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Citation for published version:
Scott, V, Haszeldine, S, Tett, S & Oschlies, A 2015, 'Fossil fuels in a trillion tonne world.' Nature Climate Change, vol. 5, pp. 419–423. DOI: 10.1038/nclimate2578

Digital Object Identifier (DOI):
10.1038/nclimate2578

Published In:
Nature Climate Change

Cite As: Scott. V., Haszeldine, R.S.H., Tett, S.F.B., Oschlies, A., Fossil fuels in a trillion tonne world, Nature Climate Change 5, 419–423, 2015.

DOI: 10.1038/nclimate2578

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 CO_2 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 CO_2 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 CO_2 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 CO_2 [3]. Current known and exploitable fossil fuel reserves are equivalent to 3100 Gt CO_2 [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 CO_2)[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 "unburnable" 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 CO_2 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 CO_2 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 CO_2 by physical trapping and subsequent gradual dissolution into formation waters in depleted oil and gas reservoirs and saline aquifers [12], and more speculatively by chemical reaction within basalts [13], and by physical trapping and hydrate formation deep within sea-bed sediments [14].

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_2 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 CO_2 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 CO_2. For methane (CH_4), given the equal or greater than density of CO_2 to CH_4 and that combusting 1 mol $CH_4 \rightarrow$ 1 mol CO_2, natural gas reservoirs have capacity to contain at least 100% of their combusted carbon content and potentially three times as much [15]. 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 formations[16]. 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 CO_2 storage capacity. Using fractured shales for CO_2 storage is being investigated [17], 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 seals [18]. Similar volume problems apply to the proposed harvesting of gas hydrates, unless the suggested method of swapping in CO_2 proves feasible[19]. 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 CO_2 as a method for climate management:

i. Cumulative capacity of carbon storage:

Theoretically, there is sufficient storage to match the CO_2 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) CO_2 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 [20]. Large scale global or regional assessments of potential saline aquifer CO_2 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_2). Differing assumptions around saline aquifer properties including their extent, thickness, porosity and permeability result in estimations of their CO_2 storage capacity that differ by several orders of magnitude [21]. Recent regional assessments of saline aquifer capacity undertaken in e.g. the UK (68 Gt CO_2) [22], Norway (57 Gt CO_2) [23], EU (≥ 100Gt CO_2) [24], US (mean 3000 Gt CO_2) [25], and North America (1740-20,550 Gt CO_2) [26], suggest early global estimates (1000 to 10,000 Gt CO_2 [27]) 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 CO_2 storage or uptake at climate-impacting scales. Further research and development is required to understand the CO_2 trapping processes and reaction rates (for both basaltic CO_2 injection and dispersion of weathering minerals), chemical interactions of distributed materials with the local environment, and establish the viability of scaling up of these CO_2 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 CO_2 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 CO_2 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 CO_2 released from distributed sources such as transportation requires taking diffuse CO_2 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 CO_2) 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 CO_2 uptake following decades of deployment effort to be around 5-10 Gt CO_2/yr, likely smaller than current, and rising, transportation emissions of 7Gt CO_2/yr.

iii. Connection from source to store:

Connecting CO_2 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_2 sources to storage sites (e.g. CCS). Under International Energy Agency CCS deployment scenarios [34] 8Gt of CO_2 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 CO_2 storage infrastructure.

Alternatively, air capture or weathering methods could allow the re-capture of diffuse CO_2 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 CO_2 concentration, so re-capturing gigatonne quantities of diffuse CO_2 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" CO_2, 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 CO_2 store [37 38].

For oil, CO_2 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 CO_2 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 CO_2 release from temporary stores would need to be re-captured and moved to permanent (geological timescale) storage.

Can direct CO_2 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 CO_2 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 CO_2 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 CO_2 storage consistent with these short term (typically to 2050) scenarios can be accommodated within estimates of total available (geological) CO_2 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 CO_2 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 carbon[45], 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_2 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 CO_2 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 CO_2 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 CO_2 emissions with permanent storage requires utilisation of enhanced weathering, and BioEnergy with CCS (BECCS) and direct CO_2 capture from the atmosphere with access to permanent CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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.

Author contributions: V.S. lead author. All (V.S., R.S.H., S.F.B.T., A.O) conceived the study and contributed to the text.

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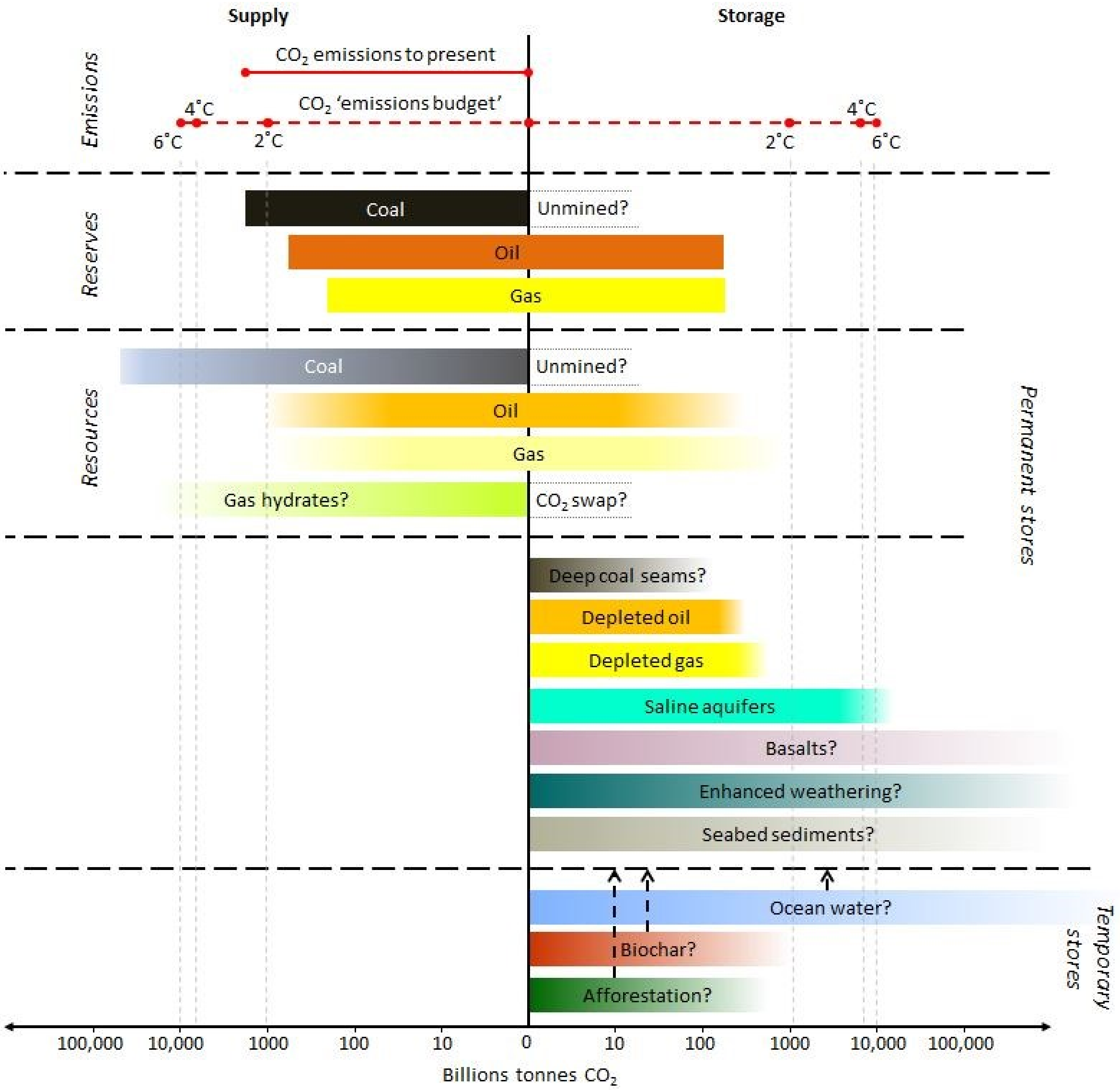

Figure 1: Sizes of fossil carbon supply - reserves and resources, and potential carbon stores divided between temporary (≤ 10^3 years) and permanent (geological timescales ≥ 10^5 years) in terms of billions tonnes CO_2 (log along x-axis). Gradient shading indicates relative degree of establishment as a carbon supply or potential large-scale carbon/CO_2 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 CO_2 if not mined, and gas hydrates might be harvestable via swapping in of CO_2. 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 CO_2 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 CO_2 storage capacities in Gt CO_2.

	SUPPLY			STORE			
C-stock	**Identified reserve (Gt CO_2)**	**Estimated resource (Gt CO_2)**		**Estimated maximum annual uptake rate (Gt CO_2)**	**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)**
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 in 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 in 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 un-proven)	≥ 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 CO_2 to be in supercritical phase, no water flooding and no additional oil or water production.
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