Our provided examples for steel and cement show rigorous application of the criteria compared to lax application could have considerable emissions consequences, i.e., likely more than or equal to 1.37 Gt CO_2e per year by 2050 across applicable sectors.

Future research should focus on operationalising the benchmark criteria we have established for 'abated' fossil fuels and industrial processes emissions. By applying our criteria to specific scenarios or processes, where detailed data on upstream fugitive methane emissions and CO_2 capture rates are available, researchers can assess the practical implications. Additionally, we recommend that future long term mitigation scenarios literature adopt these criteria in order to bridge the gap between the stringent definition presented here for what count as 'abated' emissions and modelled applications. Another area of research would be exploration of dynamic criteria based on evolving technologies and climate goals, particularly the critical inverse link between the allowable capture rate and the amount of CDR that realistically becomes available, with the former decreasing as the latter improves, and vice versa. Finally, policy efforts could focus on two key areas: developing scalable and administratively feasible regulatory frameworks for universally applying 'abated' fossil fuel and industrial process emissions criteria and formulating strategies to embed these criteria into international climate agreements.

Code and data availability

All code and output data are available on GitHub at: https://github.com/AlKhourdajie/Abated_FF_Def

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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