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PERSPECTIVE

Extended producer responsibility for fossil fuels*

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Abstract

Energy policy faces a triple challenge: increasing resilience and guaranteeing the security of supply of both fossil and non-fossil energy, minimising the impact on consumer energy prices, and retaining consistency with Paris Agreement climate goals. High prices and producer rents, however, also present an opportunity: to open a conversation about applying the principle of extended producer responsibility (EPR) to fossil fuels. We demonstrate that this could deconflict energy security and climate policy at an affordable cost by stopping fossil fuels from causing further global warming. Implementing EPR through a combination of geological CO_2 storage and nature-based solutions can deliver net zero at comparable or lower costs than conventional scenarios driven with a global carbon price and subject to constraints on CO_2 storage deployment. It would also mean that the principal beneficiary of high fossil fuel prices, the fossil fuel industry itself, plays its part in addressing the climate challenge while reducing the risk of asset stranding.

A restructuring of global energy markets is under way. In the immediate future this is in response to the Russian invasion of Ukraine, refocussing attention on the energy policy trilemma between affordability, environmental impact and security of supply. Although it plays out over a longer timescale, the same trilemma exists as nations look towards their commitments to the Paris Agreement.

Various forms of carbon pricing (such as the European Emission Trading System), and other non-price-driven demand reduction mechanisms, have identified cost-effective ways of reducing emissions, balancing affordability and impact, but potentially at the expense of security [1]. Calls [2] to reduce Europe's dependence on Russian gas accept that the fastest transition could mean a short-term reversion to coal, opening up new domestic oil and gas reserves [3], increasing near-term imports of liquified natural gas [4], alongside investment in renewable energy and efficiency. These measures imply an increase in actual and committed emissions and potentially reduced affordability in the short term.

The prospect of moratoria on Russian fossil fuel exports is driving up international oil, gas and coal prices, providing windfall profits to non-Russian fossil fuel extractors. Since 2021, oil, gas and coal prices have increased by $100–500 expressed per tonne of CO_2 generated [5] (see figure S2 in the SI), comparable to the cost of recapturing the CO_2 that they generate. Acknowledging the risk of asset stranding, companies are returning a larger share of these profits to shareholders [6] rather than investing in new extraction. This potentially exacerbates future price volatility, concentrating supply on an ever smaller number of mostly state-owned enterprises, but investment in new non-Russian fossil fuel production appears to be in direct conflict with climate goals [4]. This dilemma has been widely commented on [7, 8] but does not appear to result in reduced enthusiasm for new extraction this decade [9].

* At a time of high fossil fuel prices and rents, we show that applying the principle of extended producer responsibility to fossil fuels, implemented through a combination of geological storage and nature-based solutions, could deconflict energy security and climate policy at an affordable cost.

The immediate response to the Russian invasion of Ukraine has demonstrated that when forced to choose between security of supply and commitments to environmental legislation, governments forego the latter [9, 10]. In the longer term, those concerns can be jointly addressed through increased investment in domestic renewable energy and energy efficiency measures [11]. But this presents a risk if declining fossil fuel prices driven by potential oversupply through present commitments to new extraction undermine investment in demand reduction and substitution. Regardless, models suggest that while the restructuring of global energy markets will reduce reliance on fossil fuels by mid-century, it will not eradicate it entirely. In scenarios consistent with the Paris Agreement, around one quarter of CO_2 produced from fossil sources in 2020 is still produced at the time of net zero [12]. Figure 1 shows the median and interquartile range of 1.5 °C-consistent scenarios contributing to the IPCC's Sixth Assessment Report [13] (individual scenarios are shown in figure S1 of the SI). Even if demand reduction efforts are significantly more successful and widespread than the median scenario suggests, billions of tonnes of CO_2 will still be produced annually (red). A huge upscaling in carbon capture and storage is therefore required to reach net zero (blue), yet progress today remains slow.

This situation could be seen as an opportunity to apply another successful environmental policy to deconflict energy and climate policy: extended producer responsibility (EPR) for fossil fuels. Under EPR as implemented in France [14, 15], for example, a 'producer', meaning 'any natural or legal person who develops, manufactures, handles, treats, sells or imports waste-generating products', 'may be required […] to provide or contribute to the prevention and management of the resulting waste'. This law already applies to household chemicals, but not hydrocarbon fuels, despite the fact that almost 100% of the carbon contained in fossil fuels ending up as waste CO_2 dumped into the atmosphere. If the principle of EPR were applied across OECD countries without this exemption, anyone extracting or importing fossil fuels into the OECD would become responsible for permanent disposal of the waste CO_2 that those fuels generate. If desired, EPR could be expanded to include CO_2 resulting from methane emissions associated with fossil fuel production, although here our EPR policy only considers CO_2 resulting from the fossil fuel use directly. Once such a policy was enforced, the fossil fuels it covers would no longer contribute to global warming, allowing energy policy to focus on balancing affordability and security of supply.

Countries implementing an EPR policy for fossil fuels would be in a strong position to require trading partners to do the same: whether a country acts on the principle of EPR for fossil fuels is a simpler question than whether emission reduction measures are comparably ambitious [16]. OECD countries' pivot away from Russian oil and gas relies on both expanded domestic supply and increased imports from the Middle East and USA. This presents a unique opportunity to make these imports conditional on developing CO_2 capture and storage in producer nations, facilitating EPR-compliant fossil fuels in the future.

Capacity to dispose of all CO_2 currently generated in the OECD does not exist [17], and even if it did, adding the cost of capture and permanent storage would impact affordability: for all but large point sources, waste CO_2 would have to be recaptured from the atmosphere. Countries are, however, not committed to net zero emissions immediately, but by 2050. A Carbon Takeback Obligation (CTBO) [18, 19] would require all extractors and importers of fossil fuels within a jurisdiction to dispose permanently of a progressively increasing fraction of the CO_2 generated by their activities and the products they sell [20]. As the stored fraction increases, the cost of complying rises towards the cost of direct air capture and carbon sequestration (DACCS). It would be a decision for the fossil fuel industry and its owners (in many cases governments) whether to pass this cost on to consumers in full, or to defend its market share by accepting lower rents having realised the full cost of its activities including compensating for fossil fuels' environmental impact. The CTBO thus provides a 'backstop' climate policy [19], guaranteeing net zero emissions by 2050 independent of the evolution of energy demand and renewable and fossil fuel costs in the meantime.

Figure 2 shows a hypothetical global CTBO based on a straight-line transition to 100% producer responsibility for all CO_2 embedded in extracted fossil fuels by 2050 (red line, panel (b)). Increasing the stored fraction immediately by 3.3% per year [21] is not feasible with geological storage alone, but could be achieved using a combination of geological storage and nature-based solutions (NbS) [22, 23]. We assume here that the principle of EPR is separate from the NbS policy, with NbS acting to increase near-term ambition while acknowledging that, in the long term, the only durable way of compensating for any continued production of CO_2 from fossil sources is likely to be geological storage or measures of equal permanence, such as remineralisation [24, 25]. While NbS can increase atmospheric carbon removal immediately through better management of agricultural lands and ecosystem restoration, the extent to which managed land acts as a carbon sink globally is unclear. Scenarios that limit global warming to 1.5 °C by 2100 consistently reach geological net zero (see the black geological CO_2 emissions timeseries in figure 1), meaning any ongoing production of CO_2 from fossil sources is balanced by geological CO_2 disposal, in the second half of this century. Net CO_2 removal by the biosphere is relied upon for at most a couple of decades to compensate for ongoing fossil

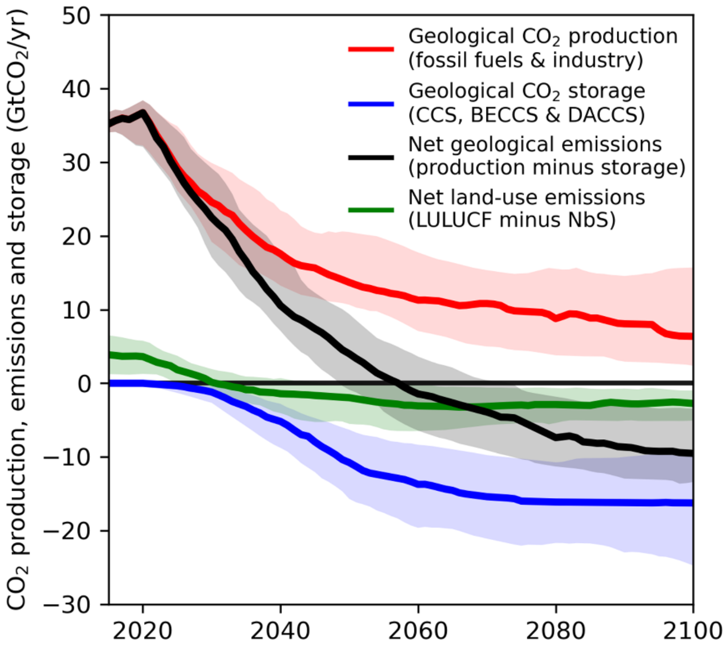

Figure 1. 1.5 °C-compatible scenario produced from IPCC's AR6 scenario database. The median and interquartile range of all 1.5 °C-compatible scenarios are plotted, showing geological CO_2 production (all CO_2 produced from fossil fuel extraction and use, plus cement) in red, geological CO_2 storage (CCS, BECCS and DACCS) in blue, net land-use emissions in green (LULUCF minus NbS), and net geological CO_2 emissions (geological CO_2 production minus geological CO_2 storage) in black. Individual scenarios used to make this figure are shown in figure S1 in the SI, and can be found in the AR6 scenario database[13].

fuel use in delivering net zero emissions to the atmosphere (green in figure 1).

Hence it would be unsafe to rely indefinitely on NbS to compensate for CO_2 generated from fossil fuel use, due to increasing risks to natural carbon sinks from climate change [26]. Notwithstanding these concerns, between now and 2050 it has been estimated [23] that up to 140 $GtCO_2$ globally might be captured through NbS at a cost of up to \$100 per tCO_2, at a rate of 5 $GtCO_2\ yr^{-1}$. This would require restoring ca. 678 million hectares of ecosystems, and improving the management of ca. 2.5 billion hectares of land. We assume, conservatively, that from 2050 onwards all ongoing NbS capacity is required to offset emissions due to these Earth system feedbacks, and essential activities such as food production [22]. Hence, the fraction of captured CO_2 that is committed to geological storage also increases linearly to 100% by 2050 (making a quadratic increase in geological stored fraction overall, pink line in panel (b)).

Although we are agnostic as to the eventual fraction of geologically stored CO_2 that is sourced from DACCS, we conservatively assume the price of CO_2 capture and geological storage increases linearly to the price of DACCS in 2050, giving a cost per tonne of CO_2 geologically stored of \$50/tCO_2 in 2020 [27–29], rising to \$300/tCO_2 in 2050 [27, 30]. This is conservative, because some point sources may remain in sectors such as steel and cement production, or through the use of Bioenergy with Carbon Capture and Storage (BECCS). BECCS is generally considered lower cost that DACCS, but is subject to additional sustainability constraints which may limit its large-scale deployment. The eventual allocation between point sources, BECCS and DACCS could be left to the market (as indicated by the thin pink and purple lines fading out in panel (b)), or given the potential dangers of over-reliance on BECCS it could be made a condition of the CTBO to ensure timely DACCS deployment.

With the EPR policy requiring a quadratic increase in the geologic stored fraction, NbS is used to fill the gap to produce a linear increase in stored fraction overall (green line, panel (b)). Assuming, also conservatively, that all NbS CO_2 removals cost \$100/tCO_2, a pure CTBO + NbS policy would only add about \$30/tCO_2 to fossil energy costs in 2030, even though it would by then be removing one third of CO_2 generated by ongoing fossil fuel use. Even if, as likely, this entire cost were passed on to the consumer, it is too cheap to substantially reduce demand for fossil fuels, leading to potentially unfeasible [19] rates of CO_2 storage in the 2030s and 2040s. Because of this, complementing the CTBO with measures to reduce fossil fuel consumption through substitution and efficiency, here represented by a global carbon price increasing linearly to \$150/tCO_2 by 2050, is a sensible precaution. This represents the net impact of all other mitigation policies in addition to those in place today, including reduced caps in emission trading systems, higher carbon taxes, and subsidies for renewable energy. The level to which demand reduction policy is successful depends on political

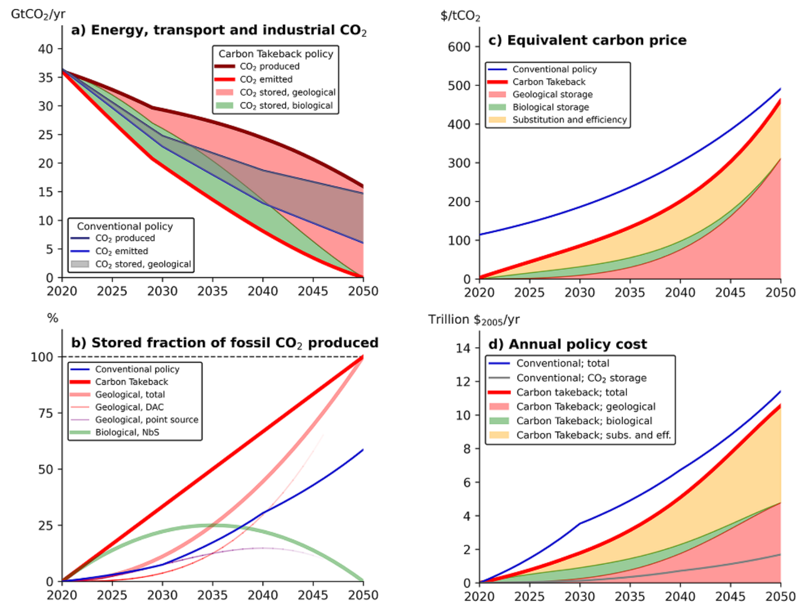

Figure 2. A global carbon takeback scenario incorporating Nature-based Solutions. The percentage of CO_2 produced by energy, transport, and industry (ETI, panel (a), brown line) that is captured and stored away from the atmosphere increases by 3.3% yr^{-1} from 2020 (panel (b), red line), resulting in net-zero emissions in 2050 (a, red line). The geological stored fraction also increases by 3.3% yr^{-1} ((b), pink line, and a, pink wedge), with the remaining storage delivered through NbS (green line and wedge). Panel (b)'s thin pink/purple lines show contributions of direct-air/point-source capture. Panel (c) shows the effective carbon price implied by the CTBO, augmented by a linearly-increasing carbon price to encourage additional substitution and efficiency. Fossil fuel demand ((a), brown line) responds to rising prices following the marginal abatement costs implied by a standard Integrated Assessment Model (IAM) [33]. A conventional policy with consistent cost assumptions but driven solely by a global carbon price is also shown (blue lines): a higher carbon price (panel (c)) delivers faster reductions in CO_2 production ((a), dark blue line) but, with no explicit requirement for CO_2 removal and exogenous constraints on storage deployment, slower reductions in emissions ((a), light blue line). Total annual policy costs (the integral under the marginal abatement cost curve plus the direct cost of CO_2 storage deployment) are shown in panel (d) [19]. More optimistic abatement cost assumptions, such as lower renewable energy costs, result in lower absolute costs but similar relative costs under both policies.

willingness to invest in non-fossil energy and the marginal abatement cost for the final third of CO_2 production, neither of which can be predicted with confidence at this time.

Using the above cost assumptions, the CTBO policy results in CO_2 production, storage and emissions timeseries shown in figure 2(a). CO_2 production is estimated using a stylised marginal abatement cost curve, based on the MESSAGE-GLOBIOM 1.0 SSP2 scenarios, driven with a carbon price trajectory (panel (c)). CO_2 storage curves are estimated using the CO_2 production and the stored fraction (panel (b)), with emissions the difference between CO_2 production and storage. This methodology is described in Jenkins *et al* [19].

Relying on carbon pricing and other demand reduction mechanisms to reduce emissions requires prices rising to \$1000/tCO_2 at net zero, across a broad range of models [19], to squeeze the last residual uses of fossil fuels out of the global energy system. One scenario (MESSAGE-GLOBIOM 1.0; SSP2-19) is shown on figure 2 (blue lines). Although some of the revenues from such high carbon prices could be recycled to alleviate impacts on consumers, their political feasibility has yet to be tested. Policies whose equivalent carbon price exceeds the cost of DACCS at the time of net zero arise because that policy pathway fails to incentivise early development of a large-scale CO_2 disposal industry; CO_2 storage is only scaled up once all cheaper mitigation options are exhausted. Hence, although carbon pricing and other demand reduction mechanisms are often seen as the most cost-effective way to drive mitigation, a global CTBO could deliver comparable policy costs (figure 2(d)) if it results in faster CO_2 storage deployment. This is reasonable, because many of the constraints on CO_2 disposal are not simply related to cost, but concern other issues such as licensing, safety and public acceptability: a license-to-operate regulation like the CTBO provides the strongest possible incentive on the fossil fuel industry itself to address these constraints and overcome them.

The proposed use of largescale CO_2 capture and storage raises several concerns—managing these risks is key to the success of an EPR policy. Investment in CO_2 capture and storage is often criticised for moral hazard, reducing incentives to reduce fossil fuel use and making mitigation more costly. Conversely, failure to require the industry to invest in timely CO_2 disposal increases the risk of more-costly mitigation options being required in future due to lack of storage capacity. There are also questions on the willingness of governments to enforce such policy, and of consumers to accept higher fossil fuel prices, although these concerns are not unique to any single climate policy, and can be managed somewhat with transparent and long-sighted regulation. Finally, there is a risk that CO_2 storage fails to materialise at sufficient scales and at reasonable costs. Again, it is not clear that a CTBO or other EPR policy is particularly riskier in this regard than other policy options—almost all ambitious mitigation scenarios in AR6 rely on gigatonne-scale CO_2 capture and storage, and EPR is one of the few policy proposals which encourages long-term, large-scale investment in this area. Ultimately, no single policy can be designed to address all these concerns. EPR legislation is not focussed on reducing demand for fossil fuels (although it does achieve this in mid-century as a side effect of adding to the cost of fossil fuel production), it is focussed on stopping the continued use of fossil fuels from resulting in additional CO_2 emissions. If, having implemented EPR for fossil fuels, policymakers determine a risk in the amount of fossil fuel extraction and use envisaged by mid-century, they would have to implement additional demand reduction policies, and see this as protecting their EPR legislation from becoming overburdened.

It might be argued that a similar outcome could be achieved through a windfall tax on fossil fuel producers with the proceeds spent on subsidising low-carbon development. This, however, would disadvantage domestic oil and gas producers, increasing reliance on overseas producers, reducing energy security. Subsidies also provide less incentive to innovate to reduce costs and lower investment security than a simple license-to-operate regulation. Moreover, subsidising low-carbon energy without specifically requiring CO_2 disposal does not stop fossil fuels from causing global warming unless complemented with a global ban on fossil fuel extraction. At present this is a geopolitically difficult option, although a progressive moratorium on fossil fuel extraction has been suggested as a route forwards [31]. The principle of a CTBO could be considered complementary to a moratorium on unabated fossil fuel use by introducing the concept of 'safe civilian use' of fossil fuels. Applying the principle of EPR through a progressive CTBO, even with conservative cost assumptions, delivers faster emissions reductions than relying on a global carbon price, at a lower cost, both per tonne of CO_2 generated, and in total (figures 2(c) and (d)), because we assume the investment certainty provided by the CTBO policy results in much faster roll-out of CO_2 storage infrastructure.

The magnitude of total policy costs depends on the marginal abatement cost of CO_2 production, the use of demand reduction policies, and the cost of carbon capture and storage. Figure 3 demonstrates how the EPR legislation reacts to various alternative assumptions. Scenarios in panels (c) and (d) assume that the marginal abatement cost of 50% CO_2 production abatement is \$100/tCO_2, substantially reducing the CO_2 produced in both CO_2-price-driven and EPR-driven scenarios. Panels (e) and (f) show the impact of more ambitious demand reduction policies, encouraging greater CO_2 production reductions by 2050. Panels (g) and (h) assume higher cost DACCS (up to \$800/tCO_2 in 2050), reducing reliance on CO_2 storage by encouraging greater use of non-fossil energy.

Across all scenarios, EPR is not intended to replace existing energy efficiency and renewable energy policies. The cost of CO_2 capture and storage exceeds the cost of CO_2 production abatement for the majority of emissions sources [19]. Hence, demand reduction policies are vital to reduce consumer demand for fossil fuels. EPR policy complements these policies, acting as a backstop to catch residual CO_2 which would otherwise be emitted.

Further, EPR policy engages the fossil fuel industry itself to develop geological storage, acknowledging that the managerial and technical expertise within these companies best supports the expansion of carbon capture and geological storage safely and rapidly. Implementing 10 GtCO_2 yr^{-1} geological storage means building CO_2 capture, transport and storage infrastructure to 25%–50% of the scale of the oil and gas industry today (assuming 10GtCO_2 yr^{-1} geological storage is required, and oil and gas today produces around 40% of global CO_2 emissions [32]). EPR legislation offers one mechanism to achieve this.

In the immediate future, if the USA, Europe and the UK are to reduce dependence on Russian gas by boosting domestic fossil fuel production and LNG imports from suppliers such as the USA, Qatar or Australia, this should be accompanied by a bold new policy to stop fossil fuels from causing further global warming by 2050. EPR for fossil fuels implemented through a progressive CTBO would deliver this, particularly if augmented with a commitment to NbS. There are risks associated with pursuing an EPR policy, some of these we discuss above. However, many of these can be mitigated by considering EPR as a tool which works alongside strong demand reduction policy, not as a substitute for it. Policymakers must invest in energy efficiency measures and renewable energy expansion in this decade to allow the principle of EPR to be applied effectively in future decades. EPR demands that any residual CO_2 produced in mid-century does not result in CO_2 emissions, while imposing the cost of complying with this requirement onto the fossil fuel industry and its customers at that time. Like any effective climate policy, EPR will increase the cost of fossil energy, but predictably over the next 30 years, allowing energy planners to respond to the next economic or geopolitical crisis without worrying about the consequences for Earth's climate.

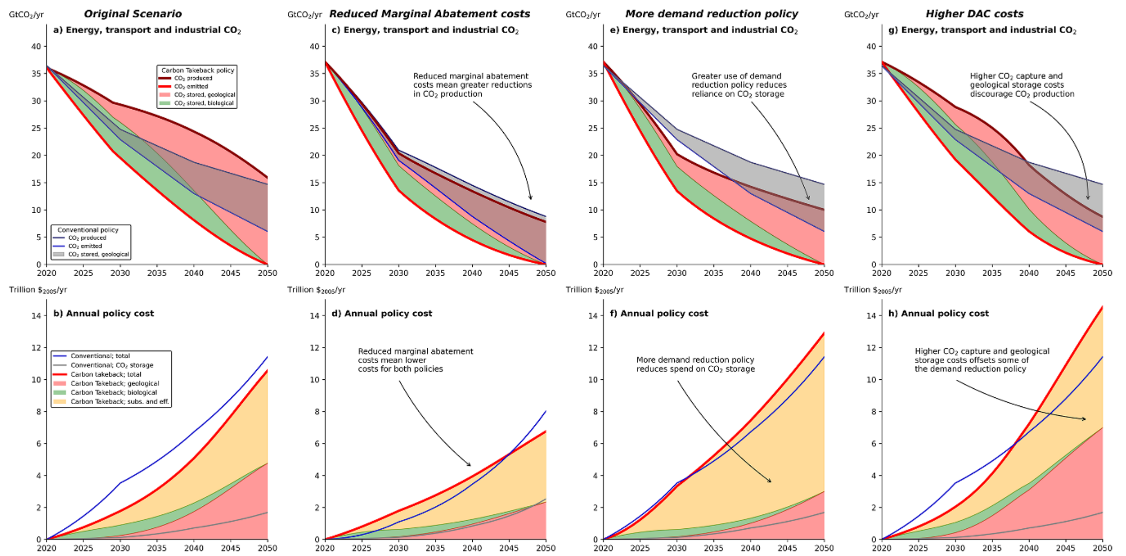

Figure 3. The robustness of a global CTBO under alternative cost assumptions. Various assumptions for the marginal abatement cost of CO_2 production, the extent of demand reduction policies, and the cost of direct air capture (DACCS) are explored. Upper panels show each policy's CO_2 production timeseries, CO_2 storage (filled regions) and CO_2 emissions timeseries; lower panels show the total annual policy costs (calculated as the integral under the marginal abatement cost curve plus the direct cost of carbon price on emissions). Panels (a) and (b) show the original policy for reference, taken from panels (a) and (d) of figure 2. Panels (c) and (d) show alternative scenarios where the marginal cost for 50% CO_2 production abatement is reduced to \$100/tCO_2 for both conventional policy and CTBO policy scenarios. Panels (e) and (f) show a CTBO scenario with increased demand reduction policy, using the original scenario's marginal abatement cost assumptions. Panels (g) and (h) show a CTBO scenario with higher DACCS costs in mid-century, using the original scenario's marginal abatement cost assumptions.

Data availability statement

The data that support the findings of this study are openly available.

Data for the MESSAGE SSP2-19 scenario shown in the figures is available via the IAMC SSP scenario database (https://tntcat.iiasa.acat/SspDb/).

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Author contributions

S J and M A conceived the study and designed the figures. All authors contributed to analysis and writing.

Conflict of interest

S J, M A, H H and M K are aligned under the Producer Accountability for Carbon Emissions (PACE) group, a voluntary group supporting producer responsibility for fossil fuel emissions.

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References

[1] Sewalk S 2016 The EU should merge energy and environmental policy to achieve energy independence from Russia *Denver J. Int. Law Policy* **45** 51–96

[2] Wagner G The case for the EU cutting off its Russian gas supply now Bloomberg.com

[3] IEA 2022 A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas (available at: https://iea.blob.core.windows.net/assets/1af70a5f-9059-47b4-a2dd-1b479918f3cb/A10-PointPlantoReducetheEuropeanUnionsRelianceonRussianNaturalGas.pdf)

[4] Ravikumar A P, Bazilian M and Webber M E 2022 The US role in securing the European Union's near-term natural gas supply *Nat. Energy* **7** 1–3

[5] Allen M Paris emissions cuts aren't enough—we'll have to put carbon back in the ground *The Conversation* (available at: http://theconversation.com/paris-emissions-cuts-arent-enough-well-have-to-put-carbon-back-in-the-ground-52175)

[6] Thomas A 2022 Shell celebrates 'momentous' 2021 results with \$8.5 billion share buyback *Energy Voice* (available at: www.energyvoice.com/oilandgas/384876/shell-share-buyback-dividend-2021-results/)

[7] Harvey F and correspondent, F H E 2022 New North Sea oil and gas licences 'incompatible with UK climate goals *The Guardian*

[8] Evans S 2022 New fossil fuels 'incompatible' with 1.5C goal, comprehensive analysis finds *Carbon Brief* (available at: www.carbonbrief.org/new-fossil-fuels-incompatible-with-1-5c-goal-comprehensive-analysis-finds/)
[9] Executive summary—World Energy Outlook 2022 Analysis *(IEA)* (available at: www.iea.org/reports/world-energy-outlook-2022/executive-summary)
[10] IOGP 2022 New study identifies Europe's supply options to replace Russian gas before 2030 *(IOGP)* (available at: www.iogp.org/blog/press-releases/eu-pr/new-study-identifies-europes-supply-options-to-replace-russian-gas-before-2030/)
[11] European Commission 2022 REPowerEU: affordable, secure and sustainable energy for Europe (available at: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en)
[12] Huppmann D *et al* 2018 IAMC 1.5 °C scenario explorer and data hosted by IIASA *Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis* (https://doi.org/10.22022/SR15/08-2018.15429)
[13] IIASA 2022 AR6 scenario explorer and database (available at: https://data.ece.iiasa.ac.at/ar6/#/login?redirect=%2Fworkspaces)
[14] Vernier J 2021 Extended producer responsibility (EPR) in France *Field Actions Sci. Rep.* **23** 22–25
[15] Légifrance 2022 Article L541-10 - Environmental Code (available at: www.legifrance.gouv.fr/codes/article_lc/LEGIARTI000041599099/)
[16] Masood E 2021 Net-zero carbon pledges must be meaningful to avert climate disaster *Nature* **592** 8
[17] Friedlingstein P *et al* 2021 Global carbon budget 2021 *Earth Syst. Sci. Data Discuss.* **14** 1–191
[18] Kuijper M 2021 *Carbon Takeback Obligation: A Producers Responsibility Scheme on the Way to a Climate Neutral Energy System* (available at: www.gemeynt.nl/bericht/carbon-takeback-obligation-a-producers-responsibility-scheme-on-the-way-to-a-climate-neutral-energy-system)
[19] Jenkins S, Mitchell-Larson E, Ives M C, Haszeldine S and Allen M 2021 Upstream decarbonization through a carbon takeback obligation: an affordable backstop climate policy *Joule* **5** 2777–96
[20] Allen M R, Frame D J and Mason C F 2009 The case for mandatory sequestration *Nat. Geosci.* **2** 813–4
[21] Helferty H 2021 We should harness oil companies to reduce greenhouse gas emissions *The Hill* (available at: https://thehill.com/opinion/energy-environment/586991-we-should-harness-oil-companies-to-reduce-greenhouse-gas-emissions)
[22] Girardin C A J, Jenkins S, Seddon N, Allen M, Lewis S L, Wheeler C E, Griscom B W and Malhi Y 2021 Nature-based solutions can help cool the planet—if we act now *Nature* **593** 191–4
[23] Nolan C J, Field C B and Mach K J 2021 Constraints and enablers for increasing carbon storage in the terrestrial biosphere *Nat. Rev. Earth Environ.* **2** 436–46
[24] Fankhauser S *et al* 2022 The meaning of net zero and how to get it right *Nat. Clim. Change* **12** 15–21
[25] Allen M R *et al* 2022 Net Zero: science, origins and implications *Annu. Rev. Environ. Res.* **47** 849–87
[26] Lowe J A and Bernie D 2018 The impact of Earth system feedbacks on carbon budgets and climate response *Phil. Trans. R. Soc.* **376** 20170263
[27] Bui M *et al* 2018 Carbon capture and storage (CCS): the way forward *Energy Environ. Sci.* **11** 1062–176
[28] Leeson D, Mac Dowell N, Shah N, Petit C and Fennell P S A 2017 Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources *Int. J. Greenh. Gas Control* **61** 71–84
[29] Irlam L 2017 Global costs of carbon capture and storage *Glob. CCS Inst.*
[30] Fasihi M, Efimova O and Breyer C 2019 Techno-economic assessment of CO_2 direct air capture plants *J. Clean. Prod.* **224** 957–80
[31] The Fossil Fuel Non-Proliferation Treaty (available at: https://fossilfueltreaty.org)
[32] McKinsey 2022 The future of oil and gas is now: how companies can decarbonize (available at: www.mckinsey.com/industries/oil-and-gas/our-insights/the-future-is-now-how-oil-and-gas-companies-can-decarbonize)
[33] Huppmann D *et al* 2019 The messageix integrated assessment model and the ix modeling platform (ixmp): an open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development *Environ. Model. Softw.* **112** 143–56