

Upstream decarbonisation through a Carbon Takeback Obligation: an affordable backstop climate policy

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Abstract

In the absence of immediate, rapid, and unprecedented reduction in global demand for carbon-intensive energy and products, the capture and permanent storage of billions of tonnes of carbon dioxide (CO₂) annually will be needed before mid-century to meet Paris Agreement goals. Yet the focus on absolute emission reductions and cheaper, more temporary forms of carbon storage means that permanent CO₂ disposal remains starved of investment, currently deployed to capture only about 0.1% of global Energy and Industrial Process (EIP) emissions. This stored fraction, the percentage of fossil EIP emissions that are captured and permanently stored, must reach 100% to stop EIP emissions causing further global warming. Here we show that a cost-effective transition can occur by mandating an increasing stored fraction through a progressive Carbon Takeback Obligation (CTBO) on fossil carbon producers and importers. By emulating the behaviour of an Integrated Assessment Model (IAM) and employing conservative assumptions for the costs of permanent carbon storage, we show that projected economy-wide costs of a CTBO policy are comparable to the costs associated with achieving similarly ambitious climate goals in IAMs employing a global carbon price, or potentially lower if the perceived policy risk cost associated with a CTBO is lower than that associated with a politically-determined carbon price. Compared to a global carbon price, an upstream CTBO has advantages of simple governance, speed, and controllability: equivalent carbon prices under a CTBO are reliably capped by the cost of direct air capture and storage, by ensuring deployment keeps pace with continued fossil fuel use, reducing the risk of punitive carbon prices or more draconian measures being required to drive out the final tranche of emissions. When combined with measures to reduce CO₂ production in the near-term, a CTBO could deliver a viable pathway to achieving net zero emissions consistent with 1.5°C by mid-century.

CO₂ storage in ambitious mitigation scenarios

The IPCC's Special Report on a Global Warming of 1.5°C concluded that “reaching and sustaining net-zero global anthropogenic CO₂ emissions *and* declining net non-CO₂ radiative forcing would halt anthropogenic global warming on multi-decadal time scales”¹. Both conditions will need to be met around mid-century to achieve the more ambitious goal of the Paris Climate Agreement, to “pursue efforts to limit the temperature increase to 1.5°C”^{2–4}. All scenarios considered by the IPCC indicate that demand reduction and substitution with low- and zero-carbon energy sources alone will be insufficient. Limiting cumulative emissions of CO₂ to deliver these ambitious goals requires some level of active CO₂ capture paired with geological-timescale carbon storage (GCS), both to reduce hard-to-abate emissions and to remove excess CO₂ from the atmosphere¹.

However, despite the clear need for capture and removal of CO₂ paired with GCS, deployment of these technologies has been very slow. In 2019, only 19 large carbon capture and storage (CCS) projects operated globally, capturing and storing just 40 MtCO₂/yr⁵ and representing less than 0.1%

of global Energy and Industrial Process (EIP) emissions. CCS and carbon removal paired with GCS are still seen as relatively expensive means of reducing the near-term flow of CO₂ emissions to the atmosphere. By contrast, numerous studies⁶⁻⁸ find carbon storage to be essential to enabling a multi-decade transition away from CO₂ production for hard-to-abate industrial sectors. Even nations with high climate ambitions, such as Sweden or the UK, are struggling to follow the IAM-consistent 1.5-2°C-compliant pathways, with emissions trajectories still substantially greater than required and investment in CCS in particular behind schedule⁹.

GCS can involve the injection of supercritical CO₂ into subsurface geological formations with subsequent immobilisation¹⁰, the incorporation of CO₂ into mineralised forms in terrestrial or ocean contexts, or in principle any other process that stores CO₂ with a negligible risk of reversal to the atmosphere over millennia. GCS is required both for CCS on existing point source emitters (e.g. industrial processes or power plants) as well as for some forms of active removal of CO₂ from the atmosphere followed by permanent disposal (e.g. direct air capture with carbon storage). While some EIP emissions can be balanced in the short term with carbon removal from nature-based solutions (NbS), the capacity of NbS to contribute to the most ambitious peak warming goals is limited simply by the timescales involved¹¹, while global warming itself may turn many current biosphere carbon sinks into sources¹². Hence sustaining net zero global CO₂ emissions over a multi-decade period will require net zero or net negative EIP emissions without reliance on NbS. Recognising this fact simplifies the problem, since it allows us to focus exclusively on the challenge of achieving net zero for hard-to-abate EIP emissions using GCS. This is a necessary, if not entirely sufficient, condition for halting global warming.

The principle of progressively increasing the fraction of CO₂ produced by burning fossil fuels which is recaptured and stored through some form of producer obligation was first put forward in 2009¹³ and expanded towards a fully-fledged policy proposal in 2015 when it was advanced in draft UK legislation¹⁴. Concerns were raised at the time about the potential cost and implications for competitiveness, hence the importance of our results shown here regarding low costs in the early stages of implementation. The policy was more recently named the Carbon Takeback Obligation (CTBO)^{15,16} and is again garnering interest as a complementary supply-side policy option to demand-side measures¹⁶. This includes calls for dedicated “Carbon Storage Units” (CSUs) as the means of measuring compliance with a CTBO^{17,18}, as well as formal consideration by the governments of the UK¹⁹ and the Netherlands²⁰. However, no study has looked at the economic implications of a CTBO as either an alternative or a complement to the suite of conventionally-modelled climate policies.

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Box

The basis of a Carbon Takeback Obligation

The simplest way to implement a CTBO is at the point of extraction, targeting only 4 products: oil, gas, coal, and the limestone used for cement. Although there is a range of industrial and commercial uses for these nationally pooled commodities, not all of which involves combustion, the very small fraction of carbon which is not immediately emitted still cannot be considered stored over geological timescales. Therefore, a policy requiring the recapture and storage of an equivalent quantity of CO₂ as is in the originally extracted product offers a simple and practical solution.

Figure 1 shows the broad interactions of a CTBO when applied to a jurisdiction. The government produces and regulates a certificate system (green arrows) obliging extractors and importers of fossil

fuels to recapture and store a fraction of the CO₂ generated by their activities and embedded within their products. This stored fraction starts out small and rises so that by mid-21st century all of the CO₂ within their products is recaptured and geologically stored. Fulfilling this obligation means extractors and importers must pay for geological carbon storage (pink arrows). These additional costs are passed to consumers by embedding them in the products sold in the wider economy (red arrows). These costs reduce the willingness of consumers to invest in products containing fossil carbon, feeding back onto levels of CO₂ production.

Blue arrows show the flow of CO₂ through the system. CO₂ is extracted from the geosphere (in the form of carbon contained in oil, gas, coal, and the limestone used for cement), and sold on to the wider economy where it is either released as CO₂ emissions or recaptured and stored.

Initially, a small stored fraction means only a small amount of produced CO₂ is recaptured and stored (panel a). With intermediate stored fractions more CO₂ is recaptured and stored (panel b), while some is still emitted. These intermediate stored fractions mean a larger GCS industry has developed, and higher costs to consumers mean CO₂ production is reduced compared to panel a. In panel c the stored fraction reaches 100%, so all of the CO₂ extracted from the geosphere is returned to commensurate storage (and all produced CO₂ flows into GCS via point source CCS or DAC). Embedded costs in products containing CO₂ result in even lower levels of CO₂ production, but because the CTBO is based on an intensity target (stored fraction of CO₂ produced), absolute production levels are discovered by the market, not limited by emission quotas.

[FIGURE 1 HERE]

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Here, we begin by analysing the portfolio of recent socio-techno-economic IAM models (shown in figure 2). These already predict their own rates of CO₂ production and GCS by means of an externally imposed carbon price, with additional constraints applied to the build rates for the necessary energy system and carbon management infrastructure. We recognise there are many instruments other than carbon pricing applied in real world mitigation policy, but carbon pricing remains the “first best” policy of choice in the integrated modelling community and a proxy for the “effective” carbon price of other policy options. Therefore, it is the benchmark with which we compare the CTBO policy in this setting. The carbon price represents the aggregate cost per tonne of CO₂ produced over a range of applied policies, including technology support and regulatory instruments. We produce scenarios in which the imposition of a CTBO creates a mandate to store carbon and is the primary driver of the rate of GCS, and consider how this could be used in isolation, or with supplementary policies, to achieve net-zero CO₂ emissions the mid-21st century, to focus on emissions pathways consistent with the long-term temperature goal of the Paris Agreement.

[FIGURE 2 HERE]

Figure 2a shows net EIP emissions to the atmosphere in “cost-effective” global IAM scenarios that meet the Paris goals through the imposition of demand-side measures represented by a global carbon price^{21,22}. Cost-effective here means all technologies are allowed to be deployed in the IAM subject to exogenous constraints on deployment rates such as availability of materials, and no mitigation options are excluded *a priori*. Global EIP emissions in scenarios that limit warming to 1.5°C (dark blue; SSPX-19) or well below 2°C (light blue, SSPX-26) decline to reach net zero either by mid-century or before 2100, respectively. Thicker lines highlight SSP2-19 and SSP2-26 scenarios from the MESSAGE-GLOBIOM IAM used further in our analysis, while the thick grey line shows a ~3°C “current

policies” scenario (SSP2-45). Red and gold lines show two idealised scenarios which incorporate a global Carbon Takeback Obligation (CTBO), discussed below.

Figure 2b presents annual CO₂ production (i.e. both CO₂ emitted to the atmosphere plus CO₂ that is stored rather than emitted), showing that significant quantities of CO₂ continue to be produced from fossil sources even as emissions decline to net zero in these IAM scenarios, much of this in “hard-to-abate” sectors, including aviation, marine shipping, steel and cement production, and load-balancing in power grids²³. Net zero emissions to the atmosphere are achieved by a combination of absolute reductions in produced CO₂ complemented by progressively balancing residual CO₂ production with GCS (figure 2c). Scenarios that explicitly exclude or minimise reliance on GCS^{24,25} have shown it is possible to limit warming to 1.5°C without GCS, but only through some combination of unprecedented consumer behaviour changes and technological innovation, potentially leveraged at sensitive intervention points in the socio-economic system²⁶. Both solutions are difficult to evaluate in traditional IAM models due to the inherent complexity of such dynamic processes. However, even models built explicitly to evaluate endogenous technological innovation have demonstrated the need for a “backstop” option in “hard-to-abate” sectors²⁷, particularly if such technological progress or consumer behaviour changes fail to materialise²⁸.

Figure 2d suggests a form this backstop might take. Blue lines present the IAM scenarios, plotting the fraction of total EIP CO₂ production that is stored permanently (the ratio $2c/2b^{29}$). This stored fraction has a similar shape across almost all 1.5°C scenarios, rising approximately quadratically to 100% by the date of net zero²⁹, and ultimately above 100% where models choose to employ net-negative CO₂ emissions. This shape is an observed result across IAMs, due to the carbon price escalation and Marginal Abatement Cost (MAC) curves they assume, rather than an exogenously imposed requirement. However, it makes intuitive sense: since the stored fraction is currently close to zero and not increasing significantly, a quadratic increase provides a smooth pathway to 100% (re)capture and storage, which is required for net zero EIP emissions by definition. The well-below-2°C scenarios show more degrees of freedom, but many also conform to this generic quadratic pathway. The red line shows a stylised scenario in which the stored fraction increases quadratically by construction, following the same pattern observed in the IAM results, but in which the stored fraction is itself the driver of decarbonisation, mandated by through a supply-side policy called a Carbon Takeback Obligation (CTBO), described next.

Carbon Takeback: from “polluter pays” to “producer responsibility”

To a good approximation, CO₂-induced warming is proportional to the total stock of carbon dioxide emitted into the atmosphere^{30–32}, minus that which is actively removed and stored. Demand-side policies such as conventional carbon pricing are designed to reduce the flow of emissions to the atmosphere but are less well-suited to limit the total stock that accumulates there. This is partly because they contain no direct link between emissions pricing and storage costs. In most IAMs, GCS is deployed at scale (represented by a combination of CCS and bioenergy with CCS, or BECCS), at a predictable cost, and with presumed public consent, all in response to increasing global carbon prices; hence the relatively smooth increase in the stored fraction in the blue lines in figure 2d. But these IAMs are intended to be cost-optimised over the entire century given the carbon price trajectory applied, with deployment at any point in time perfectly accounting for future carbon prices. There is no guarantee that such orderly deployment will take place in reality.

Additionally, perfect foresight means that IAMs only deploy GCS after exhausting all cheaper mitigation options. While this may be the “first best” policy option, it means that GCS is deployed

sufficiently late that IAMs are restricted by build-rate constraints on the one hand and the climate constraint on the other. Figure 3 demonstrates this behaviour in MESSAGE-GLOBIOM, where SSP2-19 and SSP2-26 scenarios deploy near identical GCS capacity by 2050 despite SSP2-19's approximately 10-fold higher carbon price. Consequently, in the highest ambition scenarios carbon prices rise well beyond the estimated cost of DAC+GCS to guarantee CO₂ production is restricted to levels which can be covered by the deployed GCS capacity in the mid-century. Figure 4 plots the relationship between 2050 carbon price and 2050 CO₂ emissions across a range of IAMs, showing that carbon prices rise to around \$1000/tCO₂ across a range of IAMs in order to achieve net-zero CO₂ emissions, evidence that GCS capacity has failed to keep pace with demand resulting in even more expensive measures than DAC+CCS needing to be deployed. It is likely carbon prices of this magnitude would prove politically challenging to implement.

Figure 2d indicates that 11% of EIP CO₂ production should be geologically stored by 2030 on a smooth, quadratic pathway to net zero by 2050. No country, even those with net zero targets by mid-century, explicitly report this permanently stored fraction in their Inventory Reports or Nationally Determined Contributions to the UNFCCC¹⁷, so, unsurprisingly, current planned carbon storage infrastructure deployment is not on track to achieve the scale of GCS required in the Paris-aligned IAM scenarios. The UK, for example, will achieve a stored fraction of only 1-2% of current CO₂ production (3-6 MtCO₂/yr) by 2030 if it follows its current ambition, which is set by a policy ceiling of two pilot CCS projects capturing from industry. Independent statutory advisers to the UK government recommend GCS of at least 10MtCO₂/yr by 2030⁶, increasing to at least 75-175 Mt/yr CO₂ stored by 2050 in order to achieve net zero EIP emissions¹⁷, although they also note that the quantity captured in 2030 will have to be much larger than this if we are to remain on track to achieve net-zero by 2050. From a global perspective, GCS needs to be operating at a very large industrial scale by 2030 to have any prospect of reaching the levels in 2050 required in IAM modelling to hold warming below 1.5°C²².

All current GCS projects depend to some degree on the taxpayer, whether through direct procurement, subsidies, or tax-breaks. While such incentives are necessary for first-of-a-kind investments, a transition plan to a sustainable financing model must be built in from the start to maintain confidence on all sides and avoid perverse incentives and “subsidy lock-in”. Everyone involved in the production and emission of CO₂ from fossil sources is depleting the total remaining stock that can be emitted to the atmosphere before breaching agreed warming thresholds. Hence producers, consumers and governments all have a collective responsibility to contribute to the development of GCS to ensure a smooth transition to net zero emissions as that stock is exhausted, although not all parties have equal opportunity, or equal responsibility. Governments can only spend money collected from citizens through taxation, while producers will pass rising operating costs onto their consumers. Given this, the question arises as to which consumers, or citizens, should support the investment in GCS?

Noting that one of the dominant beneficiaries of successful GCS development are the owners of fossil fuel assets, a simple way of discharging this GCS responsibility, that could be made consistent with the “polluter-pays principle”³³, is the Carbon Takeback Obligation[†]. Under a CTBO, primary extractors and, in a sub-global regime, importers of fossil carbon (including non-fuel sources such as limestone) are required to demonstrate permanent storage of a progressively increasing fraction of the CO₂ contained within the fossil carbon they extract or import. For hydrocarbons such as natural gas or oil, the denominator in the stored fraction is simply the stoichiometric conversion of those

[†] Alternatively referred to as a Carbon Storage Obligation (CSO), and previously as “mandatory sequestration” facilitated by “CCS certificates”

hydrocarbons into CO₂ terms. This fraction starts at a low and manageable level (e.g. 1%) and increases smoothly to 100%, ensuring net zero EIP CO₂ emissions, by a specified target date. The stored fraction in mid-century can continue beyond 100% to support net CO₂ removal³⁴. Storage conducted to meet the Obligation is quantised into “Carbon Storage Units” (CSUs), certificates which each represent one ton of permanently stored CO₂^{17,18}. Obligated entities (e.g. fossil fuel and cement companies) can generate CSUs themselves by storing their own or someone else’s CO₂, or can purchase them from other entities who produce CSUs for the purpose of sale. The only restriction (very important particularly in early stages) is that CSUs can only be generated by storage of CO₂ that would otherwise, under normal business practice, have ended up in the atmosphere (this is required to prevent mining or production of CO₂ purely to generate CSUs). This serves as the basis for a liquid market for CSUs that enables competition and price discovery among storage providers.

To be commensurate with the climate impact of CO₂ emissions, permanent storage must be interpreted as securing captured CO₂ in reservoirs with lifetimes greater than 10,000 years, a standard that is currently met only by GCS or alkaline metal remineralisation pathways³⁵. Storing carbon in less permanent stocks with a higher risk of reversal (e.g., vegetation and soils) could accomplish the same goal if every instance of physical reversal of stored carbon into the atmosphere were immediately remediated with commensurate storage. For the purposes of this analysis, we ignore this possibility for two reasons: 1) requiring very low-risk storage upfront reduces the need for multi-century compliance mechanisms, which are impossible to implement in an economic environment in which companies exist for less than two decades on average, and 2) a key purpose of the CTBO is to provide sustained, predictable support for a set of storage techniques that need early support. The possibility of mixing higher and lower risk storage in the context of a net zero-aligned voluntary carbon credit product is beyond the scope of this paper, but has been discussed elsewhere³⁶.

If applied across an entire jurisdiction, the cost of a CTBO would be shared among producers and consumers of carbon-intensive products, as well as by governments who could opt to divert some of the substantial profits they reap from taxing oil and gas rents toward decarbonisation enabled by a CTBO. Finally, we note that the CTBO offers several advantages when implemented as a complement to conventional climate policies, including low administrative costs (most data required, for example the location, capacity and leakage security of disused oil and gas wells, is already collected by fossil fuel producers) and higher certainty of abatement outcomes thanks to clear upstream monitoring. There are also socio-political advantages, such as the uniformity a regulatory instrument such as the CTBO provides, and the promise of harnessing the oil and gas sector as a participant rather than opponent of climate action, on the one hand, and holding them to account for the emissions associated with the products they sell, on the other^{29,37–39}.

To calculate a net-zero-compliant CTBO pathway, it is necessary to know only the date of adoption of the policy, the date by which net zero is to be achieved, and the shape of the stored fraction profile between these two points. This minimises subjectivity, maximises transparency, and makes it simple to explain, monitor and enforce. The red line in Figure 2d shows a quadratic increase from 0% in 2020 to 100% by 2050, consistent with the shape of the IAM 1.5°C scenarios, reaching 11% by 2030 and 44% by 2040. The 1.5°C IAM scenarios show a quadratically-increasing stored fraction as a *result* of demand-side climate measures. This result is by no means guaranteed and looks increasingly unlikely because policy uncertainty, perceived high costs, and lack of public acceptability have discouraged early investment in GCS⁴⁰. In contrast, the CTBO pathway uses a similar pathway as a *driver* of producer behaviour to ensure that the desired outcome—net zero EIP emissions around 2050—is achieved. A more convex profile would back-load the burden of GCS deployment onto later decades,

raising questions of temporal equity. Despite this concern, our conclusions are broadly robust to the adoption of a cubic profile for the stored fraction, which would correspond to a scenario in which a quadratic CTBO is applied to a linearly increasing fraction of global fossil carbon use, only reaching 100% in 2050 (see Supp. Info. Figure. S1). The behaviour of the stored fraction post-2050 is subject to additional policy decisions we do not explore here. Purely for simplicity, we hold the stored fraction at 100% after 2050, effectively capping cumulative CO₂ emissions beyond this point, and excluding the use of CCS to produce net negative CO₂ emissions in the second half of the 21st century.

Initially, a CTBO could be introduced in a single country or trading bloc, levied and discharged most efficiently on those very few organisations owning fossil carbon at the point of extraction or import into that jurisdiction. Multiple CTBO-implementing regions could join together and move toward a global CTBO, creating a growing international fossil fuel sub-market that requires that exported fuels be “CTBO-compliant” (associated with the right number of CSUs) as a condition for trading, for example, within commodities markets. If imposed on all extractors and importers of fossil fuels, the total costs of CO₂ disposal relative to revenues are initially small (because the stored fraction starts small) and can be passed downstream to consumers, limiting impact on competition and the threat of carbon leakage. Unlike carbon taxes and other levies aimed at changing consumer behaviour, however, there is a transparent link between a CTBO and achieving net zero emissions. In the absence of moratoria on fossil fuel extraction and/or use, both of which appear unlikely at a global scale, or a prohibitively expensive taxpayer-funded CO₂ removal programme³⁴, a CTBO is the only way of guaranteeing that we stop fossil fuels from causing global warming, and hence one of the only ways of any jurisdiction permanently “ending its contribution to global warming”⁴¹.

This type of obligation, a form of Extended Producer Responsibility, has precedent, for example with the Waste Electrical and Electronic Equipment (WEEE) Directive in the EU⁴², and the California Low-Carbon Fuel Standard (LCFS) in the US⁴³. A CTBO may be thought of as requiring vendors of fossil carbon to dispose of the unwanted CO₂ “packaging” that accompanies the energy they sell, or applying a LCFS at the point of extraction or import to (virtually) decarbonise fossil fuels themselves⁴⁴. Crucially, under a CTBO, producers would be first reducing and eventually eliminating the emissions generated by the products they sell (Scope 3 emissions in the Greenhouse Gas Protocol)⁴⁵, going beyond just their direct emissions from owned, controlled or purchased sources (Scope 1 & 2, already covered in some jurisdictions by conventional demand-side carbon pricing). Some fossil fuel companies, predominately in Europe, have begun to set aspirational net zero targets that, for the first time, encompass the carbon content of their products¹³. A regulatory CTBO framework would create a level playing field among suppliers to the region implementing it, allowing companies to invest in GCS without putting themselves at a competitive disadvantage against one another. Consider the recent ruling against Royal Dutch Shell⁴⁶ mandating a 45% cut in total Scope 1, 2, and 3 emissions by 2030. If Shell has no market into which it can sell a 45% decarbonised product and compete with other fossil fuel companies who are not subject to such a ruling it will be forced to sell off fossil fuel assets to un-obliged companies who can continue to extract. This may therefore have no effect on cumulative fossil fuel production and therefore a very low climate impact. In contrast, with a CTBO in place in one or more countries, Shell would have a pathway to produce a product that is compliant with both the Hague ruling and the CTBO. All other suppliers would be subject to the same CTBO requirement, placing Shell on a level playing field and (as a potential producer of CSUs) perhaps even at an advantage.

A fossil fuel extractor within a CTBO-implementing region that both supplies fuel to the region and exports it to non-CTBO-implementing regions could be at a disadvantage relative to non-obliged operators from other regions. The region implementing the CTBO would need to decide whether

export waivers were appropriate to allow continued competitive export without the purchase of CSUs. Additionally, the CTBO can be applied flexibly alongside other policies, or equally used to target mitigation on a subset of sectors in the wider economy. A CTBO could be applied across a nation's energy production and domestic transport sectors, while in hard-to-abate sectors taxpayer-funded CCS is used instead of, or alongside, the CTBO. This may happen if, for example, a government decides taxpayers as a whole are best placed to fund CCS for a particular industry, or that additional CCS capacity, paid for by the taxpayer, should be used to offset historical CO₂ emissions.

A crucial feature of the CTBO is that it does not itself prescribe the rate of CO₂ production, only the fraction of that production that is stored. It is therefore an intensity target, which are generally more acceptable to developing countries than absolute emission caps, potentially improving the prospects for wider participation in a CTBO than in any global cap-and-trade regime. Note that in the original proposal for a "sequestration mandate", it was proposed that the stored fraction be driven directly by cumulative emissions or warming rather than a fixed timetable⁴⁷. This would have the effect of strictly limiting cumulative emissions of CO₂ and acting as a "recursive intensity target" that punishes faster exhaustion of the carbon budget with a more rapidly increasing stored fraction. In our model we adopt the more recent, simpler formulation of a CTBO in which the stored fraction escalates predictably toward 100% by a predetermined net zero date. This results in large-scale capture and geological storage of CO₂, at a cost discovered by competition between storage providers, ultimately paid for by fossil fuel consumers and impacting the global economy. In a similar way to a global carbon price, the imposition of a CTBO affects the willingness of society to continue producing CO₂ and would have profound effects on the economy, which we consider below.

Simulating the economic impact of a global CTBO policy

In this section we simulate the CTBO policy and compare to a set of 1.5°C-compliant IAM runs driven by a global carbon price. The simulated policy incentivises the development of a CO₂ storage industry through the use of tradeable storage certificates, which can be purchased to discharge the obligation. We assume safeguards are imposed to ensure that CO₂ is not generated purely for the purpose of generating such certificates⁴⁸. Simulating the CTBO requires forward cost assumptions for capturing and permanently storing CO₂. This total cost to capture, transport and store one tonne is modelled as shown in Figure 2e and described in more detail in the Methods: crucially, we account for uncertainty in DACCS costs, with a conservative upper bound of \$600/tCO₂ that is higher even than DACCS costs for small volumes today. Although the costs of individual capture, removal, and GCS technology options are likely to drop over time through technological improvements and increased adoption, we assume that the dominant effect over the next 30 years will be a transition from cheaper, high-purity point-source capture options toward ever more diffuse streams of CO₂. As an increasing percentage of remaining emission point sources have been equipped with capture technology, reliance would necessarily shift toward direct removal of CO₂ from the atmosphere including with DAC+GCS (DACCS), mineralisation, and other removal options that employ GCS. The CTBO enforces a specific outcome, at scale permanent storage of CO₂, earlier than the assumptions that drive IAMs would otherwise simulate. In its simplest form, the CTBO is agnostic to the source of CO₂ (avoided emissions from existing facilities versus removed carbon from the atmosphere) and to the type of permanent storage, referred to as "GCS" throughout this paper, provided that storage is secure across geological timescales. It also provides implicit support to all capture technologies (including some carbon removal, or negative emissions technologies, like BECCS and DACCS) that rely on permanent geological storage of CO₂, since it spurs the development of an at-scale, open-source storage infrastructure to generate CSUs. If a policy designer were intent on providing a specific incentive for negative emissions technologies like DACCS in earlier years to help bring costs down

through learning, it would be possible to further specify that an increasing portion of the stored fraction be delivered by specific technologies, much as renewable portfolio standards in the US mandated specific technology choices among renewable energy options. The red plume in Figure 2e shows the evolution of the CTBO compliance cost per tonne of EIP CO₂ produced, assuming the cost of compliance is simply added to the relatively low global carbon prices of the “current policies” SSP2-45 scenario.

To quantify its overall impact, we need to assess the impact of this CTBO compliance cost on consumption. We construct and employ an emulator for the MESSAGE-GLOBIOM IAM to replicate the IAM’s response to a rising carbon price. The emulator takes advantage of the fact that gross EIP fossil CO₂ production in the MESSAGE-GLOBIOM IAM responds to an exponentially rising carbon price following a sigmoid MAC curve (see Methods). Note that the response of net EIP CO₂ emissions to a rising carbon price in MESSAGE-GLOBIOM is more complex because the rate of deployment of GCS appears to be exogenously constrained, being almost identical in both SSP2-19 and SSP2-26 scenarios despite their very different carbon prices.

We apply this emulator to a scenario under which this stylised CTBO policy is implemented on top of the SSP2-45 scenario; this CTBO scenario is shown in red in all panels of Figure 2. An efficient system of tradeable certificates ensures this cost is passed on to all fossil fuel users, hence acting like a global carbon price. In effect, we are comparing the impact of a CTBO that is assumed to be *additional* to current climate policies (which without a CTBO may deliver warming in excess of 3°C) with the impact of the more stringent climate policies required to keep peak warming below 1.5°C or 2°C. Gross CO₂ production under the CTBO (red plume in Figure 2b) falls to 12-26 GtCO₂/year by the time global net zero emissions are reached in 2050, which is comparable to although at the higher end of CO₂ production rates under ambitious IAM carbon pricing measures. Unlike MESSAGE-GLOBIOM, we do not impose any exogenous constraints on GCS deployment rates in the CTBO scenario: we believe this is fair, because these constraints are very poorly known and depend as much on “soft” constraints such as public acceptability and licensing conditions as on “hard” constraints such as availability of materials. We believe it is reasonable to assume that the fossil fuel industry would overcome constraints on GCS deployment much faster if required to do so to retain its license to operate under a CTBO regime than if incentivised to do so through uncertain public subsidies (as now) or a rising carbon price (as in the MESSAGE-GLOBIOM IAM).

The emulator is trained to reflect the MAC curve properties in the MESSAGE-GLOBIOM IAM, so this relatively high mid-century CO₂ production rate reflects the willingness of this IAM to continue CO₂ production even when carbon prices approach or exceed estimates of the cost of at-scale DACCS. These assumptions would change with alternate DAC cost or MAC curve estimates. After 2050, slowly increasing the assumed costs of full-chain capture, transport, and permanent storage (reflecting the need to shift away from point source CCS toward removal from the atmosphere) results in approximately constant CO₂ production and storage rates. Many scenarios would be possible for this post-2050 period, including, for example, constant or increased fossil fuel production should full chain GCS costs fall, and policymakers fail to limit absolute production through other means, or a scenario in which remaining fossil fuel producers must store *more* than 100% of the CO₂ generated by their products to compensate for past warming. However, this period is not the focus here.

Initially, abatement in the red CTBO scenario is low (see red line in Figure 2c); a result of a low carbon price in SSP2-45 and the smaller stored fraction between 2020 and 2035. By the late-2030s CO₂ emissions are driven down to below levels in well-below-2°C scenarios (light blue) through a combination of an increasing stored fraction and a CTBO compliance cost comparable to SSP2-26

carbon prices. The spread of the red plumes indicates the impact of the range of cost assumptions for full chain capture, transport, and GCS. In all panels, the dotted red boundary corresponds to higher costs and the solid red boundary corresponds to lower costs. Figure 2c shows how the implementation of a CTBO results in a more rapid scale-up of the CO₂ storage rate (and associated storage capacity) in the 2030s relative to SSP model runs, even for the higher full chain capture and GCS cost assumptions. The build rate of CCS in the CTBO is vast, but never exceeds double the range of build rates across the range of IAM scenarios. The upper end of the CTBO build rate range represents a revolutionary shift for the fossil fuel industry, but no more so than the innovation required to achieve the no-CCS scenarios suggested in refs. 24,25.

The total cost of the CTBO policy is a combination of the direct implementation cost of capturing and permanently storing CO₂ to comply with the CTBO, and the economic impact that this cost will have on the global economy relative to business as usual (SSP2-45), measured as the integrated area under the MAC curve. This combined cost is shown in figure 2f, together with estimated costs for the “1.5°C” (SSP2-19) and “well-below-2°C” (SSP2-26) scenarios. The cost of a pure CTBO-based policy, which delivers net zero global EIP emissions by 2050, is comparable to the cost of the “1.5°C” (SSP2-19) scenarios driven by a global carbon price (dark blue), which achieve similar global policy ambition. This provides evidence that a “second-best” regulatory approach to achieving net zero emissions is not necessarily substantially more costly than a “cost effective” pathway driven by a global carbon price and might be significantly more politically feasible. Note all costs in Figure 2f are relative to our “current policies” (SSP2-45) baseline.

Cost of compliance with a CTBO policy is between 3-7% of projected global GDP in SSP2 scenarios at the time of net zero (with GDP estimates from ref. 7), consistent with the range of expected reductions in GDP under ambitious mitigation pathways designed by IAMs. We note that these estimates are not a perfect proxy for impact on GDP, recognising this would be a non-marginal macro-economic transition, we would expect many positive and negative impacts on GDP which have not been captured in this estimate of the policy cost. For example, if a CTBO as an imposition on an industry proved more politically acceptable than high carbon prices, it may result in very different GDP outcomes, even though the nominal policy cost is similar.

Near term emissions decrease

Exclusive reliance on a CTBO, however, fails to bring emissions down in the short term (2020-2035), as the stored fraction is relatively small and the CTBO compliance cost correspondingly low, leading to higher cumulative net emissions by 2050. While this would only result in an additional 0.1-0.2°C warming by mid-century, it also risks “lock-in” of high-carbon infrastructure and behaviours over this initial period, leading to potential resistance to the CTBO later on. Initial mitigation efforts can be increased by applying additional measures, simulated in IAMs as a global carbon price, to supplement the CTBO policy. To illustrate this, the gold plumes apply a CTBO alongside such additional economy-wide measures to incentivise short-term emissions reductions. The emissions reductions incentives adopted for this gold scenario are at the same level as the incentives imposed in 2020 in the MESSAGE-GLOBIOM SSP2-19 scenario (applying economy-wide demand side policy instruments equivalent to an effective carbon price of \$110/tCO₂). However, unlike the MESSAGE-GLOBIOM scenario they are represented by an effective carbon price that remains constant throughout the century instead of rising exponentially, and hence the real impact of these demand-side measures declines exponentially as the economy grows and the CTBO takes effect. This results in a CTBO applied to upstream fossil fuel extractors and importers, and a downstream conventional carbon price on emitters, much as California imposes both a Low Carbon Fuel Standard on suppliers and cap-

and-trade scheme on consumers for the same transport fuel. With this joint policy, CO₂ production is reduced more rapidly in the first decade, meaning the policy is now equivalent in ambition to the “1.5°C” scenario (SSP2-19) in terms of cumulative emissions to 2050. Reassuringly, the total policy costs for the red pure-CTBO scenario, gold CTBO+ scenario, and traditional SSPX-19/SSPX-26 scenarios are comparable, with no clear cost advantage offered by exclusive reliance on a global carbon price, exclusive reliance on a CTBO, or a mixed approach. Although based on the modelled relationships between global carbon prices and EIP CO₂ production in the MESSAGE-GLOBIOM model, these costs are of the same order of magnitude as the total policy cost (in comparison to SSPX-45) from a wide range of IAMs (thin blue lines). The gold CTBO+ scenario costs between 4.5-7.5% of SSP2’s projected GDP at the time of net zero⁷, slightly higher than the red CTBO scenario’s range (3-7%). Both are well within the range supported by IAM scenarios of equivalent policy ambition.

Exclusive reliance on a global carbon price carries risks: conventional mitigation scenarios consistently show carbon prices of about \$1,000/tCO₂ are required to achieve net zero emissions around mid-century (see Figure 4), which may be politically infeasible, despite the availability of DAC+GCS at a lower unit cost. The reason is that GCS deployment rates are exogenously limited. A CTBO policy provides the fossil fuel industry itself with the strongest possible incentive (survival) to overcome those limits. Hence supply-side incentives for CO₂ storage limits effective carbon prices to the cost of DAC+GCS, originally estimated at \$600 per tCO₂, and now estimated as achievable at scale for costs as low as \$200 per tCO₂ and perhaps significantly lower^{10,49}. If, as at present, deployment rates of CCS and engineered carbon removal fail to anticipate future carbon prices under conventional demand-side climate policies such as cap-and-trade, then these technologies will only be deployed when all cheaper methods of reducing emissions are exhausted, and hence may not be available at scale when needed, leading to a need for very high carbon prices to “drive out” the last emissions^{11,42}. Introducing a CTBO now eliminates the risk of carbon prices ever exceeding the cost of DAC+GCS, de-risking global climate policy.

Conclusions: The implications of a Carbon Takeback Obligation

The CTBO creates a new requirement that carbon extractors store CO₂ at a rate commensurate with ongoing extraction as part of their social license to operate. This creates a prohibition on CO₂ emissions, not by banning the use of fossil fuels, but instead by harmonising the need to stop net emissions of CO₂ in cases where the benefits of emitting CO₂ exceed the costs of GCS. This requirement is simple to enact by government, uses existing data, provides policy certainty for investors, creates a discovered carbon value rather than a politically-imposed price, and is transparent and agnostic to technology choices. The CTBO is also likely to gain popular acceptance by simultaneously targeting a small number of perceived polluters while also providing a plausible pathway for those same actors to credibly lead a net zero transition without selling off fossil fuel production assets to less scrupulous competitors.

The policy can be introduced unilaterally by a country or region to create a new GCS-enabled fossil carbon market protected by a carbon border adjustment and can be supported by a carbon price floor such as emissions trading or tax and dividend. It delivers two needed outcomes—early and critical support for GCS and a clear pathway to an enforced net zero emissions state—and opens the possibility of a third: comprehensively managing geological carbon stocks perhaps with net negative emissions to hold ourselves responsible for historical contributions to warming. A CTBO could be discharged alongside complementary demand-side policies on individual sectors and industries with hard-to-abate emissions. For example, a CTBO could regulate all CO₂ production except in the

aviation industry, where a taxpayer-funded CCS scheme might be deemed more appropriate. Equally, a CTBO could cover only part of aviation emissions, with another part covered by other regulation requiring a portion of airline fuel to be produced through carbon capture and utilisation technology.

We have shown that the combined costs of a CTBO (both compliance costs and the effects on the economy) can be comparable to, and in most cases less, than the cost of achieving similar objectives through traditional demand-side carbon pricing in IAMs. Note that we have used relatively conservative assumptions of the cost of capture and GCS. That said, exclusive reliance on a CTBO could result in increased near-term fossil fuel extraction and the lock-in of high-carbon infrastructure, resulting in higher peak warming and higher policy costs overall. Applying demand-side policy through this near-term period with a modest effective carbon price (around \$110/tCO₂ in this work) prevents this outcome, encouraging early reductions in CO₂ production before the CTBO stored fraction increases sufficiently. Demand-side policy can remain around this modest level, leaving the market to determine the tolerated level of CO₂ production based on the cost of discharging the CTBO at a given stored fraction.

All continued fossil fuel use that is not explicitly linked with a proven and scalable CO₂ storage capability contributes to the risk of a precipitous transition when the stock of CO₂ that can be emitted into the atmosphere without removal is exhausted. The unique value of the CTBO is to create a market for CO₂ storage, spreading the cost of reducing this transition risk over all current fossil fuel users through a straightforward regulatory framework. It can therefore be implemented alongside existing climate measures such as emission trading schemes and other forms of carbon pricing. A CTBO, combined with measures to reduce near-term CO₂ production, would deliver a viable and lower-risk pathway to achieving net zero emissions.

Methods

a. What carbon storage is permitted to discharge a Carbon Takeback Obligation

The CTBO is concerned exclusively with geological-timescale carbon storage (GCS). GCS is any instance in which the carbon is expected to persist in storage for upward of 10,000 years at a negligible to low risk of reversal. Methods include the injection of supercritical CO₂ into subsurface geological formations such as saline aquifers, where the CO₂ becomes physically and chemically immobilised over time^{10,50}. Other forms of GCS include incorporation of CO₂ into mineralised forms in terrestrial or ocean contexts, or in principle any other process that stores CO₂ with a negligible risk of reversal to the atmosphere over millennia. The representative emissions pathways drawn on by the IPCC Special Report on 1.5°C (SR15) conflate such CO₂ removal with one possible technology, bio-energy with carbon capture and storage (BECCS)⁵¹, whose disadvantages and hidden costs are well-documented,^{52,53} although recent work has expanded the range of biogenic carbon removal opportunities focusing particularly on waste biomass rather than virgin feedstock⁵⁴. In this paper, we are agnostic as to the possibility of large-scale BECCS deployment and focus instead on cost assumptions based on assumed initial CO₂ disposal from traditional CCS (point source capture of relatively high-purity CO₂ streams coupled with GCS), and subsequently through more expensive forms of removal paired with GCS (e.g. engineered Direct Air Capture with GCS, also known as DACCS). We also assume that the scope for balancing energy (in which we include transport) and industrial process (EIP) emissions with nature-based solutions (NbS) is limited, since 350-500 GtCO₂ of CO₂ uptake by 2100, which is at the higher end of estimates of NbS potential⁵⁵, may be required simply to offset continued degradation of the biosphere and carbon release from earth system feedbacks due to warming¹².

b. The use of SSP IAM emissions scenarios

The IIASA SSP database⁷ contains a number of variants of the SSPs as outputted by 5 IAMs (AIM/CGE, GCAM4, IMAGE, MESSAGE-GLOBIOM, REMIND-MAGPIE, WITCH-GLOBIOM), representing complementary narratives for societal evolution over the 21st century and climate policies of varying ambition²¹. In Figure 2 we show cost-effective scenarios which achieve 1.5°C- and 2.0°C-compliant mitigation pathways driven by a given global carbon price in these IAMs (blue and grey lines). We exclude scenarios that explicitly minimise the use of GCS by delivering climate goals through exogenously imposed measures such as consumer behaviour change, noting (as stated in ref. 24,25) “it is nearly impossible to put a price tag on most of these measures, [so] none of the scenarios [with these additional measures] has been evaluated in terms of costs”. CO₂ production in 2b excludes CO₂ generated by bioenergy (hence assuming this is captured contemporaneously — the scenarios *do* include fossil CO₂ associated with bioenergy production and transport), while CO₂ storage in 2c *does* include CO₂ stored from bioenergy. This storage of biogenic CO₂ is the main source of negative emissions from BECCS modelled in these IAMs. Taken together, CO₂ storage from conventional CCS and CO₂ storage from those carbon removal pathways that involve geological storage (e.g. DAC+GCS, BECCS) provides the net total rate of GCS. The stored fraction in 2d is simply the ratio of 2c to 2b²⁹.

[FIGURE 3 HERE]

Figure 3 shows timeseries of CCS deployed in a range of SSP scenarios. Despite the carbon price of the SSPX-19 scenarios rising to approximately 10 times higher than the SSPX-26 scenarios, the GCS (BECCS+CCS) capacity remains nearly identical between these two scenarios until mid-century (dark blue and light blue GCS build rates are near identical, reflecting additional “build-rate” constraints in the IAM and the “*attempt all cheaper mitigation options first*” attitude of a perfect foresight model.

[FIGURE 4 HERE]

A consequence of this discussed in the main text is that in 2050, instead of reflecting the cost of DAC+GCS, carbon prices must rise much higher to persuade consumers to reduce their CO₂ production to levels comparable with the built GCS capacity. This is shown in figure 4, where 2050 carbon prices are plotted against 2050 CO₂ emissions across a range of IAMs and scenarios. Fitting straight lines to these shows that in each SSP variant a carbon price around \$1000/tCO₂ is required to achieve net zero.

c. The equivalent carbon price in a global CTBO

IAM carbon prices in Figure 2e are taken directly from the SSP database. Figure S2 shows that an approximately straight-line relationship between 2050 carbon prices and 2050 EIP emissions emerges as climate policy ambition is varied under each of the SSP socio-economic scenarios when calculated with IAMs, with the SSPs ranked by global primary energy consumption over the century. Scenarios with higher primary energy consumption show higher emissions for carbon prices in the range of \$10-100 per tCO₂, but also greater sensitivity of emissions to carbon prices in 2050 (the slopes of the best-fit lines). They all suggest that carbon prices around \$1000/tCO₂ produced are required to reach net zero emissions.

If the initial objective of a CTBO is incentivising the development of a CO₂ storage industry to complement other climate change mitigation measures, then any CO₂ that would otherwise have

been emitted to the atmosphere could be used to generate a tradeable Carbon Storage Unit certificate to discharge a CTBO, with safeguards to ensure CO₂ is not generated purely for the purpose of generating such certificates⁵⁶. Hence, we assume an initial full chain cost range of $C_1 = \$40\text{-}60/\text{tCO}_2$ stored, representing the cheapest, high-purity CO₂ capture opportunities.^{10,57,58} By 2050, we assume that all remaining fossil fuel use and industrial process emissions result from non-stationary or diffuse applications like air travel for which capture at source is impractical. Therefore, the final cost by 2050 is assumed to be $C_2 = \$200\text{-}600/\text{tCO}_2$ stored, which reflects a range of plausible costs for DAC+GCS^{10,59} but could equally be a mix of other carbon removal and storage options that fall below that cost range, including enhanced weathering or (if consistent with other sustainability constraints) BECCS.

We use these cost assumptions to generate an equivalent carbon price implied by the CTBO policy. The full chain cost per tonne captured, transported and stored is modelled to increase linearly between C_1 and C_2 , giving a stylised cost of CTBO compliance $C(S) = S(C_1 + (C_2 - C_1)S)$ per tonne of CO₂ produced (the red plume in Figure 2e). Assuming an efficient system of tradable storage certificates (see refs. 15 & 60), an 11% stored fraction in 2030, for example, implies a CTBO compliance cost of only \$6-13 per tonne of CO₂ generated under these assumptions, because it is distributed over all fossil fuels used in a jurisdiction, not just those that are subject to capture. After 2050, we assume DAC+GCS costs continue to rise by \$5/tCO₂ per year to reflect increased scarcity of storage. This is deliberately conservative relative to other assumptions in the literature, and any projection of DAC+CCS costs on that timeframe is necessarily speculative.

d. Emulating the impact of implementing the CTBO

We employ the use of an IAM emulator to estimate the impacts of the CTBO on EIP emissions and the global economy. Gross EIP fossil CO₂ production $F(t)$ in the MESSAGE-GLOBIOM IAM (and, to a good approximation, other IAMs, see SI) is found to respond to an exponentially rising carbon price following a sigmoid Marginal Abatement Cost (MAC) Curve:

$$F(t) = \frac{F_0(t)A_{\max}}{1 + \left(\frac{P(t)}{P_{0.5}}\right)^{\frac{r}{s}}} \quad (1)$$

where $F_0(t)$ is baseline CO₂ production, A_{\max} is the maximum abatement rate (set by a mixture of technological limits and policy ambition), $P_{0.5}$ is the carbon price required to achieve an abatement rate of $A_{\max}/2$, r is the rate of exponential carbon price increase, and s is a transition rate from low to high abatement. With appropriate choices of parameters, this emulator captures the relationship between CO₂ production rates and carbon prices across a range of models and mitigation scenarios remarkably well (see SI figure S2). $P_{0.5}$ and A_{\max} are scenario-dependent, being higher for more ambitious scenarios, reflecting the increased cost of rapid decarbonisation ($P_{0.5}$) and the resulting higher maximum abatement rates (A_{\max}): when not following a single scenario, we interpolate using the imposed carbon price. CO₂ removals, by contrast, do not appear to respond to the rising carbon price in the same way in the MESSAGE-GLOBIOM IAM: this rate is almost identical up to 2050 in both the SSP2-19 and SSP2-26 scenarios despite a factor 5 difference in carbon price, with this rate being instead set by physical constraints on BECCS deployment rates that are exogenously imposed (assumed by the modellers).

e. Calculating the total cost of the CTBO policy

Each scenario's impact on GDP is found by integrating the area under the CO₂ production MAC curve, minus the area under the corresponding SSPX-45 MAC curve. We are using SSPX-45 as a proxy

“current policies” scenario under which emissions peak around 2030, remain stable to mid-century, and then decline but fail to reach net zero by 2100, leading to warming in 2100 of around 3°C and continued warming thereafter. Hence, we are comparing the impact of a CTBO that is assumed to be *additional* to current policies against the impact of the set of climate policies that are required to meet 1.5°C and below-2°C climate goals and are more stringent than those applied in SSPX-45. The total cost for each blue scenario is found by adding the calculated reduction in GDP due to CO₂ production reductions (calculated as the area underneath the CO₂ production MAC curve for each scenario) to the direct cost of full-chain capture and storage of CO₂. For consistency among scenarios we use the same GCS cost range and dependence with stored fraction as for the CTBO policy described above in methods section (c), and use the stored fraction shape for each scenario plotted in figure 2d.

For the CTBO, CO₂ production (calculated using the IAM emulator driven by the CTBO’s equivalent carbon price in Figure 2e) and CTBO stored fraction shape (Figure 2d) together determine the resulting net CO₂ emissions (Figure 2a) and rate of storage (Figure 2c). The total cost of the CTBO policy is calculated in the same way as for blue conventional IAM scenarios: the sum of direct implementation cost of the CTBO (cost of fulfilling the GCS obligation) and the cost associated with the CTBO’s impact on global GDP relative to the baseline SSPX-45 “current policies” scenario (area under the CO₂ production MAC curve).

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Author contributions

SJ and MRA conceived the study. SJ completed the study and produced the figures. SH and EML provided input on the implementation of GCS technologies and the design of the CTBO policy. MCI provided input on the economic analysis of a CTBO policy, and expertise on integrated assessment model scenario design. All authors contributed to the writing of the text.

Data availability statement

IAMC scenarios are available via the IIASA scenarios database webpage⁸. Information on the individual SSP scenarios used in this research is available in the IIASA SSP database⁵¹.

Code availability statement

All code necessary to reproduce the figures in this research is available upon request to the corresponding author.

Declaration of interests

The authors declare no competing interests.

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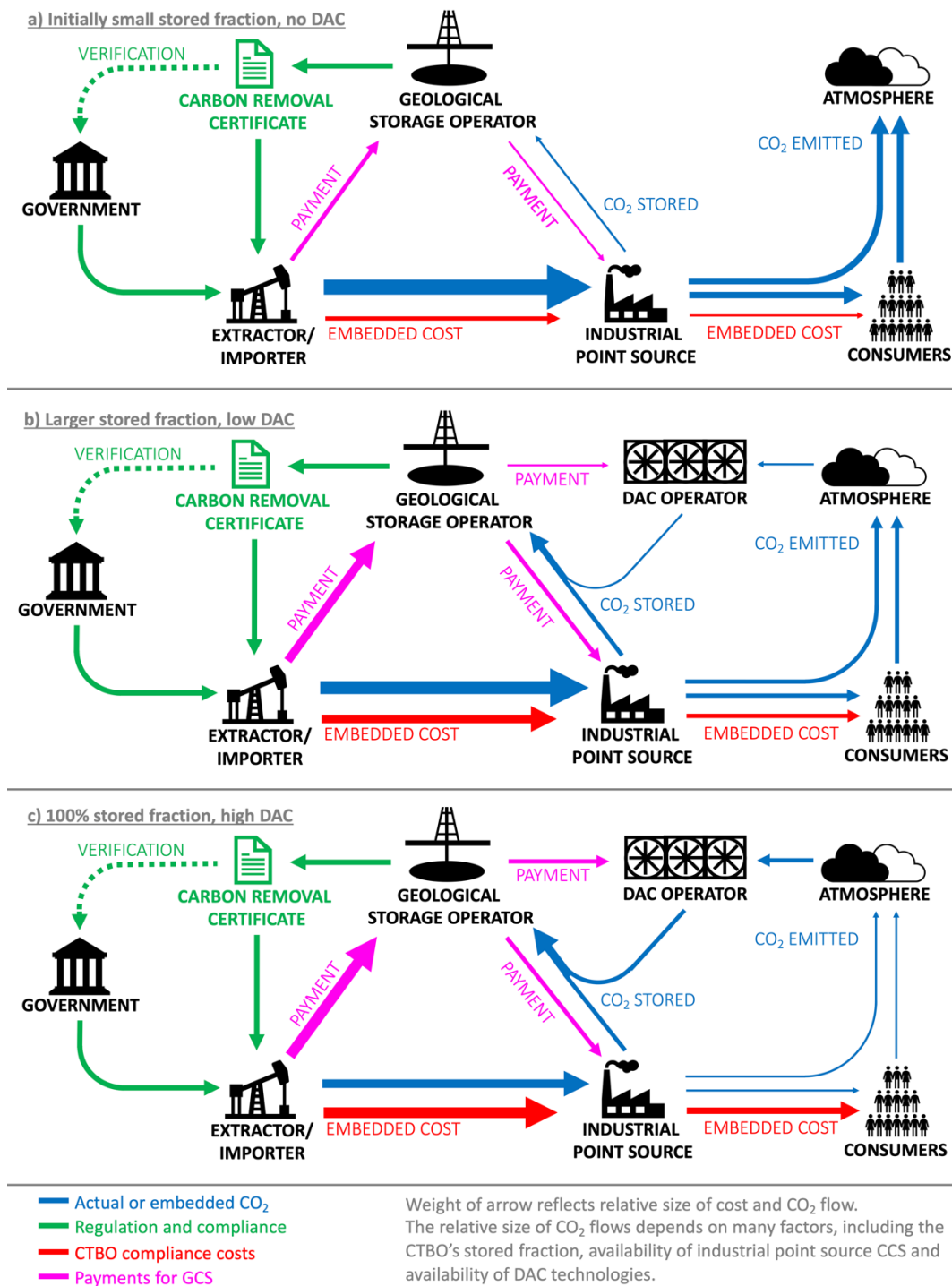


Figure 1: Pictorial description of a CTBO policy, applied with various stored fractions onto an extractor/importer in a jurisdiction. Actors are split into broad groups: Government, Extractor/Importer of fossil CO₂ products, Industrial Point Source, Consumers (who represent the wider economy), GCS Operators, and DAC Operators (with the atmosphere also represented as an additional actor). Arrows show the interactions introduced by a CTBO policy: green reflects regulatory and administrative interactions with Government, red demonstrates the direction of costs realised by fulfilling the CTBO, pink shows the direction of payments for GCS and from the storage operator to CO₂ suppliers, and blue shows the flow of CO₂ from the point of extraction/importation around the system. Panel a) shows a CTBO applied with a low stored fraction (e.g. 10%) and no DAC. Panel b) shows a CTBO applied with a 50% stored fraction some of which is supplied by DAC. Panel c) shows a CTBO applied with 100% stored fraction. The weight of arrows reflects the relative size of the flow (of costs, payments and CO₂). The overall quantity of CO₂ extracted/imported in the form of coal, oil, gas, and the limestone for cement is reduced as the stored fraction increases as a result of increased costs passed onto the consumer.

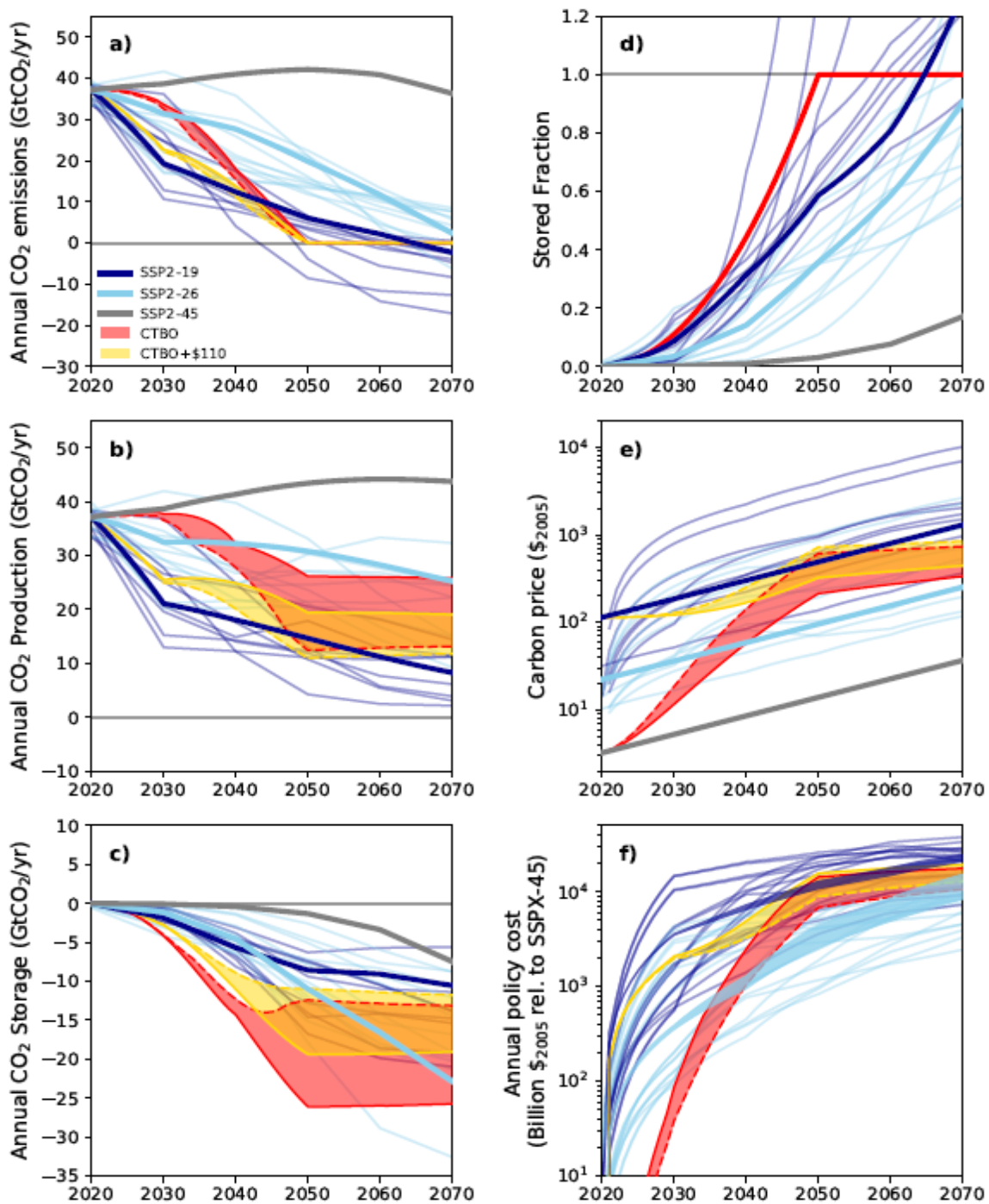


Figure 2: Comparing conventional mitigation scenarios with a global Carbon Takeback Obligation (CTBO). Thin blue lines show IAM scenarios plotted for multiple models and Shared Socioeconomic Pathways (SSPs) and two levels of climate ambition: SSPX-1.9 “1.5°C” (dark blue) and SSPX-2.6 “well-below 2°C” (light blue). Thick lines show the MESSAGE-GLOBIOM 1.0 scenario timeseries commuted with the carbon price/abatement rate emulator. A stylised CTBO policy is overlaid in red. Panel a plots the global annual Energy and Industrial Processes (EIP) net CO₂ emissions between 2020–2100 (GtCO₂/yr), which is the difference between gross annual EIP CO₂ production from fossil sources (b) and annual CO₂ storage (c). Note that panel c also includes storage from BECCS. Panel d plots the stored fraction, or the fraction of EIP CO₂ produced from fossil sources (b) that is stored using GCS (c) in each year. Panel e plots the carbon price driving the mitigation in the IAMs shown in panel a (\$2005), compared with the cost of compliance with the CTBO. Panel f shows the cost of each scenario (sum of reduction in GDP relative to the SSPX-4.5 used as a proxy for “current policies” scenario, plus the direct implementation cost of capture and storage). The yellow scenario shows an alternative CTBO policy, where as well as the CTBO compliance costs the model includes a constant carbon price equal to the 2020 carbon price in the MESSAGE-GLOBIOM SSP2-19 scenarios (\$110) over the entire period, resulting in cumulative emissions consistent with the SSP2-19 scenario at consistently similar or lower overall policy cost.

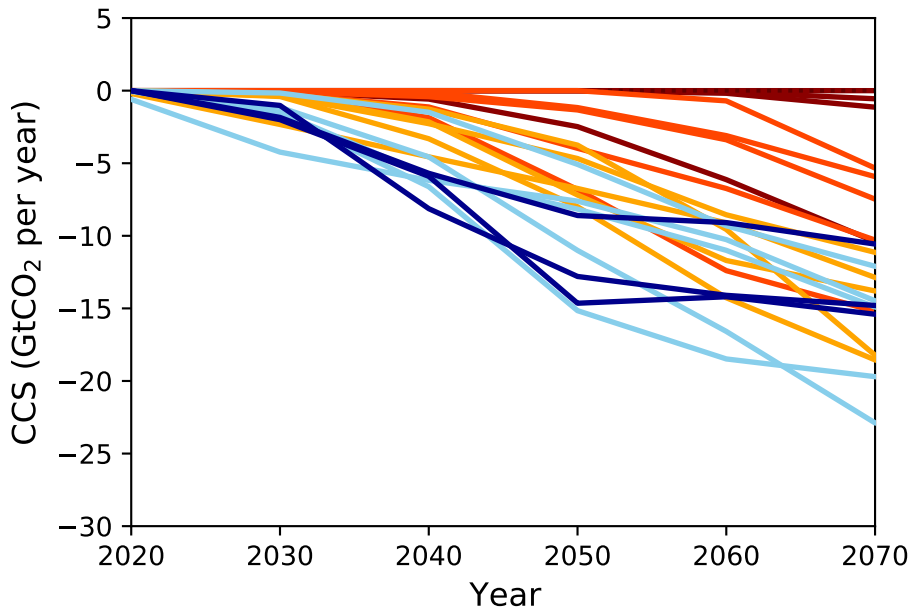


Figure 3: CCS deployment in SSP scenarios. Scenarios coloured by ambition (dark blue = SSP2-19, light blue = SSP2-26, orange = SSP2-45, red = SSP2-60, dark red = SSP2-85) covering all IAMs which provide CCS capacity outputs, building from 0 GtCO₂/yr in 2020. Note that CCS deployment rates up to 2050 are, with only one exception, similar in both SSP2-19 and SSP2-26 scenarios despite effective global carbon prices that can differ by an order of magnitude.

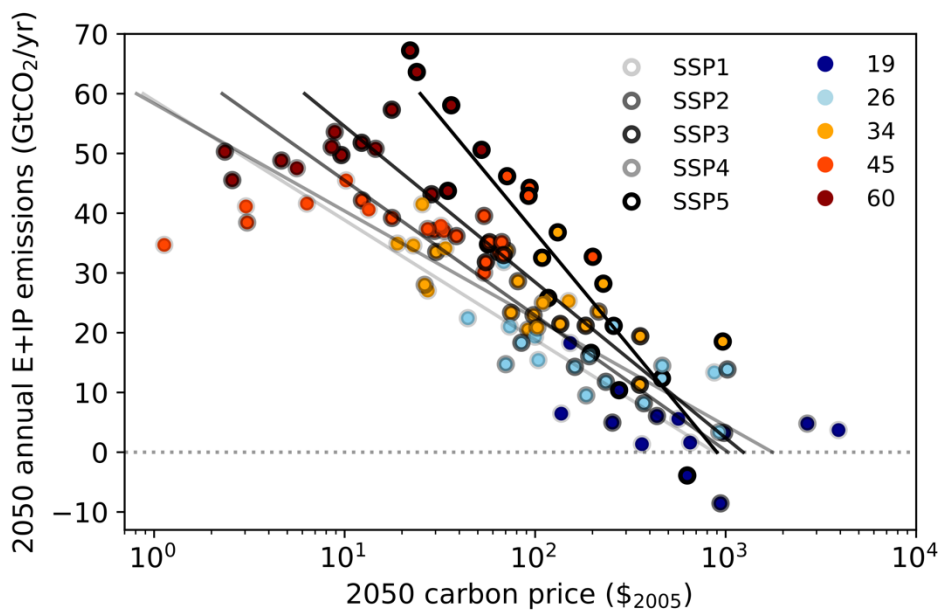


Figure 4: Relationship between 2050 EIP emissions and 2050 carbon price in a range of Shared Socioeconomic Pathways (SSPs, indicated by shade of grey circles) and climate ambition (1.9 to 6.0 W/m² in 2100, colours). Best-fit lines show that, independent of the SSP followed, achieving net zero emissions in 2050 requires a 2050 carbon price of approximately \$1,000 /tCO₂ (\$875-\$1800/tCO₂) in IAM scenarios driven by a global carbon price. Grey-scale circles show SSPs ordered by global primary energy consumption over the century: 1, 4, 2, 3, 5.