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PERSPECTIVE

Fossil fuels in a 'trillion tonne' world.

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Abstract:

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 CO₂ re-capture 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 CO₂ containment as 'temporary' <1000 yr; or 'permanent' > 100,000 yr. Using 'temporary' stores is inefficient and defers an inter-generational 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 CO₂ consequences. Extraction of conventional natural gas is uniquely holistic because it creates 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, to date, un-proven in sufficiency.

1. Introduction:

The 2014 IPCC Working Group 2 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' ¹. A temperature rise of 2°C is consistent with combustion and release of around 1 trillion tonnes of carbon (1000 Gt C) ². The 2013 IPCC Working Group 1 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 Gt C, equivalent to emission of 1100 Gt CO₂ ³. Current known and exploitable fossil fuel reserves are equivalent to 3100 Gt CO₂ ^{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 (~45000 Gt CO₂) ⁵. 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 between the assessments and implications of "un-

burnable” fossil carbon reserves^{6 7}, contrasted against fossil fuel industry statements of the low risk to their reserves and resource development strategies^{8 9}.

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 3 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”¹⁰.

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

2. Assessing carbon stocks and storage options:

Table 1 and Figure 1 assess global fossil carbon supply stocks – coal, oil and gas; and potential carbon storage options. Storage options can be considered as two categories; 1) enhancing and sustaining the overall quantity of carbon contained by components of the natural carbon cycle, or 2) engineering the isolation of additional CO₂ from the carbon cycle. The former includes various methods to increase the carbon content of terrestrial systems (afforestation, biochar), and the ocean (fertilisation, deep ocean injection). These natural carbon systems predominantly provide “temporary” storage for only tens-to-hundreds of years duration. The latter requires engineering to isolate the storage of CO₂ for “permanent” geological-timescales. Long (‘permanent’) duration storage is technically viable by enhancing natural weathering of rocks (grinding and dispersal of silicates or carbonates)¹¹, or engineered injection into suitable subsurface rock formations. These can securely contain injected CO₂ by physical trapping and subsequent gradual dissolution into formation waters in depleted oil and gas reservoirs and saline aquifers¹², and more speculatively by chemical reaction within basalts¹³, and by physical trapping and hydrate formation deep within sea-bed sediments¹⁴.

The availability of engineered sites for geological storage is not equally proven. We here propose three categories of fossil carbon extraction and associated potential CO₂ storage ranging from 1) easy to manage and inherently secure; 2) complex to manage although expected to be secure; 3) speculative extraction of fossil fuel producing no reservoirs, requiring storage innovation.

1) The storage sites to which engineering and legal permissions allow easiest access are those reservoir rocks which formerly contained fluid hydrocarbons; these are both a carbon stock supply, and a potential store. For oil, assuming the reservoir is at sufficient depth (below ~800m) for injected CO₂ to be in dense phase (supercritical), at most a quarter to a third of the carbon produced can be returned to that reservoir for storage as CO₂. For methane (CH₄), given the equal or greater than density of CO₂ to CH₄ and that combusting 1 mol CH₄ → 1 mol CO₂, natural gas reservoirs have capacity to contain at least 100% of their combusted carbon content and potentially three times as much¹⁵. Injection to these

capacities does not raise the pressure above discovery pressure 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.

2) By contrast, managed storage in saline aquifers requires raising the formation pressure, such that their capacity is determined by assessment of i) the ability of the containing structures (faults and caprocks) to withstand the additional pressure without opening or slipping, and ii) the rate at which the local increase in pressure can be reduced by dissipation through the surrounding formations¹⁶. Production of formation water can relieve pressure and so create additional storage capacity though disposal of mineral rich formation water requires careful environmental management.

3) Unlike oil and gas reservoirs, the extraction of coal, unconventional hydrocarbons from oil sands, or fracturing shale rocks, does not explicitly create geological CO₂ storage capacity. Using fractured shales for CO₂ storage is being investigated¹⁷, but it is also suggested that fracturing shales could reduce the availability of saline aquifer storage by breaking the shale cap-rocks of secondary and tertiary seals¹⁸. Similar volume problems apply to the proposed harvesting of gas hydrates, unless the suggested method of swapping in CO₂ proves feasible¹⁹. Hence, balancing this carbon currently relies on separately investigated, developed and managed carbon storage.

3. Matching carbon extraction with storage

Carbon storage is often considered to be “available”. However experience with power plant CCS development informs us that numerous scientific and practical problems need to be overcome. Here we categorise carbon storage issues relevant for carbon balancing. Four factors determine the global scale feasibility for storing CO₂ as a method for climate management:

i. Cumulative capacity of carbon storage:

Theoretically, there is sufficient storage to match the CO₂ resulting from the usage of current fossil fuel reserves (Figure 1 and Table 1). While current oil and gas reserves are comparable to the estimated capacities of many storage proposals, extraction and use of substantial amounts of existing coal reserves will exceed the estimated storage capacities of all but sub-surface 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) CO₂ 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 projects²⁰. Large scale global or regional assessments of potential saline aquifer CO₂ 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 CO₂). Differing assumptions around saline aquifer properties including their extent, thickness, porosity and permeability result in estimations of their CO₂ storage capacity that differ by several orders of magnitude²¹. Recent regional assessments of saline aquifer capacity undertaken in e.g. the UK (68 Gt CO₂)²², Norway (57 Gt CO₂)²³, EU (≥ 100Gt CO₂)²⁴, US (mean 3000 Gt CO₂)²⁵, and North America (1740-20,550 Gt CO₂)²⁶, suggest early global estimates (1000 to 10,000 Gt CO₂²⁷) may be conservative. But, the debate on the validity of assumptions for assessing saline aquifer capacities is far from

concluded ^{28 29}, and practical experience indicates that well-researched options may be found unsuitable requiring alteration of injection plans ³⁰.

Basalts – continental ³¹ and seafloor ³², seafloor sediments ¹⁴, enhanced chemical weathering through the distribution of ground silicates and carbonates ¹¹, and deep ocean waters ²⁷ 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 CO₂ storage or uptake at climate-impacting scales. Further research and development is required to understand the CO₂ trapping processes and reaction rates (for both basaltic CO₂ injection and dispersion of weathering minerals), chemical interactions of distributed materials with the local environment, and establish the viability of scaling up of these CO₂ injection or material processing and distribution methods ^{11 33}.

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

ii. 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 CO₂ sinks and continued non-fossil carbon release from e.g. land use change or climatic feedbacks should also be considered.

Carbon capture and storage (CCS) methods, designs, costs and proven engineering are already available for capture at, and transport to injection from, large stationary point sources (power plant and industry). Establishment of large scales of CCS deployment (Gt CO₂ 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 ¹⁶.

Balancing CO₂ released from distributed sources such as transportation requires taking diffuse CO₂ from the atmosphere exploiting either a chemical (e.g. weathering or direct air capture) or biological (e.g. forests, biochar, ocean fertilisation, bioenergy with CCS) process. Table 1 summarises global estimates for the potential annual uptake (Gt CO₂) of these methods. However, as with cumulative capacities the potential for overlapping resource demands means caution must be taken in adding the contributions of different methods to avoid double counting. We assess the maximum technically achievable diffuse CO₂ uptake following decades of deployment effort to be around 5-10 Gt CO₂/yr, likely smaller than current, and rising, transportation emissions of 7Gt CO₂/yr.

iii. Connection from source to store:

Connecting CO₂ 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 CO₂ sources to storage sites (e.g. CCS). Under International Energy Agency CCS deployment scenarios ³⁴ 8Gt of CO₂ would be transported and stored per year in 2050 - twice the mass of current annual delivered to market oil. However, CCS offers potential to at least partially integrate fossil fuel supply and CO₂ storage infrastructure.

Alternatively, air capture or weathering methods could allow the re-capture of diffuse CO₂ from the atmosphere. While this has the advantage of not having to directly connect source and store, enabling them to be remote from each other, the logistics of carbon capture scale inversely to the CO₂ concentration, so re-capturing gigatonne quantities of diffuse CO₂ requires vast operations similar to current global extractive industries or agriculture.

Looking at the different fossil fuels in turn, CCS on coal power plant is estimated to be capable of reducing the full lifecycle greenhouse gas emissions by around 70%, with CCS on natural gas power plant reducing the lifecycle emissions by around 85% ³⁵. There is technical capability to considerably reduce the greenhouse gas emissions associated with production and supply of natural gas ³⁶ such that CCS on natural gas power plant 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" CO₂, which 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 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 CO₂ store ^{37 38}.

For oil, CO₂ emissions associated with production and processing can largely be addressed directly by CCS. But, emissions from transportation can only be addressed by diffuse uptake methods. The same applies for distributed (e.g. domestic) use of natural gas. Emissions inherent to industrial processes which use fossil fuel for heat or feed (e.g. 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.

iv. Climate impact of storage timescales:

The success of any large-scale management of fossil fuel usage through carbon or CO₂ storage depends on both the security and longevity of the storage. Here, we have suggested categorisation of carbon storage as either 'temporary' or 'permanent'. Temporary stores equilibrate the majority of their carbon content with the atmosphere on the timescale of ocean turnover (1000 years) 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 ³⁹. Permanent storage secures carbon for timescales of greater than 100,000 years – the period over which carbon perturbations are removed from the surface carbon cycle.

Here, there is a societal choice between i) enabling usage of temporary storage, which could be deployed as a mechanism to 'buy time' and increased capacity to engineer permanent storage. Or, ii) using only more limited 'permanent' storage. The former position is "doing

something rather than nothing” (and could bring significant co-benefits e.g. enhanced agricultural production ⁴⁰), but perhaps entails “borrowing from the future” in the expectation that the time bought will enable the enactment of long-term solutions. Over a timescale of decades to centuries such an approach could be less efficient, because low concentrations of gradual CO₂ release from temporary stores would need to be re-captured and moved to permanent (geological timescale) storage.

Can direct CO₂ 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 the world ocean. 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 ⁴¹. Although some portion of any injected CO₂ would likely remain in the ocean on much longer timescales, overall this suggests that the deep ocean is a ‘temporary’ store.

4. Implications

Mitigation scenarios envisage reducing CO₂ 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 ⁴². The demand for permanent CO₂ storage consistent with these short term (typically to 2050) scenarios can be accommodated within estimates of total available (geological) CO₂ storage capacity ^{43 44}. 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 to date 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 CO₂ storage, and/or as yet un-established 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 carbon⁴⁵, 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 CO₂ storage created by methane extraction is proven and secure and equivalent in volume ⁴⁶. The associated subsurface and extraction infrastructure (wells, platforms) and gas supply pipeline and pipeline routes can be used, via CCS on the power or industrial plant, to geologically store the CO₂ resulting from combusting methane in a systematic re-filling of depleted gas-fields.

By contrast, continued combustion of coal and unconventional hydrocarbon reserves requires connection to separately developed CO₂ storage resources. Matching the rate of re-capture 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 CO₂ emissions with permanent storage requires utilisation of enhanced weathering, and BioEnergy with CCS (BECCS) and direct CO₂ capture from the atmosphere with access to permanent CO₂ storage. But applying these 'CCS' methods at sufficient global scale presents unprecedented technical, economic and societal challenges, where there is no prior 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. Further, the relevance of temporary carbon storage to climate mitigation needs scientific investigation and policy discussion. If the intention is to stabilise climate in the long-term, short-term storage is an interim approach. Hence, successful utilisation of temporary carbon storage is reliant on ensuring continuous maintenance or replacement by permanent carbon storage.

We conclude that while matching the utilisation 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 upon. The stated intention of multiple governments and industries to develop CCS for point sources since the 1990s has yet to make any relevant impact ¹⁶. 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 CO₂ 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. After the first intentional CO₂ storage for climate purposes at Sleipner (Norway), in 1996, there is as yet no clear route to CCS within established industrial and energy systems. Thus innovating even larger tonnages of CO₂ 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 pricing and trading emissions has struggled to incentivise CO₂ 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 years, at the scale demanded by the climatic budget for total global emissions requires radical innovation.

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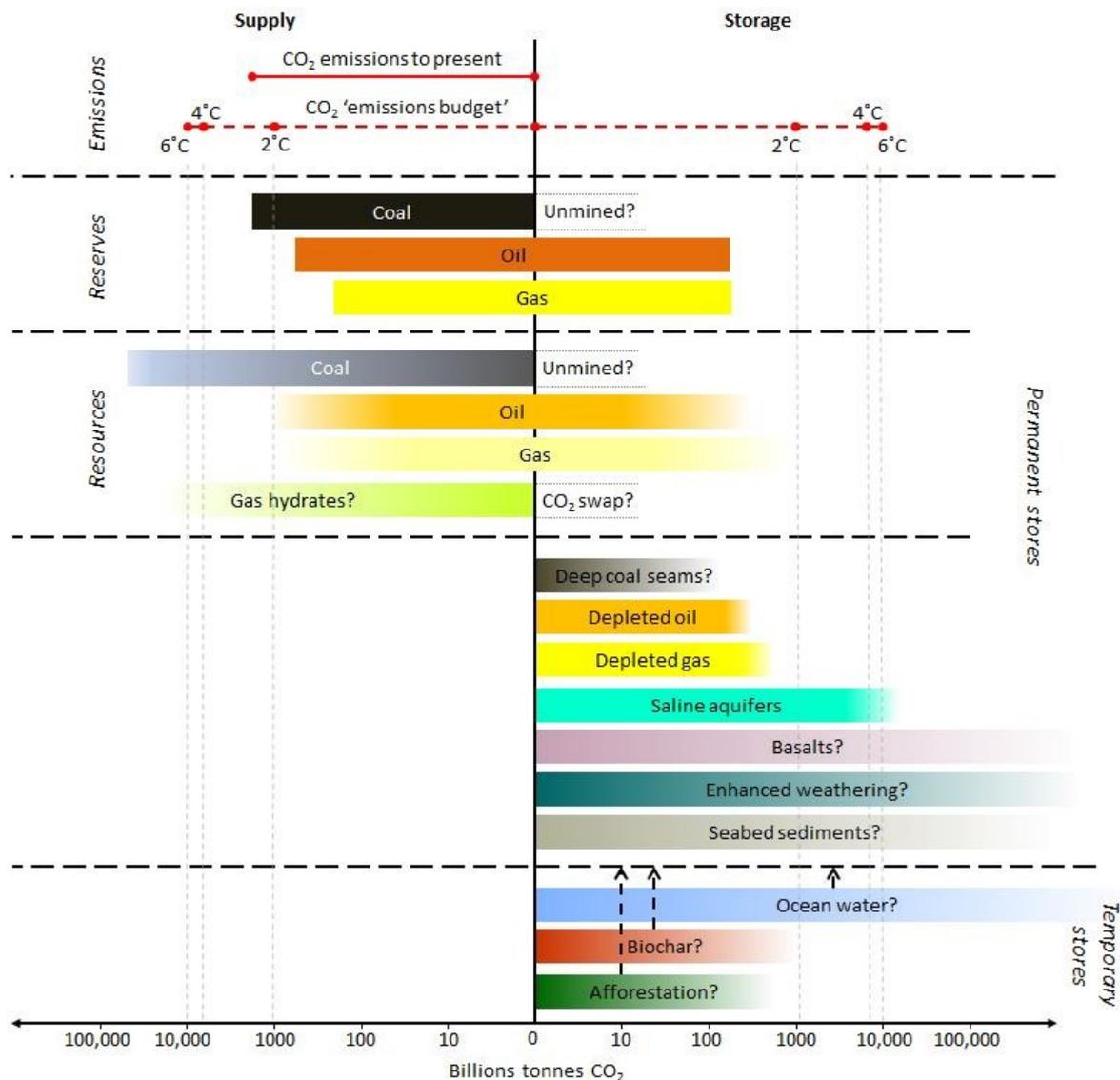


Figure 1: Sizes of fossil carbon supply - reserves and resources, and potential carbon stores divided between temporary ($\leq 10^3$ years) and permanent (geological timescales $\geq 10^5$ years) in terms of billions tonnes CO₂ (log along x-axis). Gradient shading indicates relative degree of establishment as a carbon supply or potential large-scale carbon/CO₂ store e.g. oil and gas reserves are well quantified; large scale storage in storage in saline aquifers is established; basalts and ocean water have large theoretical storage potentials but are un-established. Oil and gas reserves and resources are both a fossil carbon supply and a carbon store (see text Section 2). Coal seams could be used to store CO₂ if not mined, and gas hydrates might be harvestable via swapping in of CO₂. The natural carbon cycle would slowly transfer small amounts of the carbon content of temporary stores into permanent storage – dashed arrows – but the majority of their carbon content has the potential to be equilibrated with the atmosphere within the timescale of ocean turnover. Dotted vertical lines indicate CO₂ emissions budget associated with 2°, 4° and 6°C climate warming. For sources of data see Table 1.

Table 1 [supplementary information]: Estimated global fossil fuel reserves, resources and CO₂ storage capacities in Gt CO₂.

| C-stock | SUPPLY | | STORE | Estimated range of total cumulative capacity (Gt CO ₂) | Re-use capacity (R= proportion produced CO ₂ that could be stored in origin site) ¹ | Longevity of storage (years) |
|---------------------------------------------|-----------------------------------------|------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|------------------------------------|
| | Identified reserve CO ₂ (Gt) | Estimated resource (Gt CO ₂) | | | | |
| Coal | 1940 ⁴ 1960 ⁵ | 42360 ⁵ | Rate limited by infrastructure deployment | Assuming un-mined: <200 ²⁷ , 65-137 (North America) ^{26,2} | R=0 | > 10 ⁴ |
| Oil (all) | 710 ⁴ 680 ⁵ | 1440 ⁵ 1445 ⁴⁸ | Rate limited by infrastructure deployment | EOR all depleted reserves: 140-320 ^{49,3} | R ≤ 0.25-0.33 | > 10 ⁴ |
| Shale oil | (included above) | 150 ⁴⁸ | - | 0 | R=0 | - |
| Gas (all) | 450 ⁴ 420 ⁵ | 1695 ⁵ | Rate limited by infrastructure deployment | For all reserve 560-1300 (theoretical), 420-940 (effective), 250-560 practical ⁵¹ | 1 ≤ R ≤ 3 | > 10 ⁴ |
| Shale gas | (included above) | 445 ⁴⁸ | - | 0 (although under initial investigation ¹⁷) | R=0 | - |
| Gas hydrates | 0 | 3700-37000 ⁵² | - | 0 | 0 | - |
| Afforestation | - | - | 3-5.5 ³⁹ | ≤ 700 ⁵³ | - | ~ 10 ² |
| Biochar | - | - | < 3.5 | ≤ 1500 ^{54,55} | - | ~ 10 ³ |
| Ocean fertilisation | - | - | ~ 3.5 for Fe ³⁹ | ≤ 400-800 (100 yrs application) ⁵⁶ | - | ~ 10 ² -10 ³ |
| Deep ocean water | - | - | Unknown (injection technology unproven) | ≥ fossil resource ²⁷ | - | ~ 10 ³ |
| Deep sea sediments | - | - | Unknown | Un-established: potentially > 10 ^{4,14} | - | > 10 ⁴ |
| Saline aquifers | - | - | Rate limited by infrastructure deployment | 100-10,000 ²⁷ , N. America 1740-20550 ²⁶ , EU ≥ 100 ²⁴ | - | > 10 ⁴ |
| Enhanced weathering | - | - | Global potential un-established – limited by logistical scale and uncertainty in reaction rates and saturation. Estimates of ≤ 3.5 for tropical land olivine distribution; < 0.6-1 applying 4Gt carbonate/yr to ocean ⁵⁷ ; ≤ 1/Gt applying 3Gt olivine to ocean ⁵⁸ . | Un-established: potentially ≥ fossil resource | - | > 10 ⁴ |
| Basalts | - | - | Unknown (feasibility of large masses of injection of CO ₂ un-established). | Un-established: potentially ≥ fossil resource ^{13,32} | - | > 10 ⁴ |
| BECCS (not a storage resource) | | | 2.5-10 ^{59,60,61} | As for engineered storage options above | | |
| Direct air-capture (not a storage resource) | | | Technology unproven - suggested ≤ 2-10 | As for engineered storage options above | | |

¹ Generalised assumptions: depth sufficient for CO₂ to be in supercritical phase, no water flooding and no additional oil or water production.

² As CO₂ storage in coal seams is generally considered as part of Enhanced Coal Bed Methane (ECBM) production, the produced and used C should be considered against the stored CO₂ 47Khoo, H. H. & Tan, R. B. Environmental impact evaluation of conventional fossil fuel production (oil and natural gas) and enhanced resource recovery with potential CO₂ sequestration. *Energy & Fuels* **20**, 1914-1924 (2006).

³ Includes EOR, so accounting for additional oil should be considered 50 Jaramillo, P., Griffin, W. M. & McCoy, S. T. Life cycle inventory of CO₂ in an Enhanced Oil Recovery System. *Environmental science & technology* **43**, 8027-8032 (2009).

References (We suggest references to Table 1 – 22 to 42 – as supplementary material.)

- 1 Intergovernmental Panel on Climate Change. Climate Change 2014: Impacts, Adaptation, and Vulnerability - Summary for Policymakers. (2014).
- 2 Allen, M. R. *et al.* Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458**, 1163-1166 (2009).
- 3 IPCC. Fifth Assessment Report Summary for Policy Makers, Working Group 1: the physical science basis (2013).
- 4 BP. Statistical Review of World Energy 2012. (2012).
- 5 Bundesanstalt für Geowissenschaften und Rohstoffe. Reserves, resources and Availability of Energy Resources. (2012).
- 6 Carbon Tracker & Grantham Institute. Unburnable Carbon. (2013).
- 7 HSBC Global Research. (2013).
- 8 ExxonMobil. Energy and Carbon - Managing the Risks. (2014).
- 9 Royal Dutch Shell. Letter on the issue of "stranded assets". (2014).
- 10 Intergovernmental Panel on Climate Change. Climate Change 2014: Mitigation of Climate Change - Summary for Policymakers. (2014).
- 11 Hartmann, J. *et al.* Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics* **51**, 113-149 (2013).
- 12 Sathaye, K. J., Hesse, M. A., Cassidy, M. & Stockli, D. F. Constraints on the magnitude and rate of CO₂ dissolution at Bravo Dome natural gas field. *Proceedings of the National Academy of Sciences* **111**, 15332-15337 (2014).
- 13 Goldberg, D. S., Kent, D. V. & Olsen, P. E. Potential on-shore and off-shore reservoirs for CO₂ sequestration in Central Atlantic magmatic province basalts. *Proceedings of the National Academy of Sciences* **107**, 1327-1332 (2010).
- 14 House, K. Z., Schrag, D. P., Harvey, C. F. & Lackner, K. S. Permanent carbon dioxide storage in deep-sea sediments. *Proceedings of the National Academy of Sciences* **103**, 12291-12295 (2006).
- 15 Orr, F. M. Storage of CO₂ in geologic formations. *SPE* **54** (2004).
- 16 Scott, V., Gilfillan, S., Markusson, N., Chalmers, H. & Haszeldine, R. S. Last chance for carbon capture and storage. *Nature Climate Change* (2012).
- 17 US National Energy Technology Laboratory. Interdisciplinary Investigation of CO₂ Sequestration in Depleted Shale Gas Formations. (2013).
- 18 Elliot, T. & Celia, M. Potential Restrictions for CO₂ Sequestration Sites Due to Shale and Tight Gas Production. *Environmental science & technology* **46**, 4223-4227 (2012).
- 19 Schicks, J. M. *et al.* New approaches for the production of hydrocarbons from hydrate bearing sediments. *Energies* **4**, 151-172 (2011).
- 20 Scottish Carbon Capture and Storage. *Global CCS Projects Map*, <<http://www.sccs.org.uk/map.html>> (2014).
- 21 Bradshaw, J. *et al.* CO₂ storage capacity estimation: Issues and development of standards. *International Journal of Greenhouse Gas Control* **1**, 62-68 (2007).
- 22 British Geological Survey & The Crown Estate. (2013).
- 23 Norwegian Petroleum Directive. (2014).
- 24 Stewart, R. J., Scott, V., Haszeldine, R. S., Ainger, D. & Argent, S. The Feasibility of a European-Wide Integrated CO₂ Transport Network. *Greenhouse Gases: Science and Technology* **4** (2014).
- 25 U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team. National assessment of geologic carbon dioxide storage resources. (2013).
- 26 US National Energy technology Laboratory. North American Carbon Storage Atlas. (2012).

- 27 IPCC. *IPCC Special Report on Carbon Dioxide Capture and Storage*. (Cambridge University Press, 2005).
- 28 Thibeau, S. & Mucha, V. Have we overestimated saline aquifer CO₂ storage capacities? *Oil & Gas Science And Technology-Revue De L Institut Francais Du Petrole* **66**, 81-92, doi:10.2516/ogst/2011004 (2011).
- 29 Cavanagh, A. & Wildgust, N. Pressurization and brine displacement issues for deep saline formation CO₂ storage. *Energy Procedia* **4**, 4814-4821 (2011).
- 30 Hansen, O. *et al.* Snøhvit: The History of Injecting and Storing 1 Mt CO₂ in the Fluvial Tubåen Fm. *Energy Procedia* **37**, 3565-3573 (2013).
- 31 McGrail, B. P. *et al.* Potential for carbon dioxide sequestration in flood basalts. *Journal of Geophysical Research: Solid Earth (1978–2012)* **111** (2006).
- 32 Goldberg, D. S., Takahashi, T. & Slagle, A. L. Carbon dioxide sequestration in deep-sea basalt. *Proceedings of the National Academy of Sciences* **105**, 9920-9925 (2008).
- 33 Moosdorf, N., Renforth, P. & Hartmann, J. Carbon dioxide efficiency of terrestrial enhanced weathering. *Environmental Science & Technology* (2014).
- 34 IEA. Technology Roadmap: Carbon capture and storage. www.iea.org (Paris, 2009).
- 35 Hammond, G. P., Howard, H. R. & Jones, C. I. The energy and environmental implications of UK more electric transition pathways: A whole systems perspective. *Energy Policy* (2012).
- 36 ICF International. Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries. (2014).
- 37 Hyder, Z., Ripepi, N. S. & Karmis, M. E. A life cycle comparison of greenhouse emissions for power generation from coal mining and underground coal gasification. *Mitigation and Adaptation Strategies for Global Change*, 1-32 (2014).
- 38 Roddy, D. J. & Younger, P. L. Underground coal gasification with CCS: a pathway to decarbonising industry. *Energy & Environmental Science* **3**, 400-407 (2010).
- 39 Keller, D. P., Feng, E. Y. & Oschlies, A. Potential climate engineering effectiveness and side effects during a high CO₂-emissions scenario: a comparative assessment. *Nature Communications* **5**, doi:10.1038/ncomms4304. (2014).
- 40 Sohi, S. P. Carbon storage with benefits. *Science* **338**, 1034-1035 (2012).
- 41 Khatiwala, S., Primeau, F. & Holzer, M. Ventilation of the deep ocean constrained with tracer observations and implications for radiocarbon estimates of ideal mean age. *Earth and Planetary Science Letters* **325**, 116-125 (2012).
- 42 International Energy Agency. World Energy Outlook. (2012).
- 43 Dooley, J. J. Estimating the supply and demand for deep geologic CO₂ storage capacity over the course of the 21st Century: A meta-analysis of the literature. *Energy Procedia* (2013).
- 44 Szulczewski, M. L., MacMinn, C. W., Herzog, H. J. & Juanes, R. Lifetime of carbon capture and storage as a climate-change mitigation technology. *Proceedings of the National Academy of Sciences* **109**, 5185-5189 (2012).
- 45 Myles Allen. (Guardian Newspaper, 2013).
- 46 Haszeldine, R. S. Deep geological CO₂ storage: principles reviewed, and prospecting for bio-energy disposal sites. *Mitigation and Adaptation Strategies for Global Change* **11**, 369-393 (2006).
- 47 Khoo, H. H. & Tan, R. B. Environmental impact evaluation of conventional fossil fuel production (oil and natural gas) and enhanced resource recovery with potential CO₂ sequestration. *Energy & Fuels* **20**, 1914-1924 (2006).
- 48 U.S. Energy Information Administration. Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States. (2013).
- 49 IEA Greenhouse Gas R&D Programme. CO₂ storage in depleted oilfields: global application criteria for carbon dioxide enhanced oil recovery. (2009).

- 50 Jaramillo, P., Griffin, W. M. & McCoy, S. T. Life cycle inventory of CO₂ in an Enhanced Oil Recovery System. *Environmental science & technology* **43**, 8027-8032 (2009).
- 51 IEA Greenhouse Gas R&D Programme. CO₂ storage in depleted gas fields. (2009).
- 52 Krey, V. *et al.* Gas hydrates: entrance to a methane age or climate threat? *Environmental Research Letters* **4**, 034007 (2009).
- 53 Canadell, J. G. & Raupach, M. R. Managing Forests for Climate Change Mitigation. *Science* **320**, 1456-1457 doi:10.1126/science.1155458 (2008).
- 54 Woolf, D., Amonette, J. E., Street-perrott, F. A., Lehmann, J. & Joseph, S. Sustainable biochar to mitigate global climate change. *Nature Communications* **1**, doi:doi:10.1038/ncomms1053 (2010).
- 55 Lehmann, J., Gaunt, J. & Rondon, M. Bio-char sequestration in terrestrial ecosystems – a review. *Mitigation and Adaptation Strategies for Global Change* **11**, 403-427, doi:10.1007/s11027-005-9006-5 (2006).
- 56 Aumont, O. & Bopp, L. Globalizing results from ocean in situ iron fertilization studies. *Global Biogeochemical Cycles* **20** (2006).
- 57 Harvey, L. Mitigating the atmospheric CO₂ increase and ocean acidification by adding limestone powder to upwelling regions. *Journal of Geophysical Research* **113**, C04028 (2008).
- 58 Köhler, P., Abrams, J. F., Völker, C., Hauck, J. & Wolf-Gladrow, D. A. Geoengineering impact of open ocean dissolution of olivine on atmospheric CO₂, surface ocean pH and marine biology. *Environmental Research Letters* **8**, 014009 (2013).
- 59 Van Vuuren, D. P., Van Vliet, J. & Stehfest, E. Future bio-energy potential under various natural constraints. *Energy Policy* **37**, 4220-4230 (2009).
- 60 Azar, C. *et al.* The feasibility of low CO₂ concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change* **100**, 195-202 (2010).
- 61 McGlashan, N. R., Workman, M. H. W., Caldecott, B. & Shah, N. Negative emissions technologies. (Grantham Institute, 2012).