

# Fossil fuels in a trillion tonne world

Vivian Scott<sup>1\*</sup>, R. Stuart Haszeldine<sup>1</sup>, Simon F. B. Tett<sup>1</sup> and Andreas Oschlies<sup>2</sup>

**The useful energy services and energy density value of fossil carbon fuels could be retained for longer timescales into the future if their combustion is balanced by CO<sub>2</sub> recapture and storage. We assess the global balance between fossil carbon supply and the sufficiency (size) and capability (technology, security) of candidate carbon stores. A hierarchy of value for extraction-to-storage pairings is proposed, which is augmented by classification of CO<sub>2</sub> containment as temporary (<1,000 yr) or permanent (>100,000 yr). Using temporary stores is inefficient and defers an intergenerational problem. Permanent storage capacity is adequate to technically match current fossil fuel reserves. However, rates of storage creation cannot balance current and expected rates of fossil fuel extraction and CO<sub>2</sub> consequences. Extraction of conventional natural gas is uniquely holistic because it creates the capacity to re-inject an equivalent tonnage of carbon for storage into the same reservoir and can re-use gas-extraction infrastructure for storage. By contrast, balancing the extraction of coal, oil, biomass and unconventional fossil fuels requires the engineering and validation of additional carbon storage. Such storage is, so far, unproven in sufficiency.**

The 2014 IPCC Working Group II Report assesses, with high confidence, the risks of global aggregate impacts associated with global average temperature increase in excess of 2 °C to be high<sup>1</sup>. A temperature rise of 2 °C is consistent with the combustion and release of around 1 trillion tonnes of carbon (1,000 GtC)<sup>2</sup>. The 2013 IPCC Working Group I Report calculates the remaining global carbon budget from 2011 onwards consistent with the political goal of limiting global temperature rise to less than 2 °C to be 300 GtC, equivalent to the emission of 1,100 GtCO<sub>2</sub> (ref. 3). Current known and exploitable fossil fuel reserves are equivalent to 3,100 GtCO<sub>2</sub> (refs 4,5), three times greater than this cumulative emissions budget. A conservative estimate of the additional fossil carbon resource that could be extracted is 30–50 times greater (~45,000 GtCO<sub>2</sub>)<sup>5</sup>. Assigning a future value to fossil carbon is a rapidly emerging policy dilemma because the release limit is expected to be reached before 2050, well within the timescales of infrastructure (power and industrial plant) and financial (institutional investor) investment cycles. A debate has emerged about the assessments and implications of ‘unburnable’ fossil carbon reserves<sup>6,7</sup>, contrasted against fossil fuel industry statements of the low risk to their reserves and resource development strategies<sup>8,9</sup>.

Should the stated political intention to mitigate climate change be enacted, either the extraction of fossil carbon must be massively restricted with its expected energetic output replaced by other sources (reduced energy demand, renewable and nuclear energy generation), or the released carbon must be ‘permanently’ stored. The 2014 IPCC Working Group III finds that “mitigation policy could devalue fossil fuel assets” and that “availability of carbon capture and storage would reduce the adverse effect of mitigation on the value of fossil fuel assets”<sup>10</sup>.

The Earth system provides multiple options to engineer carbon storage of varying capacities and on different timescales. Here we undertake a global-scale assessment to consider the availability of storage, the rate at which storage can be engineered, and the security of storage to preserve climate and fossil fuel asset values. We also examine how the extraction of different types of fossil fuel creates, or requires, availability of secure storage capacity.

## Assessing carbon stocks and storage options

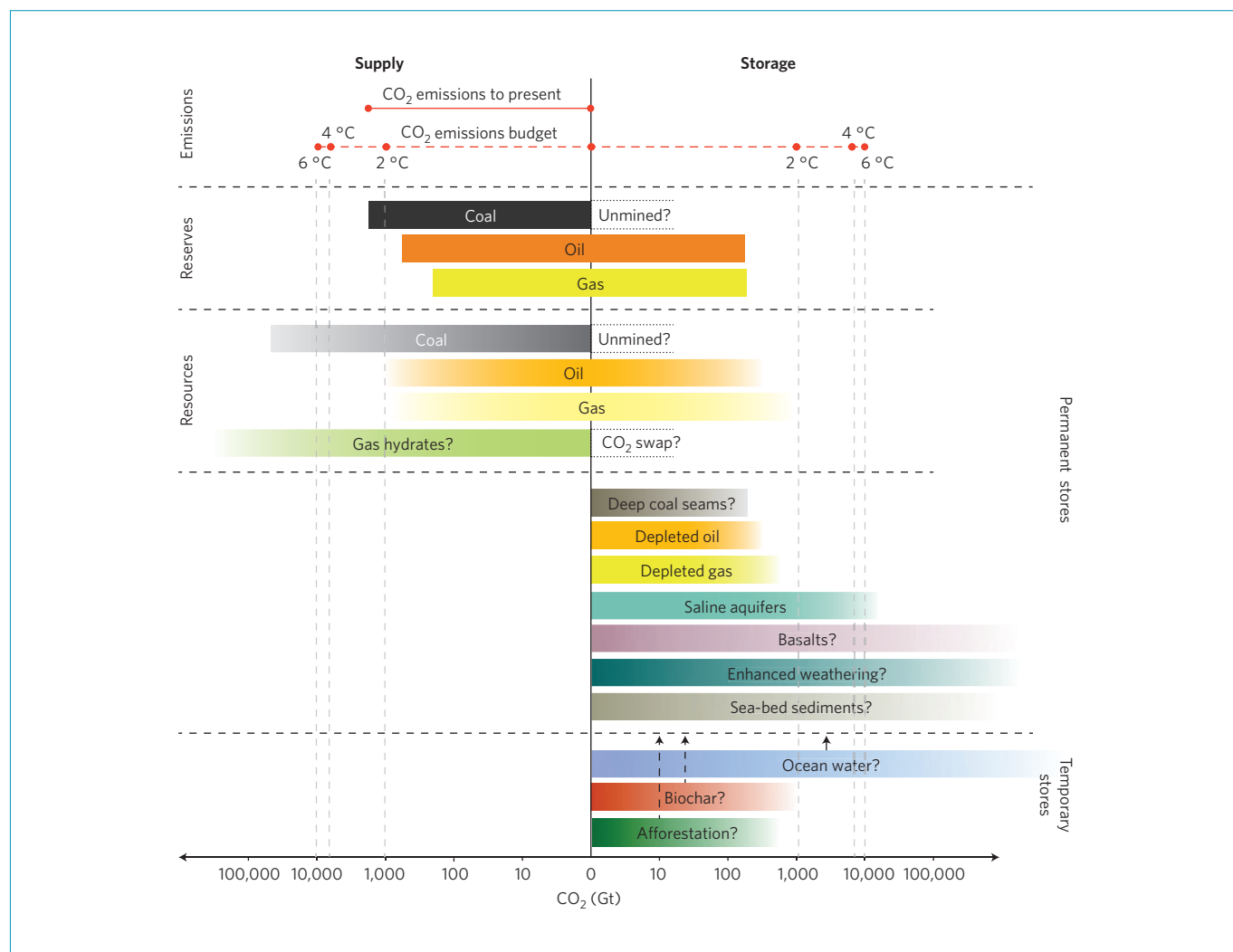
Figure 1 and Supplementary Table 1 assess supply stocks of global fossil carbon — coal, oil and gas — and potential carbon storage

options. Storage options can be considered as two categories: first, enhancing and sustaining the overall quantity of carbon contained by components of the natural carbon cycle; or second, engineering the isolation of additional CO<sub>2</sub> from the carbon cycle. The first category includes various methods to increase the carbon content of terrestrial systems (afforestation, biochar) and the ocean (fertilization, deep-ocean injection). These natural carbon systems predominantly provide ‘temporary’ storage for durations of only tens to hundreds of years. The second category requires engineering to isolate the storage of CO<sub>2</sub> for ‘permanent’ geological timescales. Long-duration (‘permanent’) storage is technically viable by enhancing the natural weathering of rocks (grinding and dispersal of silicates or carbonates)<sup>11</sup>, or by engineered injection into suitable subsurface rock formations. These can securely contain injected CO<sub>2</sub> by physical trapping and subsequent gradual dissolution into formation waters in depleted oil and gas reservoirs and saline aquifers<sup>12</sup>, and more speculatively by chemical reaction within basalts<sup>13</sup>, and by physical trapping and hydrate formation deep within sea-bed sediments<sup>14</sup>.

The availability of engineered sites for geological storage is not equally proven. We here propose three categories of fossil carbon extraction and associated potential CO<sub>2</sub> storage ranging from: (1) easy to manage and inherently secure; (2) complex to manage although expected to be secure; to (3) speculative extraction of fossil fuel producing no reservoirs, requiring storage innovation:

**Category 1.** The storage sites to which engineering and legal permissions allow easiest access are those reservoir rocks that formerly contained fluid hydrocarbons; these are both a carbon stock supply and a potential store. For oil, assuming the reservoir is at a sufficient depth (below ~800 m) for injected CO<sub>2</sub> to be in dense phase (supercritical), at most one-quarter to one-third of the carbon produced can be returned to that reservoir for storage as CO<sub>2</sub>. For methane, given that the density of CO<sub>2</sub> is equal to or greater than CH<sub>4</sub>, and that combusting 1 mol CH<sub>4</sub> → 1 mol CO<sub>2</sub>, natural gas reservoirs have the capacity to contain at least 100% of their combusted carbon content and potentially three times as much<sup>15</sup>. Injection to these capacities does not raise the pressure above that at discovery so the risk to caprock integrity is negligible. However, inadequately cemented legacy wells present a possible leakage pathway so case-by-case reservoir suitability assessment is still necessary.

<sup>1</sup>School of GeoSciences, University of Edinburgh, Edinburgh EH9 3FE, UK. <sup>2</sup>GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstr. 1-3, 24148 Kiel, Germany. \*e-mail: [vivian.scott@ed.ac.uk](mailto:vivian.scott@ed.ac.uk)



**Figure 1 | Sizes of fossil carbon supply (reserves and resources) and potential carbon stores divided between temporary ( $\leq 1,000$  yr) and permanent (geological timescales  $\geq 100,000$  yr) in Gt CO<sub>2</sub>.** Gradient shading indicates relative degree of establishment as a carbon supply or potential large-scale carbon/CO<sub>2</sub> store: for example, oil and gas reserves are well quantified; large-scale storage in saline aquifers is established; basalts and ocean water have large theoretical storage potentials but are unestablished (indicated by a question mark). Oil and gas reserves and resources are both a fossil carbon supply and a carbon store (see 'Category 1' in 'Assessing carbon stocks and storage options'). Coal seams could be used to store CO<sub>2</sub> if not mined and gas hydrates might be harvestable through swapping in of CO<sub>2</sub>. The natural carbon cycle would slowly transfer small amounts of the carbon content of temporary stores into permanent storage (dashed arrows) but most of their carbon content has the potential to be equilibrated with the atmosphere within the timescale of ocean turnover. Dotted vertical lines indicate CO<sub>2</sub> emissions budget associated with 2 °C, 4 °C and 6 °C climate warming. For sources of data see Supplementary Table 1.

**Category 2.** By contrast, managed storage in saline aquifers requires raising the formation pressure, such that their capacity is determined by assessment of: first, the ability of the containing structures (faults and caprocks) to withstand the additional pressure without opening or slipping; and second, the rate at which the local increase in pressure can be reduced by dissipation through the surrounding formations<sup>16</sup>. Production of formation water can relieve pressure and so create additional storage capacity, although the disposal of mineral-rich formation water requires careful environmental management.

**Category 3.** Unlike oil and gas reservoirs, the extraction of coal or unconventional hydrocarbons from oil sands, or fracturing shale rocks, does not explicitly create geological CO<sub>2</sub> storage capacity. Using fractured shales for CO<sub>2</sub> storage is being investigated<sup>17</sup>, but it is also suggested that fracturing shales could reduce the availability of saline aquifer storage by breaking the shale caprocks of secondary

and tertiary seals<sup>18</sup>. Similar volume problems apply to the proposed harvesting of gas hydrates, unless the suggested method of swapping in CO<sub>2</sub> proves feasible<sup>19</sup>. Hence, balancing this carbon currently relies on separately investigated, developed and managed carbon storage.

### Matching carbon extraction with storage

Carbon storage is often considered to be 'available'. However, experience with power plant carbon capture and storage (CCS) development informs us that numerous scientific and practical problems need to be overcome. Here we categorize carbon storage issues relevant to carbon balancing. Four factors determine the global-scale feasibility for storing CO<sub>2</sub> as a method for climate management:

**Cumulative capacity of carbon storage.** Theoretically, there is sufficient storage to match the CO<sub>2</sub> resulting from the use of current fossil fuel reserves (Fig. 1 and Supplementary Table 1).

Although current oil and gas reserves are comparable to the estimated capacities of many storage proposals, the extraction and use of substantial amounts of existing coal reserves will exceed the estimated storage capacities of all but subsurface stores, weathering or the deep ocean. Of these alternative stores, only saline aquifers currently have an established potential to contain large quantities (millions of tonnes) of CO<sub>2</sub> from burning fossil fuels.

At present there are a handful of commercial-scale CCS projects using saline aquifers for storage and a small number of research projects<sup>20</sup>. Large-scale global or regional assessments of potential saline aquifer CO<sub>2</sub> storage capacity rely on desk-based screening of potential formations applying estimated storage efficiencies (the percentage of total pore space that can be filled by CO<sub>2</sub>). Differing assumptions around saline aquifer properties, including their extent, thickness, porosity and permeability, result in estimations of their CO<sub>2</sub> storage capacity that differ by several orders of magnitude<sup>21</sup>. Recent regional assessments of saline aquifer capacity undertaken in, for example, the UK (68 GtCO<sub>2</sub>)<sup>22</sup>, Norway (57 GtCO<sub>2</sub>)<sup>23</sup>, the European Union (≥100 GtCO<sub>2</sub>)<sup>24</sup>, the USA (mean 3,000 GtCO<sub>2</sub>)<sup>25</sup> and North America (1,740–20,550 GtCO<sub>2</sub>)<sup>26</sup> suggest early global estimates (1,000–10,000 GtCO<sub>2</sub>)<sup>27</sup> may be conservative. But, the debate on the validity of assumptions for assessing saline aquifer capacities is far from concluded<sup>28,29</sup> and practical experience indicates that well-researched options may be found to be unsuitable, requiring the alteration of injection plans<sup>30</sup>.

Basalts (continental<sup>31</sup> and seafloor<sup>32</sup>), seafloor sediments<sup>14</sup>, enhanced chemical weathering through the distribution of ground silicates and carbonates<sup>11</sup>, and deep-ocean waters<sup>27</sup> are all very large potential stores with capacities that could theoretically match or exceed fossil fuel resources. But, while active areas of research, none of these are currently established in their viable cumulative capacities, or in the engineered technical ability to deliver sufficient access or levels of deployment to enable CO<sub>2</sub> storage or uptake on climate-impacting scales. Further research and development is required to understand the CO<sub>2</sub> trapping processes and reaction rates (for both basaltic CO<sub>2</sub> injection and dispersion of weathering minerals), and chemical interactions of distributed materials with the local environment, and to establish the viability of scaling up of these CO<sub>2</sub> injection or material processing and distribution methods<sup>11,33</sup>.

The capacities of temporary stores are (with the exception of deep-ocean water) lower than those of fossil reserves and the potential for some overlap in terms of their resource demands (for example, land area) must be considered to avoid double counting. However, they are still likely to have an important carbon and wider environmental role particularly in the mitigation efforts of rural or less-developed regions.

**Comparing rates of release and uptake.** To avoid climate impacts and potential feedbacks associated with peak warming, any carbon storage method needs to match the rate at which fossil carbon is released. Here, the uptake of natural CO<sub>2</sub> sinks and continued non-fossil carbon release from, for example, land-use change or climatic feedbacks should also be considered.

CCS methods, designs, costs and proven engineering are already available for capture at large stationary point sources (power plant and industry), and transport to injection sites. The establishment of large scales of CCS deployment (GtCO<sub>2</sub> stored globally per year) is a considerable challenge requiring decades of build. However, initiating such deployment is proving slow and arduous for primarily political and financial, rather than technical, reasons<sup>16</sup>.

Balancing CO<sub>2</sub> released from distributed sources such as transportation requires taking diffuse CO<sub>2</sub> from the atmosphere by exploiting either a chemical (for example, weathering or direct air capture) or biological (for example, forests, biochar, ocean

fertilization or bioenergy with CCS) process. Supplementary Table 1 summarizes global estimates for the potential annual uptake (GtCO<sub>2</sub>) of these methods. However, as with cumulative capacities, the potential for overlapping resource demands means caution must be taken when adding the contributions of different methods to avoid double counting. We assess the maximum technically achievable diffuse CO<sub>2</sub> uptake following decades of deployment effort to be around 5–10 GtCO<sub>2</sub> yr<sup>-1</sup>, probably smaller than current, and rising, transportation emissions of 7 GtCO<sub>2</sub> yr<sup>-1</sup>.

**Connection from source to store.** Connecting CO<sub>2</sub> sources to storage can be either direct or indirect. In both cases this is a substantial practical challenge of permission, financing and construction. Using geological storage (or deep-ocean injection) requires very large infrastructure to directly connect concentrated CO<sub>2</sub> sources to storage sites (for example, CCS). Under International Energy Agency CCS deployment scenarios<sup>34</sup>, 8 GtCO<sub>2</sub> yr<sup>-1</sup> would be transported and stored in 2050 — twice the current annual mass delivered to market oil. However, CCS offers the potential to at least partially integrate fossil fuel supply and CO<sub>2</sub> storage infrastructure.

Alternatively, air capture or weathering methods could allow the recapture of diffuse CO<sub>2</sub> from the atmosphere. While this has the advantage of not having to connect the source and store directly, enabling them to be remote from each other, the logistics of carbon capture scale inversely to the CO<sub>2</sub> concentration, so recapturing gigatonne quantities of diffuse CO<sub>2</sub> requires vast operations similar to current global extractive industries or agriculture.

Looking at the different fossil fuels in turn, CCS on coal power plants is estimated to be capable of reducing the full lifecycle greenhouse gas emissions by around 70%, with CCS on natural gas power plants reducing them by around 85% (ref. 35). There is the technical capability to considerably reduce the greenhouse gas emissions associated with production and supply of natural gas<sup>36</sup> such that CCS on natural gas power plants could offer a ‘closed loop’ system with near-zero emissions. This can also apply to the increasing number of gas discoveries globally, which have high percentages of ‘associated’ CO<sub>2</sub> that has previously been vented. Reducing the greenhouse gas emissions associated with coal mining and transportation is challenging. Methods such as coal-bed methane extraction or underground coal gasification producing gas *in situ* are likely to be the most promising, as the produced gas can be supplied to use as for natural gas, and the depleted coal seam could potentially be used as a CO<sub>2</sub> store<sup>37,38</sup>.

For oil, CO<sub>2</sub> emissions associated with production and processing can largely be addressed directly by CCS. But emissions from transportation can be addressed only by diffuse uptake methods. The same applies for distributed (for example, domestic) use of natural gas. Emissions inherent to industrial processes that use fossil fuel for heat or feed (for example, cement, steel, chemicals) vary in scale and complexity, and corresponding cost to collect. These perhaps provide the most essential services from fossil carbon, so are arguably the most valuable to balance. Here, clustering of sources to enable sharing of CCS operations is particularly beneficial.

**Climate impact of storage timescales.** The success of any large-scale management of fossil fuel usage through carbon or CO<sub>2</sub> storage depends on both the security and longevity of the storage. Here, we have suggested categorization of carbon storage as either temporary or permanent. Temporary stores equilibrate most of their carbon content with the atmosphere on the timescale of ocean turnover (1,000 yr) or less. While a small proportion of their carbon may be secured for long timescales, the possible future release of most of it must be accounted for. They may also have more immediate carbon cycle feedbacks<sup>39</sup>. Permanent storage secures carbon on timescales of greater than 100,000 yr — the

period over which carbon perturbations are removed from the surface carbon cycle.

Here, there is a societal choice, between: enabling usage of temporary storage, which could be deployed as a mechanism to 'buy time' and increase capacity to engineer permanent storage; or using only more limited permanent storage. The former position is 'doing something rather than nothing' (and could bring significant co-benefits, for example, enhanced agricultural production<sup>40</sup>), but perhaps entails 'borrowing from the future' in the expectation that the time bought will enable the enactment of long-term solutions. On a timescale of decades to centuries such an approach could be less efficient, because low concentrations of gradual CO<sub>2</sub> release from temporary stores would need to be recaptured and moved to permanent (geological timescale) storage.

Can direct CO<sub>2</sub> injection into the deep ocean act as a large-capacity store of last resort? The attraction is the immense storage available. Estimates of the time, based on radiocarbon and other tracers, since parcels of deep-ocean water last returned its carbon to the surface show large variation. Over much of the world ocean, carbon isolation timescales are less than a few hundred years, with the deep regions, particularly of the North Pacific, having carbon timescales of up to a few thousand years<sup>41</sup>. Although some portion of any injected CO<sub>2</sub> would be likely to remain in the ocean on much longer timescales, overall this suggests that the deep ocean is a temporary store.

### Implications

Mitigation scenarios envisage reducing CO<sub>2</sub> emissions from fossil fuel through a combination of replacement by low-carbon energy sources, reduced demand through efficient energy usage and CCS on large point sources<sup>42</sup>. The demand for permanent CO<sub>2</sub> storage consistent with these short-term (typically to 2050) scenarios can be accommodated within estimates of total available (geological) CO<sub>2</sub> storage capacity<sup>43,44</sup>. Implicitly assumed in such scenarios is that climate preservation measures will substantially restrict the extraction and unmitigated combustion of current fossil fuel reserves — especially coal, and subsequently oil and gas. Should this assumption prove invalid — and so far no government has explicitly restricted the extraction of fossil carbon to mitigate climate change — sufficient carbon storage capacity is technically known to enable current reserves of fossil fuels to be used and contained. However, the technical efficiency is not established, costs are unknown—possibly prohibitive — and current experience with the very slow uptake rate of CCS suggests that a much reduced rate of extraction and use would still need to be enforced.

Considering timescales beyond 2050, the ability to undertake continued combustion of further fossil fuel resources in a climate-constrained system relies on exploiting the largest estimates of saline aquifer CO<sub>2</sub> storage, and/or as yet unestablished basalt injection, possibly deep-ocean injection, deep-sea sediment injection and accelerated mineral weathering. Enacting these increasingly speculative scenarios should be expected to become progressively more difficult.

We suggest, therefore, fossil fuel reserve extraction beyond any global emissions budget corresponding to an agreed climate target, or conversion of fossil resources to reserves, will need to be matched not just by the proof of creation of an equivalent tonnage of stored carbon<sup>45</sup>, but by the proof that the carbon has been emplaced into permanent storage. If carbon storage can be developed adequately and rapidly enough, then abated combustion enables fossil fuel use to continue longer, making the challenge of climate mitigation and conversion from a fossil fuel-based energy (and economic) system more manageable.

Such extraction-to-store matching is conceptually most straightforward for natural gas (methane) sourced from conventional porous geological reservoirs and used, at the top of a

usage hierarchy, to mitigate emissions in petrochemical, industry, or electricity generation. The subsurface CO<sub>2</sub> storage created by methane extraction is proven, secure and equivalent in volume<sup>46</sup>. The associated subsurface and extraction infrastructure (wells, platforms) and gas supply pipeline and pipeline routes can be used, through CCS on the power or industrial plant, to geologically store the CO<sub>2</sub> resulting from combusting methane in a systematic refilling of depleted gas fields.

By contrast, continued combustion of coal and unconventional hydrocarbon reserves requires connection to separately developed CO<sub>2</sub> storage resources. Matching the rate of recapture for diffuse emissions from transport and heat is unlikely, and the cumulative capacity of suitable carbon sinks is limited. The use of temporary stores will require additional maintenance by future generations. To fully balance distributed CO<sub>2</sub> emissions with permanent storage requires utilization of enhanced weathering, bioenergy with CCS and direct CO<sub>2</sub> capture from the atmosphere with access to permanent CO<sub>2</sub> storage. But applying these CCS methods on a sufficient global scale presents unprecedented technical, economic and societal challenges, where there is no previous analogue for success.

To better inform this debate on plausible mitigation pathways there is a pressing need to address the imbalance between detailed knowledge of fossil carbon stocks and the comparatively naive understanding of potential carbon stores. Research and development into finding and extracting fossil fuels dwarfs research into understanding and creating carbon stores. Furthermore, the relevance of temporary carbon storage to climate mitigation needs scientific investigation and policy discussion. If the intention is to stabilize climate in the long term, short-term storage is an interim approach. Hence, successful utilization of temporary carbon storage is reliant on ensuring continuous maintenance or replacement by permanent carbon storage.

We conclude that while matching the utilization of fossil fuel reserves to carbon stored might seem technically possible, matching permanent storage to the current rate and cumulative tonnage of release from fossil carbon is practically unrealistic in the present type of market-driven setting. Here, the experience of CCS should be reflected on. The stated intention of multiple governments and industries to develop CCS for point sources since the 1990s has yet to make any relevant impact<sup>16</sup>. Current CCS proposals highlight that there are many perils of detail in navigating cultural, legal, regulatory and economic systems. To provide several examples: the long-term ownership of CO<sub>2</sub> or stored carbon needs to be accepted, probably by governments; the legal claim for storage needs to be ratified; resident publics need to agree; regulators, business and finance communities need to develop terms that allow a return on investment; and somebody needs to pay for all of these actions. Since the first intentional CO<sub>2</sub> storage project for climate purposes took place in Sleipner (Norway) in 1996, there has been no clear route to CCS within established industrial and energy systems. Thus innovating even larger quantities of CO<sub>2</sub> storage into less-proven storage sites using commercial market methods is likely to take many decades to evolve.

Working carbon storage indirectly through a market by pricing and trading emissions has struggled to provide an incentive for CO<sub>2</sub> storage. Working carbon storage directly, through a certificate of carbon production linked to a demonstration of equivalent carbon storage, appears simpler, but may be hard to enact across an economy and between nations. The deployment of measures to manage carbon stocks in the next 30–40 yr, on the scale demanded by the climate budget for total global emissions, requires radical innovation.

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## Author contributions

V.S. was the lead author. V.S., R.S.H., S.F.B.T. and A.O conceived the study and contributed to the text.

## Additional information

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## Competing financial interests

The authors declare no competing financial interests.