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Limiting global average temperature rise to 1.5°C requires an unprecedented reduction in fossil fuel consumption. To track the fossil fuel industry and its individual companies against 1.5°C-consistent pathways, we propose a new methodology that complements existing methodologies in four main ways: it uses publicly available data, the focus is on absolute fossil fuel production (as a proxy for embedded emissions), rather than carbon intensities associated with their use; it includes coal which is commonly excluded; and it is applicable regardless of whether the company has set a target. We evaluate the largest 142 producers of coal, oil, and gas against three 1.5°C IPCC SSP (RCP-1.9) pathways from 2014 and the IEA Net Zero Emissions pathway from 2020. We find that these 142 companies would produce up to 68%, 42%, 53% *more* than their cumulative production budgets for coal, oil, and gas respectively by 2050 if they continued the trend of their average growth rates from 2010-2018.

Introduction

Meeting the climate goals negotiated in the 2015 Paris Agreement requires the rapid reduction of the use of fossil fuels and implies that significant amounts of fossil fuel reserves will remain unburnt [1, 2, 3, 4]. The prolonged use of coal poses a particular threat to meeting climate goals, and more than 40 countries have committed to end all investment in new coal domestically and internationally following COP 26 [5]. Many countries, however, including some who are among the largest emitters, have not committed to phasing out the production or use of coal, or other fossil fuels, with the current commitments post-COP 26 expected to still lead to around 2.6°C warming (with a range of 2 °C to 3.7 °C) [6].

While increasing national ambition towards decarbonization is important, it is increasingly recognized that companies will be a critical determinant of whether climate goals are achieved [7, 8]. Some investors and asset managers have elected to exclude fossil fuel companies from their portfolios [9], and/or are pressuring the fossil fuel companies to align their activities with the Paris Agreement. Coinciding with such actions there has been an increasing number of emission reduction targets announced by fossil fuel companies [10]. However, recent work demonstrates that only one of the major oil and gas companies has targets that are consistent with 1.5 °C-aligned IPCC pathways [10].

Aligning the promises and performance of any individual entity's climate goals requires the global carbon budget, or 1.5°C and well-below 2°C mitigation pathways, to be allocated over time to each entity [11]. This is not a straight-forward task. For nations, there has been a 30-year ongoing process of international negotiations culminating with the National Determined Contributions based loosely around "common but differentiated responsibilities and respective capabilities" [12, 13]. Yet, allocation methodologies are fundamental for tracking progress, assigning responsibilities, and examining financial risks of inaction. For companies in particular, this information is crucial for stakeholders to assess investment risks and make informed and climate-safe decisions [14]. In recent years, several methods have been developed to assess the alignment of companies to the Paris goals, including for specific carbon-intensive sectors such as the fossil fuel sector [15-17]. A special approach is needed for fossil fuel companies, since it is the use of their product, often by third parties (as socalled scope 3 emissions), that has most influence on global emissions [17, 18].

Several methodologies to track the performance of the fossil fuel industry and its individual constituents against climate goals have been developed to date, but each has key shortcomings we intend to address in this paper. First, current methodologies vary in their complexity, with some requiring comprehensive corporate carbon accounting methods with details of the companies' processes that are not publicly available or costly to obtain (a comprehensive review of the methods is in the Supplementary Materials). In particular, the Science Based Targets initiative uses an intensity approach for oil and gas companies, requiring granular company data that is not freely available (though companies can currently not set targets as the methodology is being re-designed) [16]. Our proposed approach requires less data and only data that is publicly available, promoting transparency and ease of use. Second, methodologies relying on carbon intensity metrics need to be complemented with absolute emission reduction levels to ensure global carbon budgets are not exceeded [10, 15, 19]. A recent Shell legal ruling demonstrates that courts can conclude that intensity targets are not sufficient [20, 21]. We therefore focus on comparing fossil fuel *production* to Paris-compliant fossil fuel demand projections, thus shifting the focus from *intensity* to *absolute* measures. Third, coal is excluded from many current methodologies, whereas our method includes coal. Finally, our approach enables us to evaluate a uniquely large dataset of 74 coal companies representing 56% of global coal production, 67 oil companies representing 75% of global oil production, and 70 natural gas companies, responsible for 74% of global natural gas production during the period 2010-2020. These companies together have produced 70% of global fossil fuels on a primary energy basis over the same period.

Our analysis is presented in two parts: firstly, we demonstrate how our method can be used to evaluate the performance of individual companies and develop company-specific pathways consistent with limiting temperature rise to 1.5°C compared to pre-industrial levels, and secondly, we apply our methodology to the performance of a sample of 142 fossil fuel companies.

Using production as an absolute measure to assess Paris alignment

Almost all decarbonization scenarios that are consistent with limiting warming to well-below

2°C (WB2D) require a rapid future decline in fossil fuel use. Aligning production with these demand constraints informs fossil fuel producers of the unavoidable need to change their business model, complementing the current carbon intensity convergence models for science-based target setting. For a company to align with the Paris goals, the following is required; the underlying decarbonization pathway used should be consistent with "well-below 2°C above pre-industrial levels" and "pursuing efforts to limit global temperature rise to 1.5°C"; the base year from which progress is measured must be consistent with the initial year of the decarbonization pathway; and the decarbonization pathway should commence in 2015 or prior [14]. If companies use a base year that is not aligned with the commencement of the underlying decarbonization pathway, it is difficult to evaluate their alignment with that particular decarbonization pathway. For example, if a company sets a base year of 2015 but compared itself with a decarbonization pathway commencing in 2010, the company may have been misaligned historically without being held accountable. In other words, a peer company that has been compliant with the pathway from the base year onwards would be unfairly disadvantaged.

We use three sample pathways commencing in 2014 to demonstrate our method. The three pathways we use are from different models (all using a 1.9 Representative Concentration Pathway (RCP), consistent with 1.5°C) and applied to three different Shared Socio-economic Pathways (SSPs); the Asia-Pacific Integrated Modeling/Computable General Equilibrium (AIM/CGE SSP1-RCP1.9, "SSP1-RCP1.9" hereafter), the Model for Energy Supply Strategy Alternatives and their General Environmental Impact-Global Biosphere Management Model (MESSAGE-GLOBIOM SSP2-RCP1.9, "SSP2-RCP1.9" hereafter), and the Global Change Assessment Model modeling (GCAM4 SSP5-RCP1.9, "SSP5-RCP1.9" hereafter). We chose SSP2 given it is the "middle of the road" scenario, as well as SSP1 ("the green road") and SSP5 (the "fossil-fueled development") scenarios for comparison (see Methods for an explanation). The pathways model different levels of cumulative fossil fuel production levels by 2050 and require varying levels of Carbon Capture and Storage (CCS) coupled with fossil fuel use, and other forms of carbon removal, such as bioenergy with CCS (BECCS) and direct air capture with CCS (DACCS). In 2050, total CCS (including fossil CCS, BECCS and DACCS) required under the scenarios is 6.3, 8.6 and 32.4 $GtCO_2$/year respectively for SSP-1, -2 and -5. In addition, in the year 2050 under SSP1-RCP1.9, SSP2-RCP1.9 and SSP5-RCP1.9 respectively, 68%, 38% and 187% of the CO_2 emissions of fossil fuel and industry (after deducting Carbon Capture and Storage) should be offset by land use improvements and carbon dioxide removal. In 2050, SSP5-RCP1.9 relies on net-negative CO_2 emissions from 2050 while SSP1-RCP1.9 and SSP2-RCP1.9 involve net-negative CO_2 emissions from 2060. The different characteristics of the three scenarios therefore result in different levels of fossil fuel production budgets. We also model the implications of following the International Energy Agency Net Zero Emission (IEA NZE) pathway, which starts in 2020, for comparison. Compared to the three pathways (SSP1,2,5-RCP1.9), IEA NZE is also consistent with 1.5°C without a temperature overshoot (with a 50% probability), while also providing a pathway for the energy sector to achieve net-zero CO_2 emissions by 2050. It relies on 7.6 $GtCO_2$/year of total CCS in 2050. The IEA is an organization whose reports are widely cited among fossil fuel producers and governments.

Allocating the global fossil fuel production budget among producers in a way that is consistent with the IPCC pathways can be achieved using various approaches that account for historical production levels, carbon intensities, reserve levels, costs and economic capabilities, geopolitical settings, socioeconomic equity principles, and many more (see Supplementary Materials, Section 2). Alternatively, allocating future production budgets according to reserves can create large differences compared to a production method, particularly for State-Owned entities that have typically higher reserve-to-production ratios (Supplementary Materials [17, 23]). For demonstration purposes, our method allocates the future production budget using average 2010-2014 production levels for two reasons; i) due to data availability (widely available compared to other variables such as reserves or costs), and ii) to account for recent production prior to the base year of 2014, and thus not relying on a single observation in time. Few significant differences are found between the choices for allocating the budget according to historical contributions 1980-2014 and 2010-2014 (see supplementary Fig. 3). By using the average production rate of 2010-2014 as an allocation mechanism, this study has a clear advantage due to the large amount of production data available using a freely available dataset resulting in the ability to assess 142 fossil fuel companies. In time, it is hoped that increased disclosure by companies will allow scholars and others to explore alternative criteria for distributing the carbon budget. Here, we allocate the annual global production budgets under each decarbonization scenario to each company based on their share of global production in 2010-2014 (see table 1) and evaluate their performance from 2014 onwards. This means we adopt a grandfathering approach, whereby companies with higher production shares in 2010-2014 get a larger production share going forward, which has implied equity limitations. Collectively however, it means that if each company stays within its production "budget", global production will stay within the production limits under the decarbonization scenario, provided of course, that the required levels of CCS under the decarbonization scenario are actually deployed. Companies would ideally play an active role in ensuring these levels of future CCS are able to be met, and be required to verify that the CCS requirements associated with their own production have been, and will continue to be, met under their chosen trajectory. We show summary figures for the top five coal producers in Table 1.

Fig. 1 demonstrates the application of our method to two example companies, BHP (a1 and a2) and Glencore (b1 and b2). The average production between 2010 and 2014 was 1.25% (BHP) and 1.45% (Glencore) of the world's total coal production. Allocating the companies 1.25% and 1.45% of global Paris-aligned coal production pathways (three IPCC scenarios) from 2015 onwards, we find that whilst BHP's production is aligned with all three scenarios, Glencore has overproduced under two scenarios (SSP1-RCP1.9 and SSP2-RCP1.9), with cumulative production between 2014 and 2020 equaling 15.4 EJ, compared to an allowance of 11.8 EJ, 12.0 EJ, and 15.6 EJ under SSP1-RCP1.9, SSP2-RCP1.9 and SSP5-RCP1.9 respectively (in Fig. 1a, we convert production to EJ for all companies using [21], see details in Supplementary Materials). If we project the companies' production based on 2010-2018 production growth rate (removing 2019-2020 because of COVID), both companies will finish their entire production budget (until 2050) early under SSP1 and SSP2 respectively (BHP/Glencore: 2040/2027 (SSP1-RCP1.9) and 2044/2026 (SSP2-RCP1.9)), with Glencore also finishing its entire SSP5 production budget early in 2036. In 2050, SSP1-RCP1.9, SSP2-RCP1.9 and SSP5-RCP1.9 rely on 13%, 29% and 45% of global cumulative coal production to have been paired with CCS. If the companies follow the IEA NZE pathway (again receiving 1.25% and 1.45% of global production) and continue at the 2010-2018 production growth rate from 2014 until 2050, they will finish their budgets in 2043 (BHP) and 2029 (Glencore). This last result reflects the incorporation of the most recent production levels in the IEA models, which are higher than modelled under SSP1 and SSP2. Whilst the IEA therefore requires a much faster annual decarbonization than SSP1 and SSP2, the IEA still allows a larger cumulative production budget for coal (Fig. 1b). Figures and details for each of 142 companies covering coal, oil and gas can be found in the Supplementary Data.

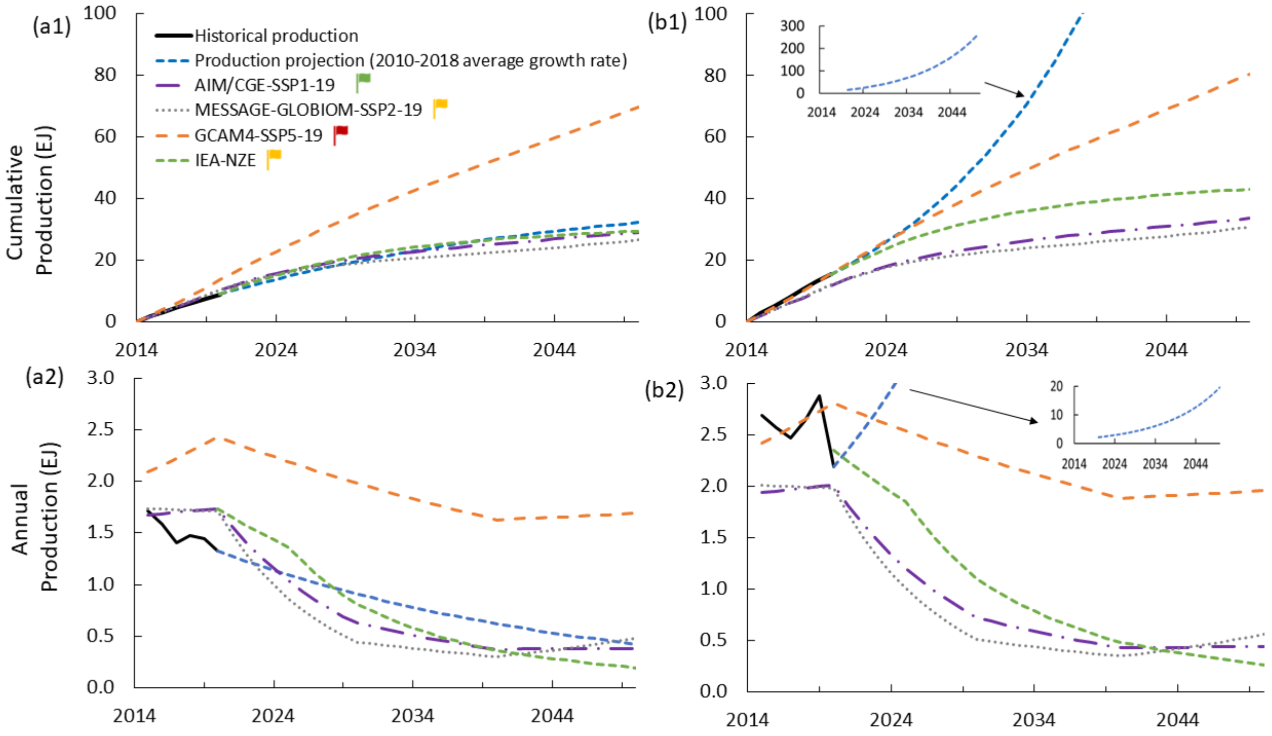

Fig. 1. Alignment of a sample company, BHP and Glencore, with 1.5°C climate pathways since 2014 in forms of: a) cumulative production; b) annual production. This figure demonstrates the performance of a sample company, BHP (a1 and a2) and Glencore (b1 and b2), against three IPCC scenarios and the IEA Net Zero Emissions scenario. Using a grandfathering approach, production pathways are allocated to an individual company based on the company's average production between 2010 and 2014, and aligned with AIM/CGE - SSP1-RCP1.9 (purple long dash-dot), MESSAGE-GLOBIOM SSP2-RCP1.9 (grey dot) and GCAM SSP5-RCP1.9 (orange short dash), commencing in 2014, and the IEA NZE scenario, commencing in 2020 (green short dash). The flags following the pathway descriptions indicate the reliance on CCS, with red, yellow and green reflecting very high, medium, and low to medium levels of CCS respectively. Specific CCS requirements under each scenario can be found in Figure 2. None of the pathways involve very low or zero requirements of CCS. The 2019-2020 production budget of the IEA NZE was obtained by downscaling the world's actual production.

The company's production is projected forward using their average production growth between 2010-2018 (blue short dash).

Table 2 displays the performance of the top 5 mis-aligned companies compared to the "middle of the road" (SSP2) scenario. For coal, oil and gas, the companies with the highest production overshoot in percentage terms, have a small share of global production of less than 1% between 2010-2014, and except for coal, are mainly Investor-Owned Companies. These companies have emitted 2.7-3.3, 1.6-2.8, and 1.8-5.3 times their production budget between 2014-2020 (metric 1 [14]) for coal, oil and gas respectively, and are estimated to finish their total production budget (until 2050) between 2020 and 2031 (metric 2 [14]). In terms of absolute fossil fuel production overshoot, the largest 5 companies are mostly state-owned entities, and have collectively been producing larger shares of global production between 2014-2020, between 8.5 and 14%. Overall, we find that 64%, 63% and 70% of coal, oil and gas companies respectively are currently misaligned with the SSP2-RCP1.9 Paris aligned pathway (see Supplementary Data).

In Fig. 2 we demonstrate how the method can be applied to many companies given the large data availability of the input variables. We show the aggregate production alignment with our 1.5°C consistent IPCC scenarios for 74 coal companies, 67 oil companies, and 70 gas companies. Continuing an average growth rate of 2010-2018, the combined coal, oil, and gas production of these companies will exceed their cumulative production budget by 65%, 33% and 53% respectively, by 2050 according to SSP1-RCP1.9. Furthermore, 13%, 7% and 14% of the respective cumulative emissions from each fossil fuel coal, oil and gas, respectively, in 2050 needs to be mitigated with CCS. Under SSP2-RCP1.9, the production of coal, oil and gas will exceed their cumulative production budget by 68%, 34% and 20% respectively by 2050, similar to the SSP1-RCP1.9 pathway except a higher allowance for gas production. The utilization in combination with CCS also needs to be at the rate of 29%, 0% and 20% respectively in 2050. If companies align themselves with SSP5-RCP1.9 they will receive higher production budgets but that production will consequently need to be mitigated by higher deployment rates of CCS. The production of coal and oil will still exceed their cumulative production budget by 17% and 3% by 2050 with the average growth rate of 2010-2018, but the gas companies will produce 26%

less than the upper limit of the budget. Their production with CCS will need to be at a rate of 45%, 1% and 23% of cumulative emissions from coal, oil, and gas utilization respectively by 2050.

Our findings confirm that reducing coal production is particularly important to meet the Paris goals. It is also important to note that the pathways used in this study rely on significant levels of carbon removals in the second half of this century. In fact, even after the specific fossil fuel cumulative production has leveled off in some scenarios, CCS deployment continues to grow in combination with other negative emissions technologies like BECCS and DACCS. If such removals do not take place, carbon budgets will be exceeded, along with the 1.5ºC target. Note that the use of scenarios with high levels of negative emissions technologies should be carefully considered. Recent research has challenged assumptions of the potential decarbonisation role that can be played by CCS due to deep uncertainties over the sustainable injection rate, especially in certain regions [24], as well as other uncertainties such as food security, biodiversity and several others [25, 26].

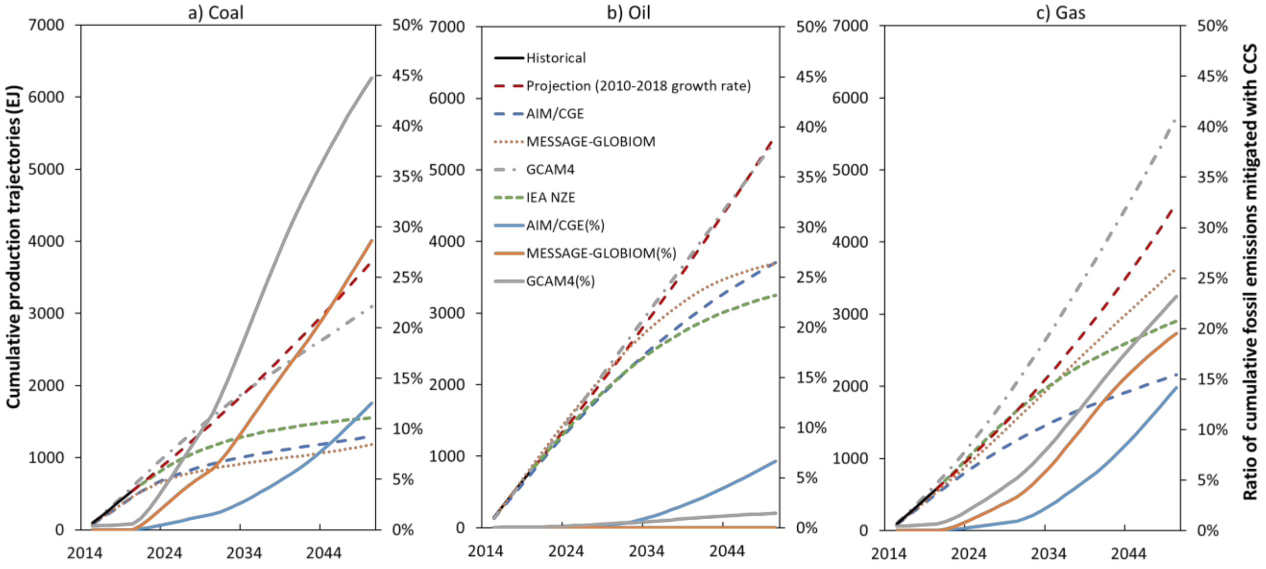

Fig. 2 global fossil fuel companies' collective production trajectories (cumulative production volume in the unit of exajoule) including: a) 74 coal companies, b) 67 oil companies, and c) 70 gas companies. This figure demonstrates the production performance of companies against AIM/CGE modelling for SSP1-RCP1.9 (blue dash), ratio of cumulative fossil emissions mitigated with CCS (blue solid line), MESSAGE-GLOBIOM for SSP2-RCP1.9 (orange dot), ratio of cumulative fossil emissions mitigated with CCS (orange solid line), GCAM4 for

SSP5-RCP1.9 (grey dash dot dash), ratio of cumulative fossil emissions mitigated with CCS (grey solid line), which commences in 2014, and the IEA NZE scenario (green dash), commencing in 2020. The global production budgets are downscaled to the company level based on each companies' average production share of the global production between 2010 and 2014 (see equations 1 and 2). The projection (red dash) is based on the average growth rate of 2010-2018.

Discussion and conclusions

In this article we have proposed a simple and transparent method to evaluate a wide range of fossil fuel companies against climate scenarios. Our methodology complements the current carbon intensity convergence models for science-based target setting in two ways. First, the findings can help fossil fuel companies set Science-based targets without conducting carbon accounting. Many fossil fuel companies struggle to provide complete carbon accounting, especially for scope 3 emissions [19]. Second, this method complements the previous Science-based targets setting method by providing an alternative way to measure their performance, i.e. production budget or production trajectories for a time series. Our simple method can not only be applied to oil and gas but also coal producers, supplementing the SBTi standard that only focuses on the oil and gas industry [16].

Global stakeholders can use our results to easily assess fossil fuel companies' performance against NZE and 1.5 °C scenarios without in-house expertise in carbon accounting. This method provides a transparent, but approximate, assessment using publicly available production data, thus increasing accessibility and consistency. By focusing solely on production, we avoid carbon accounting methods that increase data requirements and analytical complexity, such as the use of poorly reported scope 3 emissions [19]. Thus, for the fossil fuel companies where absolute emissions or intensities are not provided or cannot be determined, we provide interested parties with a straightforward methodology. We encourage all fossil fuel companies to use our method to set their production targets in addition to their emissions targets. This will help to improve the transparency and consistency for global stakeholders to assess their climate risks. Our method offers a useful contribution to be considered by the Science Based Targets initiative, which is currently revising their SBTi Oil & Gas standard, and to extend the standard to include coal [16].

We evaluate the largest 142 producers of coal, oil, and gas against three 1.5°C IPCC SSP-1.9 pathways from 2010. We find that the 142 companies would produce up to 65%, 33% and 55% more than the cumulative production budget of coal, oil and gas respectively by 2050 if they continued the trend of the average growth rate of 2010-2018. We clearly highlight the CCS required under the three different IPCC scenarios for each fossil fuel (IEA only has cumulative CCS available, demonstrated in the Supplementary data). Coal production in particular will need to be paired with CCS such that up to 40% of the cumulative fossil fuel emissions have been captured and stored by 2050. In a number of RCP-1.9 pathways, even after fossil fuel production has been substantially reduced into the second half of the century, CCS must continue to expand to draw down accumulated carbon dioxide in the atmosphere. Depending on the pathway, CCS rates after mid-century can range from around 5,000 million to over 20,000 million tonnes of CO_2 per annum – some two orders of magnitude more than current global CCS capacity, the feasibility of which is highly uncertain [27]. Furthermore, the reliance on negative emissions technologies later in the century to recover from a carbon budget overshoot is a high-risk strategy [28]. In order for companies to claim Paris-alignment, we argue they must be held accountable for the achievement of the levels of mitigation via CCS (including fossil CCS, BECCS and DACCS) projected under their specified pathway. This would include, for example, requirements to produce credible forward deployment plans for CCS, and to report annual CCS development and project capital invested, and actual capacity in service (e.g. million tonnes per year of CO_2 being captured and sequestered), to give credibility to such pathways.

The approach demonstrated in this manuscript comes with inevitable caveats and limitations (see Supplementary Materials). Nevertheless, it provides a valuable new approach for evaluating fossil fuel producers’ alignment with 1.5°C fossil fuel demand trajectories. This is an important tool for a range of stakeholders seeking to assess the performance of fossil fuel companies against Paris Compliant decarbonization pathways, as well as informing fossil fuel producers of the clear and unavoidable need for them to transform their businesses. For stakeholders such as regulators, policy makers, consumers, and investors to effectively implement climate-safe decisions, it is important they have access to granular, robust, and accessible information. Specifically, our work can be used to provide guidance for the practical operationalization of a fossil fuel non-proliferation treaty, which is increasingly being called for by nations, Nobel Laureates, academics and health organisations [29].

Of course, the tool presented here has limitations when it comes to major global shocks and energy supply disruptions. Fossil fuel producers can find themselves being pushed in two opposing directions by such shocks. On the one hand, governments and investors demand they respond to the threat posed by climate change and reduce their direct and indirect contributions to global GHG emissions. On the other hand, shocks such as the invasion of Ukraine and the subsequent sanctions imposed by NATO aligned countries can lead to very high energy prices, as experienced recently in Europe and Asia. As a result, fossil fuel companies find themselves being pushed to increase oil and gas, and even coal production. This is motivated both by the desire of governments to minimise the burden on their constituents, but also by companies and its investors seeking to take advantage of the windfall profits that are flowing. The crucial question is whether this 'off-ramp' from their decarbonisation pathway is temporary and reversible, or whether it might be adopted strategically to extract longer term relaxation of efforts to decarbonise.

Methods

We source the equity production data of global coal, oil and natural gas producers in the year 2010-2018 from the Carbon Major Project hosted by the Climate Accountability Institute at https://climateaccountability.org/carbonmajors.html. In addition, we sourced coal production data in the year of 2010-2018 of the top 50 Chinese coal producers (ranking by production rate in 2017) from the *China Coal Industry Yearbook*, and companies' public disclosures. The production data of fossil fuel has been converted to the unit of exajoule (EJ) to be consistent with fossil fuel demands projections from IEA and IAMs. The conversion factors are sourced from *Statistical Review of World Energy* [24] and are provided in the sheets 'conversion coal', 'conversion oil' and 'conversion gas' of the Supplementary Data. Coal, oil and gas are converted from million tonnes, million barrels and billion cubic feet, respectively, to exajoules using these conversion factors.

The datasets combined cover 74 coal companies representing 56% of the global coal production, 67 oil companies representing 76% of the global oil production and 70 natural gas companies with 76% of the global natural production during 2010-2020. There are 142 companies in total with several of them producing more than one type of fossil fuel. The world's annual production data is sourced from the *Statistical Review of World Energy* [24]. We distinguish between Investor-Owned Companies (IOCs) and State-Owned Entities (SOEs), where companies are classified as state-owned if more than 50% of the company is owned by a government [17].

Fossil fuel demand trajectories are extracted from Integrated Assessment (IAM) scenarios from the SSP database hosted by the IIASA Energy Program at https://tntcat.iiasa.ac.at/SspDb. There are 13 SSPs-1.9 scenarios available from the six IAM frameworks including AIM/CGE, GCAM4, IMAGE, MESSAGE-GLOBIOM, REMIND-MAGPIE, WITCH-GLOBIOM which represent the primary IPCC 1.5 °C trajectories. As it is suggested that "across all 13 available scenarios, net zero GHG emissions are reached around 2055–2075 (rounded to the nearest 5 years)" and these scenarios will limit end-of-century radiative forcing to 1.9 Wm^{-2} scenarios, and consequently restrict median warming in the year 2100 to below 1.5 °C [30]. Consequently, "all scenarios keep warming to below 2 °C with a more than 66% probability, and maximum (peak) median temperature estimates vary from 1.5 °C to 1.8 °C" [30], which is consistent with 1.5 °C of warming above pre-industrial levels with a "low" overshoot. The International Energy Agency (IEA) has also recently published the *Net Zero Emissions Roadmap* with a fossil fuel demand trajectory which is also adopted in this study [31].

The five "Shared Socioeconomic Pathways" (SSPs) examine how changes in global societal behaviour, demographics and economics over the next century could impact on global emissions, and are used extensively in IPCC Sixth Assessment Report. The SSPs are based on the five narratives: a world of sustainability-focused growth and equality (SSP1); a "middle of the road" world where trends broadly follow their historical patterns (SSP2); a fragmented world of "resurgent nationalism" (SSP3); a world of ever-increasing inequality (SSP4); and a world of rapid and unconstrained growth in economic output and energy use (SSP5). A Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory that was adopted by the IPCC prior to the development of the

SSPs. The RCPs are labelled after a possible range of radiative forcing values in the year 2100 (e.g. the RCP2.6= 2.6 W/m^{2}and produces average global temperature anomolies of around 2 degrees above pre-industrial levels by 2100). Since the IPCC Fifth Assessment Report the original pathways have been combined with Shared Socioeconomic Pathways. The SSPs each produce different RCPs given the level of carbon taxation applied to the global economy (e.g. SSP1-RCP2.6 and SSP5-RCP8.5). Along with these new scenario-pathway combinations, new RCPs have also been introduced, including RCP1.9, which are the RCP consistent with 1.5 degrees above pre-industrial levels.

For composing 1.5 °C Paris-aligned production trajectories for individual fossil fuel producers, we follow [9] to identify Paris Compliant Pathways. This approach first requires the selected decarbonisation pathways to be consistent with a "well-below" 2°C or in our case 1.5 °C pathways (given we focus on 1.5 °C consistent pathways). Second, it requires the base year from which progress is measured to be consistent with the starting year of the underlying base year (for an explanation see [14]).

Eligible decarbonisation pathways and base year used. To identify eligible pathways, we select IPCC IAM pathways that are consistent with 1.5°C and start in 2015 or prior. We have identified six pathways that commence in 2010 and seven that commence in 2005. For demonstration purposes, we have chosen to use three RCP1.9 scenarios pathways (i.e. AIM/CGE SSP1, MESSAGE-GLOBIOM SSP2, GCAM4 SSP5). These three scenarios were chosen because they are publicly available in the IIASA database[1], were developed by modelling groups recognized by the IPCC, represent illustrative 1.5-degree pathway archetypes from three different socio-economic pathways [32], and are aligned with our "Paris Compliance" requirement that the decarbonization pathway begins on or prior to 2015. The scenarios we use have historical data from 2010-2014, and model from 2015 onwards [30]. Therefore, the year 2014 was selected as the base year. We have not made any amendments to these scenarios to account for a potential mismatch between the global production in the base year and that used in the IPCC IAM pathways. As stated in the Supplementary Materials of [30] the 2010 emissions for each of these scenarios fall within the uncertainty range of estimate historical global CO_2 emissions in that year

[30]. Note that we could apply our methodology to any other IPCC or global decarbonization pathways that apply different allocation methods provided they also complied with our “Paris Compliance” requirements. Using earlier base years and other allocation methods would require more data but is an option that is certainly worth exploring.

For comparison purposes, we also use the IEA’s NZE roadmap demand projections which starts from 2020. This pathway uses real-world performance tracing back to 2010 as it has taken the global fossil fuel companies’ historical performance into account. Thus, if the global fossil fuel companies follow IEA’s NZE roadmap from 2020 forward, 1.5°C limits would be kept. In terms of cumulative production, global fossil fuel companies may follow any of the three SSPs-1.9 scenarios from the base year 2010 or IEA's NZE roadmap from the base year 2020 to be on track with 1.5 °C trajectories, but with the proviso that they are able to verify that CCS requirements have been, and will continue to be, met under the trajectory. We indicate the riskiness of the different pathways given their high reliance on CCS by including “flags”; a “red” flag for SSP5, an “yellow ” flag for SSP2 and IEA NZE, and a “green” flag for SSP1. Using the IEA NZE pathway does ignores the inequality of budget allocation by shifting the base year, allowing companies to ignore their production prior to 2020 [14]. Note that all the scenarios below rely on different assumptions on societal and economic developments, and reliance on extensive use of CCS and carbon removal technologies. We demonstrate these differences in Table 3 for the scenarios we use. Finally, if a company’s production is not currently aligned with a pathway does not necessarily mean it cannot re-align itself; a company’s commitments to future production and CCS levels may make its plans aligned with a cumulative 1.5 °C production budget and CCS requirements.

Allocation of the production budget using average production 2010-2018. There are many ways to allocate a burnable fossil fuel production budget. For demonstration purposes, we allocate the annual production budget based on a company’s share of the world’s total production from 2010 to 2014. A number of studies have concluded that any new investment in fossil fuel-based assets will be inconsistent with a 1.5 degree scenario without stranding assets [30, 33, 34], which is consistent with the 2010 base year of the SSP-1.9 scenarios that we use. Note that if a decarbonisation scenario starting in 2005 is applied, the allocation would be the average share of production between 2005 and the year to which historical production is used, making the company accountable since the year production is projected from.

The equation is given as:

$$\mathrm{CPB}_{\mathrm{i,j,k}} = \mathrm{GPB}_{\mathrm{j,k,e}} \cdot \mathrm{RCP}_{\mathrm{i,j,k}} \qquad (1)$$

$$\mathrm{RCP}_{\mathrm{i,j,k}} = \frac{\sum_{k=2010}^{k=2014} CP_{i,j,k}}{\sum_{k=2010}^{k=2014} TCP_{j,k}} \qquad (2)$$

Where $\mathrm{CPB}_{\mathrm{i,j,k}}$represents the annual Company Production Budget (CPB) in the year k of company i for fuel j (in EJ). $\mathrm{GPB}_{\mathrm{j,k,e}}$ represents the global production budget (GPB) for fuel j in the year k of the chosen decarbonisation pathway e (in EJ). $\mathrm{RCP}_{\mathrm{i,j,k}}$represents the ratio of company i's production to the world's annual production during the period 2010-2014. $\sum_{k=2010}^{k=2014} \mathrm{CP}_{i,j,k}$ is the sum of company i's production of fuel j from the year 2010 to 2014 (in EJ) while $\sum_{k=2010}^{k=2014} \mathrm{TCP}_{j,k}$ is the sum of the world's total annual production from the year 2010 to 2014 (in EJ). The world's annual production data is sourced from the *Statistical Review of World Energy* [23].

Even if production exceeds the global production budget under a certain scenario, it does not necessarily mean that the 1.5 °C carbon budget would be exceeded since the carbon budget is directly related to the energy consumption rather than the production. However, aligning the production trajectories with fossil fuel demands gives an optimal benchmark for companies and their stakeholders to maximize profit without oversupplies over time in a carbon-constrained world.

Remaining production budget (RPB). We deduct the company's accumulative production since 2010 from the company's cumulative company production budget from 2010 to 2050. Thus,

$$\mathrm{RPB}_{\mathrm{i,j,k,e}} = \mathrm{TCPB}_{\mathrm{j,e}} - \sum_k \mathrm{CP}_{\mathrm{i,j,k}} \qquad (3)$$

$$TCPB_{j,e} = \sum_{k=2010}^{2050} \mathrm{CPB}_{\mathrm{i,j,k}}$$

Where $\mathrm{RPB}_{\mathrm{i,j,k}}$ represents the remaining production budget from the company *i* that produces fuel *j* from year *k* to 2050 for scenario e (three SSPs-1.9 scenarios and IEA NZE). $\mathrm{TCPB}_{\mathrm{j,e}}$ is the total production budget for scenario e, which is the sum of the annual CPB's from equation 1 between 2010-2050. $\sum_k \mathrm{CP}_{\mathrm{i,j,k}}$ represents the sum of company *i*'s production of fuel *j* from the base year to the year *k*.

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Code availability: All code that support the findings in this study are available in the data repository for which accession codes will be available before publication.

	2010-2014 production (EJ) (a)		**2015-2020 allowance (EJ)** (% of global in (a) * global allowance SSP1, -2 and -5 2015-2020)			**2021-2050 allowance (EJ)** (% of global in (a) * global allowance SSP1, -2, and 5 2021-2050)		
		% Global	**SSP1**	**SSP2**	**SSP5**	**SSP1**	**SSP2**	**SSP5**
Global Coal	809	100%	816	824	1079	1502	1298	4475
Coal India (India)	46	5.7%	46	47	61	85	73	254
CHN Energy (China)	46	5.7%	46	47	61	85	73	253
Peabody Energy (USA)	21	2.6%	21	22	29	39	34	117
China National Coal Group (China)	18	2.2%	18	18	24	34	29	100
Datong Coal Mine Group (China)	14	1.7%	14	14	19	26	22	77

Table 1: Production allowance (in Exajoules) for the largest five coal producers. Production allowances (EJ) under the IPCC 1.5C AIM/CGE SSP1-RCP1.9, MESSAGE-GLOBIOM SSP2-RCP1.9, and GCAM SSP5-RCP1.9 scenarios, based on share of global production between 2010-2014.

	% of global production required to be paired with CCS per year											
	SSP1				**SSP2**				**SSP5**			
	‘20	**‘30’**	**‘40**	**‘50**	**‘20**	**‘30’**	**‘40**	**‘50**	**‘20**	**‘30’**	**‘40**	**‘50**
Coal	0%	1.5%	5.6%	12.6%	0%	6.0%	16.6%	28.6%	0.6%	11.5%	30.3%	44.7%
Oil												
Gas												

Panel a: top 5 mis-aligned producers by percentage production overshoot (metric 1)

	Ownership	Production		Performance (against SSP2)	
		% global (2010-2014)	Absolute production overshoot (EJ)	Metric 1: Performance to date (2014-2020)	Metric 2: Estimated year to finish total production budget
Coal					
Whitehaven Coal, Australia	IOC	0.07%	1.41 EJ	3.29	2020
Jinneng Group Co., China	SOE	0.61%	9.50 EJ	2.88	2020
Shanxi Coal IMP. & EXP. Group Co., China	SOE	0.17%	2.55 EJ	2.82	2020
Baise Mining Group Co., China	SOE	0.04%	0.52 EJ	2.79	2025
Huadian Coal Industry Group Co., China	SOE	0.27%	3.86 EJ	2.73	2031
Oil					
EQT Corporation, USA	IOC	0.01%	0.29 EJ	2.80	2023
Novatek, Russian Federation	IOC	0.10%	1.57 EJ	2.27	2024
Pioneer, USA	IOC	0.09%	1.54 EJ	2.27	2023
EOG Resources, USA	IOC	0.22%	2.58 EJ	1.85	2024
Polish Oil & Gas, Poland	SOE	0.01%	0.12 EJ	1.56	2026
Gas					
Antero, USA	IOC	0.10%	3.32 EJ	5.72	2021
EQT Corporation, USA	IOC	0.23%	4.76 EJ	3.95	2022
Rosneft, Russian Federation	SOE	0.83%	8.40 EJ	2.44	2025
Wintershall, Germany	IOC	0.34%	2.25 EJ	1.93	2029
Repsol, Spain	IOC	0.45%	0.07 EJ	1.82	2031

Panel b: top 5 mis-aligned producers by absolute fossil fuel production overshoot (EJ)

Coal					
Coal India, India	SOE	5.68%	24.23 EJ	1.52	2024
CHN Energy, China	SOE	5.66%	15.09 EJ	1.32	2025
Jinneng Group Co., Ltd. , China	SOE	0.61%	9.50 EJ	2.88	2020
Yankuang Group Co,.Ltd., China	SOE	1.02%	8.48 EJ	2.01	2022
Shandong Energy Group Co.,Ltd., China	SOE	1.48%	7.33 EJ	1.60	2022
Oil					
Rosneft, Russian Federation	SOE	3.11%	11.94 EJ	1.29	2029
Iraq National Oil Company, Iraq	SOE	2.52%	11.01 EJ	1.35	2029
Abu Dhabi National Oil (ADNOC), UAE	SOE	2.83%	5.61 EJ	1.16	2030
Gazprom, Russian Federation	SOE	1.09%	4.13 EJ	1.31	2028
Canadian Natural Resources, Canada	IOC	0.46%	2.96 EJ	1.51	2026
Gas					
National Iranian Oil Company (NIOC), Iran	SOE	4.64%	14.53 EJ	1.43	2033
Rosneft, Russian Federation	SOE	0.39%	8.40 EJ	2.44	2025
PetroChina (CNPC), China	SOE	2.63%	5.39 EJ	1.32	2037
EQT Corporation, USA	IOC	0.11%	4.76 EJ	3.95	2022
Nigerian National Petroleum, Nigeria	SOE	0.75%	4.05 EJ	1.67	2030

Table 2: Top 5 mis-aligned companies for coal, oil and gas based on percentage overshoot (panel a) and absolute fossil fuel production overshoot (panel b). Metric 1 measures the performance since the base year (cumulative production since the base year 2014 relative to MESSAGE GLOBIOM SSP2-consistent production pathway). The absolute production overshoot (EJ) an absolute measure of Metric 1(the absolute difference between the cumulative production since the base year 2014 relative to MESSAGE GLOBIOM SSP2-consistent production pathway). Metric 2 estimates year that the company's total production budget (until 2050) will be fully produced if production continues at 2010-2018 growth levels. Companies that did not have 2020 data yet have been excluded from this table.

Model – Scenario	Variable (Emissions $MtCO_2/yr$)	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
AIM/CGE - SSP1-RCP1.9	CO_2	35,783	37,234	19,057	8,229	1,795	-2,181	-3,757	-4,338	-4,390	-4475
GCAM4 - SSP5- RCP1.9	CO_2	35,775	41,976	35,675	4,908	-8,996	-9,658	-9,489	-12,165	-18,181	-26,395
MESSAGE-GLOBIOM - SSP2- RCP1.9	CO_2	40,314	40,931	23,633	11,524	3,779	-1,511	-6,540	-10,609	-12,411	-13,049
AIM/CGE - SSP1- RCP1.9	CO_2 Fossil Fuels and Industry	31,157	33,620	19,133	10,936	5,574	1,944	515	-203	-492	-861
GCAM4 - SSP5- RCP1.9	CO_2 Fossil Fuels and Industry	32,647	40,366	31,325	14,394	10,380	7,453	2,844	-4,535	-13,106	-22,551
MESSAGE-GLOBIOM - SSP2- RCP1.9	CO_2 Fossil Fuels and Industry	33,152	36,455	22,912	13,020	6,064	1,876	-2,973	-6,872	-8,159	-8,887
AIM/CGE - SSP1- RCP1.9	CO_2 Land Use	4,626	3,614	-76	-2,706	-3,779	-4,126	-4,272	-4,136	-3,899	-3,614
GCAM4 - SSP5- RCP1.9	CO_2 Land Use	3,128	1,610	4,350	-9,486	-19,376	-17,111	-12,333	-7,630	-5,075	-3,844
MESSAGE-GLOBIOM - SSP2 RCP1.9	CO_2 Land Use	7,162	4,477	722	-1,496	-2,285	-3,386	-3,567	-3,736	-4,251	-4,162
AIM/CGE - SSP1- RCP1.9	CO_2 Carbon Capture and Storage	0	0	471	3,098	6,316	5,726	5,623	5,305	5,405	5,254
GCAM4 - SSP5- RCP1.9	CO_2 Carbon Capture and Storage	1,813	2,637	11,205	26,831	33,103	35,968	36,146	33,253	31,133	32,624
MESSAGE-GLOBIOM - SSP2- RCP1.9	CO_2 Carbon Capture and Storage	0	0	1,846	5,695	8,602	9,090	10,569	12,510	12,919	13,607
IEA	CO_2 Carbon Capture and Storage	0	39	1,664	5,619	7,600	NA	NA	NA	NA	NA

Table 3. IPCC scenarios used in this study. IPCC scenarios used in this study with their global carbon budget (CO_2), CO_2 Fossil Fuels and Industry, CO_2 Land Use and CO_2 Carbon Capture and Storage (including fossil CCS, BECCS and DACCS).

Supplementary Materials

Evaluating fossil fuel companies’ alignment with 1.5°C climate pathways

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Supplementary text

Our supplementary text consists of five main sections:

1. The remaining production budget for global fossil fuel companies under different decarbonisation scenarios
2. Allocation of global fossil fuel production budgets – robustness and discussion
3. Comparison and contribution to prior work
4. Different carbon accounting methods and allocations: Bottom-up and top-down responsibility for corporate climate target setting
5. Limitations of this study

1. The remaining production budget for global fossil fuel companies under different decarbonisation scenarios

The remaining production budget for global fossil companies has been allocated to individual companies (**Supplementary Figure 1**) based on the three IAM SSPs-1.9 scenarios from 2021 to 2050. For instance, BHP has a historical contribution in 2010-2020 of 19 EJ. As the total production budget for BHP in the AIM/CGE SSP1, MESSAGE-GLOBIOM SSP2 and GCAM SSP5 scenarios are 29, 27 and 70 EJ respectively, the remaining production budgets for BHP Billiton are calculated as 10, 8 and 51 EJ. The details for 142 companies are provided in the Supplementary Data.

2. Robustness of the allocation method and discussion

There has been a long-term debate around whether a production budget should be allocated to current reserve-rich companies, given that any new exploration would lead to extra economic and environmental costs. However, as the reserves are concentrated in a few companies, the budget varies significantly with different approaches to the allocation of production and reserves [15]. When allocating the production budget by reserves in 2017, the largest ten oil-reserve companies represent 70% of the world's production budget, however, they only represent 28% based on their average production share of the years 2010-2014. A similar situation applies to the natural gas industry. The largest ten gas reserve companies could be allocated 60% of the world's production budget by reserve share in 2017, but only 34% by production share over the years 2010-2014.

Some reserve-rich companies have very high reserve-to-production ratios. For example, the biggest oil reserve is reported to be Petroleos de Venezuela with 18% of the world's total reserves, but they only produced 2% of the world's total oil during 2010-2014, due to limited extraction technologies.

Adding a weight of historical contribution for calculating the allocation could also lead to different production budgets. The largest ten oil and gas reserve companies have contributed 32% and 31% of the world's production since 1980. Gazprom, Russia has contributed 17% of the world's gas production since 1980, which is more than the rest of the nine companies combined (14%) (**Supplementary Figure 2**). It could be argued that the company should be allocated less production budget than others as they should share equal rights for development, but the production of smaller companies is constrained by the technologies and geopolitical factors. Companies' shares of world production also vary across years. Using production shares in different years for allocation leads to different budgets for individual companies. However, there is no one-size-fits-all solution. The average production rate of 2010-2018 proposed in this study has advantages in reflecting the current technologies and geopolitical factors. In addition, the production rate has the highest level of availability among all options (**Supplementary Table 1**).

3. Comparison with and contribution to previous work

This study has concentrated on the upstream producers to provide top-down production budgets and trajectories. These production budgets and trajectories can also be converted to carbon inventories and budgets based on an upstream production perspective.

Compared to carbon intensity targets in Dietz et al. [10], this study uses production budgets, which can be converted into absolute carbon budgets for upstream production-based Scope 3 emissions and operational emissions (i.e. part of scope 1, **Supplementary Table 2**). This information can supplement the use of carbon intensity targets and be adopted by upstream producers. As also mentioned in [10], "A two-part test may be appropriate, whereby companies can be aligned with climate goals either on the basis of their GHG intensity and decarbonization goals, as set out in this paper, or their absolute GHG emissions and plans to wind down O&G production" – which is the approach used in our study.

Our approach increases the transparency of climate targets even though it reduces the flexibility for companies. **Supplementary Table 3** has listed the 70 companies compared with the companies used in [8]. In addition, this study makes the first attempt in setting science-based targets for coal companies, which are not covered by the Science-Based Target initiative or the literature to date. We analysed 74 global coal companies.

4. Different carbon accounting methods and climate target methods: Bottom-up and top-down responsibility for corporate climate target setting

The life-cycle carbon emissions of fossil fuels include upstream emissions from exploration, production and processing, midstream emissions from transport, storage and trading, and downstream emissions from logistics, retail, and final fuel combustion. Many low- or zero-carbon solutions such as carbon capture and storage (CCS), natural CO_2 removal and renewables generation applied to the production processes will have an impact on the life-cycle carbon emissions and therefore should also be included in companies' carbon emission accounts.

When it comes to the climate responsibility of fossil fuel companies, it is common to conduct a bottom-up carbon accounting approach, focusing on either upstream use of inputs, downstream sold product or the combination of both, based on the boundary of the company's operational control, financial control or equity share [14] (**Supplementary Table 4**). Heede [28] proposed an upstream production-based (UPB) carbon accounting method which includes the emissions embodied in the upstream use of sold products (e.g. crude oil). The accounting scope only covers the emissions converted from combustible energy products, while the emissions from non-energy use (e.g. asphalt, lubricants, waxes, white-spirits and other distillates, olefins, petrochemical feedstock) are relatively minor and thus the emissions embodied in the use phase of non-energy products are excluded. The direct emissions from production have been included but the emission reductions from carbon removal technologies such as carbon capture and storage (CCS) and natural CO_2 removal, are excluded due to the difficulty in collecting data at a company-scale.

In contrast, SBTi's two accounting methods ("Well-to-Wheel" and "Use of Sold Product") are mainly focused on the emissions from the use of sold products. The "Well-to-Wheel" accounting includes emissions from exploration and production, downstream logistics and retail, energy efficiency services, carbon transfer and removal, renewables, and electricity production, distribution, and retail. Well-to-Wheel (WTW) accounting is more holistic compared to pure Use of Sold Product (USP) and aims to encourage producers to reduce the direct emissions from production, while the pure USP accounting is more applicable to producers who have not recorded the emissions from their production processes but only have the statistics of sold products.

Global fossil fuel producers tend to only target the emissions from their operations and ignore the emissions from the Use of Sold Products. This can be camouflaged by proposing a carbon intensity target while avoiding setting absolute emission reduction targets, based on Use of Sold Products which will directly lead to the reduction of fossil fuel production and profits.

Compared to bottom-up methods, this study adopted a top-down climate responsibility approach for fossil fuel companies by linking emissions directly to fossil fuel production. From a macro perspective, the global fossil fuel and carbon emissions share a natural bond and can be considered a coherent whole. This facilitates our alignment with IPCC and IEA's carbon mitigation trajectories, and enables public accessibility and transparency, as the top-down climate responsibility only requires the data of production.

Upstream, midstream, downstream, and integrated companies and applicable methods

All companies can apply the pure downstream USP methods based on an equity share principle, while upstream and integrated companies involved in the upstream productions can adopt the upstream production-based accounting method [14] (see **Supplementary Table 4**). For the top-down allocation methods, they are similar to upstream production-based method, and can be applied to upstream and integrated companies.

The pure USP and WTW methods are more comprehensive in calculating the individual companies' emissions accommodating their complex industrial processes (**Supplementary Table 5**). This should encourage individual companies to apply mitigation policies and negative-carbon technologies to operations.

However, there could be double counting for USP emission between upstream and downstream companies. For example, the emissions embodied in crude oil can be accounted twice by upstream companies and downstream final energy producers if there were no deduction of the overlapping parts in the supply chain between the companies. Also, there is no mechanism to pass the mitigation credit embodied in the energy products along the supply chain.

The UPB, the Burnable Fossil Fuel Allowance (BFFA) method [15] and the method presented in this paper only allocate the responsibility to upstream companies via emissions embodied in upstream products such as crude oil. The responsibility of midstream and downstream producers can be explored in future research. The emissions from processes such as transport, storage, and trading are not included in the method.

Climate target setting methods for fossil fuel producers

Sectoral Decarbonisation Approach. The Sectoral Decarbonisation Approach (SDA) sources the sectoral intensity pathway from Energy Technology Perspectives and regulates a corporate's intensity reduction targets by conducting the intensity convergence based on the sectoral intensity pathway. This "emissions pathway approach" should be distinguished from the "carbon budget approach" [11]. The original approach only provided a benchmark for Scope 1 and 2 emissions from an energy users perspective (i.e. secondary energy use perspective) rather than producers [13]. SBTi applies the SDA mechanism to energy producers covering the Scope 3 emissions from their Use of Sold Product. SBTi provides the preliminary standard for the oil and gas industry [14].

Dietz et al. [10] applies the SDA mechanism to energy producers covering the Scope 1 and 2, and emissions from the Use of Sold Product (part of Scope 3 emissions, excluding the emissions embodied in supply chain). The study develops intensity benchmark based on the Climate Change (IPCC)/Integrated Assessment Modeling Consortium (IAMC) 1.5°C Scenarios, to which companies' intensity targets are compared. The method does not necessarily converge the intensity to a sectoral level, i.e. it does not provide a reduction trajectory for companies. Instead, it makes a direct comparison between companies' targets and benchmarks. There are several challenges for adopting this revised

SDA method. For example, companies usually set targets in different scopes. Some of them focus on absolute emission targets (e.g. Scope 1-2) while others set intensity targets. In order to compare their targets with the benchmarks, they need their emissions to be converted to intensity of Scopes 1, 2 and 3 use of sold products. They must also assume that "emissions intensity of activities outside the scope of the target remains constant at the level in the latest disclosure year" [10].

Most fossil fuel companies disclose Scope 1 and 2 emissions while only some companies report emissions from use of sold product (part of Scope 3 emissions). Dietz et al. [10] listed self-disclosures of emissions by the world's top 54 gas and oil companies. 53/54 report Scope 1; 47/54 report Scope 2; 23/54 report emissions from use of sold product (part of Scope 3 emissions). Thus, it is possible to calculate the Scope 1-3 carbon intensity for most oil and gas companies by estimating the USP for the companies that do not have self-reported data. Many oil and gas companies are listed companies and they usually report their emissions in sustainability reports. However, when it comes to coal companies, particularly those concentrated in developing countries, challenges arise in calculating trajectories due to the lack of self-disclosures for Scope 1 and 2 emissions.

The advantages of the method provided by Dietz et al. [10] include both its flexibility and popularity. The intensity target allows companies to adopt various mitigation means such as carbon capture and storage, energy efficiency, and renewable production to offset the emissions, thus cutting down the carbon intensity. Many fossil fuel producers have published their intensity target, and it is pragmatic to build on what they have committed.

Least Cost Method. The Least Cost Method (LCM) was developed by Carbon Tracker for setting climate targets for individual companies and has been adopted by the SBTi. The approach prioritises the production from cheaper suppliers in the energy market, reflecting their greater financial viability as a guide to investors. It is assumed that the lowest cost projects will be the most competitive in a world with low demand for fossil fuels. It requires the estimation of energy price and demand projections combined with energy cost curve modelling as the allocation principle.

The LCM approach has the benefits of reflecting global financial markets – low cost producers will sustain production with the weakening of overall fossil fuel demand/prices. The LCM approach provides a capital expenditure budget for an individual company against the benchmark (i.e. a cost curve for fossil fuel production under the carbon budget), which offers fossil companies with an incentive to change their business model and an investment guide for shareholders.

A limitation of the LCM approach is that it is data intensive requiring high-level details for energy supply at the individual project level, including production cost, which reduces the accountability and transparency for the public and stakeholders. Carbon Tracker uses third-party data sourced from Rystad UCube, which is not free to the public.

Burnable Fossil Fuel Allowance. The Burnable Fossil Fuel Allowance (BFFA) method was proposed by Rekker et al. [15] and allocates producers a burnable fossil fuel allowance based on their 2010 production or 2010 reserves.

One of the advantages of the method is that it uses a production allowance. Relying only on production data makes it transparent and means it can be applied to many companies, given data is available for many primary energy producers globally.

The drawback of the method is that it assumes a linear relationship with a time series of past production, and therefore does not align with changes in future energy demands. Also, the method is consistent only with 2°C, i.e. not conformant with Paris compliant conditions.

This study. This study assigns the production trajectories to companies aligning with the energy demand projections from IEA's Net-Zero Emissions (NZE) roadmaps and several IPCC 1.5°C scenarios. The principle to allocate the annual energy production quota for individual fossil fuel companies based on their market share reflects current geopolitical and market realities. We follow the "grandfather" allocation approach that have been adopted in SBT methods (**Supplementary Table 6**) and propose the production budget allocation based on the "historical production shares" principle.

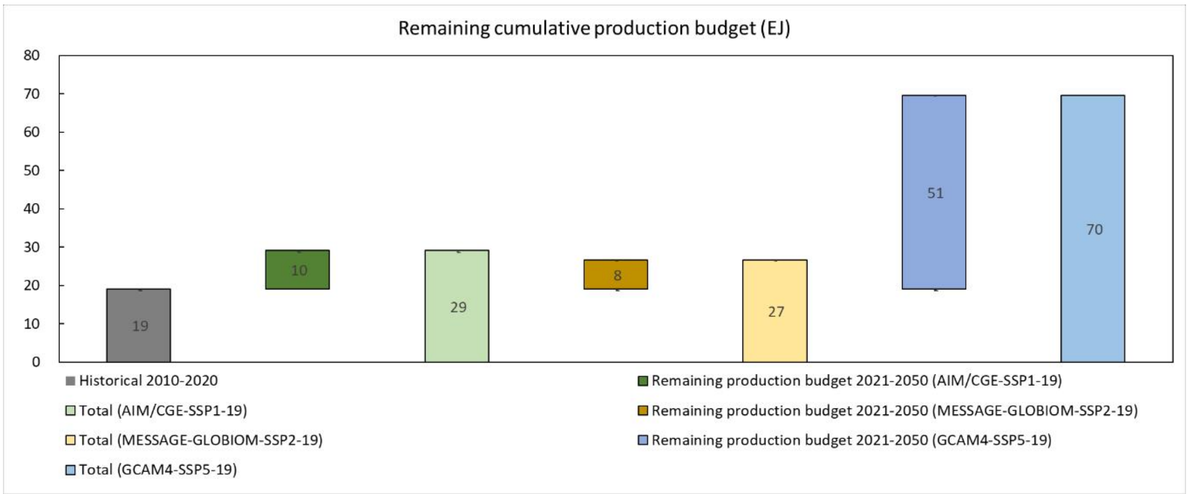
Our method is advantageous in providing a simple metric (i.e. production trajectories for a time series) without having to calculate scope 1-3 emissions, thus enhancing the method's transparency and consistency. The method only offers one universal target for a company, making it comparable with that of other companies, covering not only the oil and gas industry but also coal production. It is also beneficial for stakeholders without a technical background to measure the company's performance against NZE and 1.5 °C scenarios. Our method can also be applied to other 1.5 °C scenarios as long as they meet the Paris Compliance conditions outlined in Rekker et al. [12].

A disadvantage of the method is the lack of accounting for any carbon credits or offsets used by companies. The method requires direct production reduction, which threatens the profits of most fossil fuel companies, and thus it would not be an easy approach to adopt. The method does not account for any reductions in direct emissions (scope 1), leaving less mitigation options for individual companies.

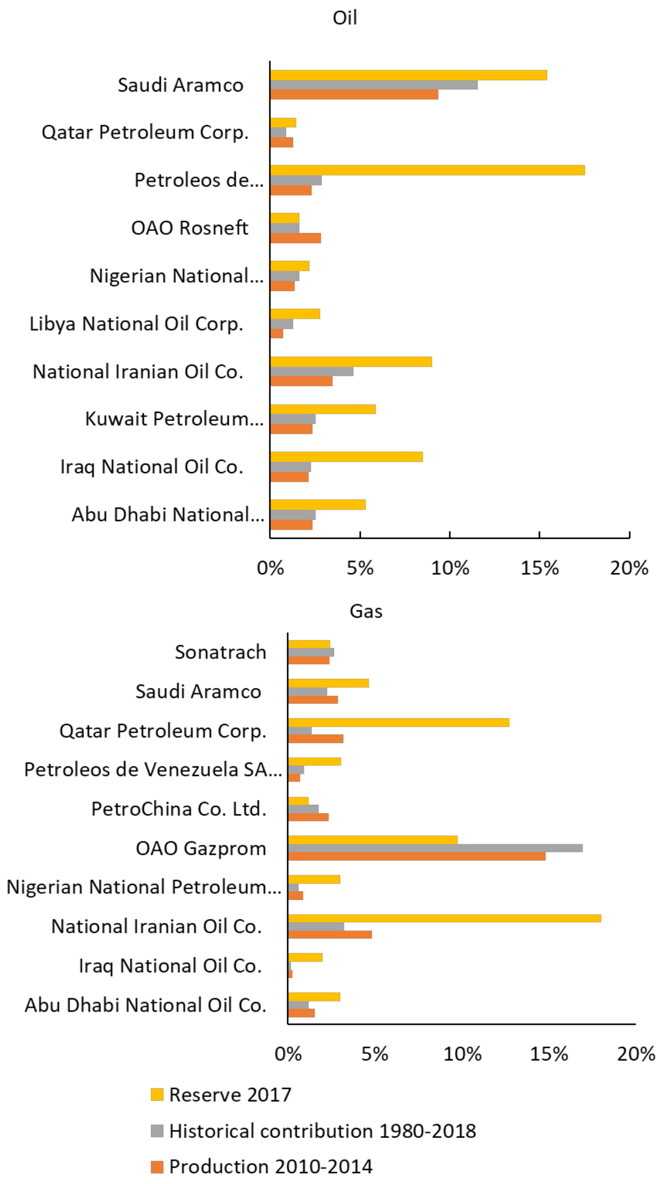
In sum, there is not one method that provides a silver bullet to providing climate targets for fossil fuel producers. However, the combination of all these methods will provide better transparency for stakeholders and complement each other's drawbacks. A summary of the methods can be found in **Supplementary Table 7**.

5. Limitations of this study

While this study provides a new approach for fossil fuel producers to evaluate their alignment with 1.5°C fossil fuel demand trajectories, it comes with caveats and limitations. First, we rely on the energy demand projected in IEA-NZE and IAMs models. The projected energy demands may involve ambitious behavioral change and improvements in efficiency, which may not be achieved. Second, since the approach only focuses on the production budget, there is no rewarding mechanism for scope 1 and 2 emissions mitigation actions from producers, which represent about 12%-20% of total emissions [10, 28], although these emissions will fall with the reduction of fossil energy production. Third, the method assigns the production budget based on recent production rates since 2010, which might not reflect most recent geopolitical and market factors. Furthermore, our approach does not consider factors such as penalizing for historical contribution, energy equality, or national energy security, which may weigh very differently in a potentially volatile political climate. There are many elements that remain challenging to the allocation of the carbon budget and should be further explored in future research. Namely, we have not accounted for equity in our method, i.e. ensuring that companies in developing countries get a larger share of the remaining fossil fuel production budget than companies in developed countries. Our approach focuses on upstream producers and cannot replace the methods that have been developed by SBTi and adopted by downstream producers.



Supplementary Figure 1. The remaining oil production budget from 2021 to 2050 for BHP under three scenarios. This figure shows the total oil production budget between 2011-2050 for BHP under the IPCC AIM/CGE SSP1 (light green), MESSAGE-GLOBIOM SSP2 (light yellow) and GCAM SSP5 (light blue) and the remaining production budget between 2021-2050 under the IPCC SSP1 (green), SSP2 (yellow) and SSP 5(blue).



Supplementary Figure 2. Historical contribution (1980-2018), reserves (in 2017) and production (2010-2014) levels as a percentage of the world for the largest ten oil and natural gas companies (based on reserves).

	Data availability	Company coverage (public)
Production (upstream)	High	Coal 74; Oil 67; Gas 70 (2010-2018)
Reserves	Low	Coal: NA; Oil 76; Gas 75 (in 2017)
Historical contribution	Low	Coal:27; Oil: 35; Gas: 37 (1980-2018)
Sold products (downstream)	Low	46 Oil and Gas combined (in 2018, Dietz et al., 2021).

Supplementary Table 1. Data availability for different allocation methods. This table displays how many companies have publicly available data for production levels, reserves in 2017, historical contribution between 1980-2018 and sold products.

	This Study	**Dietz et al. (2021) [10]**
Target	Annual and cumulative production 2010-2050	Carbon intensity of: Use of Sold Products/ Mixed Oil and gas Intensity
Production data	Complete 2010-2018 for all companies Base year in 2010	Varies across companies No fixed base year setting Benchmark from 2014
Scope 1 accounting	Our data can be converted to upstream operation emissions	Company self-reported data
Scope 1 budget	Can be converted to upstream operation emissions	NA
Scope 2 accounting	NA	Company self-reported data
Scope 2 budget	NA	NA
Scope 3 accounting	Can be converted to upstream production-based	Use of Sold Products
Scope 3 budget	Can be converted to upstream production-based	NA

Supplementary Table 2. Carbon accounting and target setting of this study compared with Dietz et al. [10].

Company Name	**Dietz et al. 2021 [8]**	**This study**	**Company Name**	**Dietz et al. 2021**	**This study**
Abu Dhabi National Oil (ADNOC), UAE	NA	√	Novatek, Russian Federation	√	√
Anadarko, USA	NA	√	Obsidian / PennWest, Canada	NA	√
Antero, USA	NA	√	Occidental, USA	√	√
Apache, USA	√	√	Oil and Natural Gas Corporation, India	NA	√
Bahrain Petroleum Corporation	NA	√	OMV Group, Austria	√	√
BHP Billiton, Australia	NA	√	Pertamina, Indonesia	NA	√
BP, UK	√	√	Petoro, Norway	NA	√
Canadian Natural Resources, Canada	√	√	PetroChina (CNPC), China	√	√
Chesapeake, USA	NA	√	PetroEcuador	NA	√
Chevron, USA	√	√	Petroleo Brasileiro (Petrobras), Brazil	NA	√
CNOOC (China National Offshore Oil), China	√	√	Petroleos de Venezuela, Venezuela	NA	√
ConocoPhillips, USA	√	√	Petroleos Mexicanos (PEMEX), Mexico	NA	√
CONSOL Energy, USA	NA	√	Petroleum Development Oman, Oman	NA	√
Devon Energy, USA	√	√	Petronas, Malaysia	NA	√
Ecopetrol, Colombia	√	√	Pioneer, USA	√	√
Egyptian General Petroleum, Egypt	NA	√	Polish Oil & Gas, Poland	NA	√
EnCana, Canada	NA	√	PTTEP, Thailand	NA	√
ENI, Italy	√	√	Qatar Petroleum, Qatar	NA	√
EOG Resources, USA	√	√	Repsol, Spain	NA	√
EQT Corporation, USA	NA	√	Rosneft, Russian Federation	√	√
Equinor, Norway	√	√	Royal Dutch Shell plc, The Netherlands	√	√
ExxonMobil, USA	√	√	Santos, Australia	√	√
Gazprom, Russian Federation	√	√	Sasol, South Africa	NA	√
Hess, USA	√	√	Saudi Aramco, Saudi Arabia	√	√
Husky, Canada	NA	√	Sinopec, China	NA	√
Inpex, Japan	√	√	Sonangol, Angola	NA	√
Iraq National Oil Company, Iraq	NA	√	Sonatrach, Algeria	NA	√
Kuwait Petroleum Corp., Kuwait	NA	√	Southwestern, USA	NA	√
Libya National Oil Corp., Libya	NA	√	Suncor, Canada	NA	√
Lukoil, Russian Federation	√	√	Syrian Petroleum, Syria	NA	√
Marathon, USA	√	√	Total, France	√	√
Murphy Oil, USA	NA	√	TurkmenGaz, Turkmenistan	NA	√
National Iranian Oil Company (NIOC), Iran	NA	√	Wintershall, Germany	NA	√
Nigerian National Petroleum, Nigeria	NA	√	Woodside, Australia	√	√
Noble Energy, USA	√	√	YPF, Argentina	NA	√

Supplementary Table 3. Comparison of the companies in this study and Dietz et al. [10].

		Upstream Companies	Midstream Companies	Downstream Companies	Integrated Companies
Bottom-up	Upstream Production-based	√			√
	Pure Use of Sold Product	√	√	√	√
	Well-to-Wheel	√	√	√	√
Top-down	BFFA	√			√
	This study	√			√

Supplementary Table 4. Bottom-up and top-down methods suitable for upstream, midstream, downstream and integrated companies.

		Upstream Production-based (UPB)	**Pure Use of Sold Product (USP)**	**Well-to-Wheel (WTW)**
Upstream	Exploration, Production and Processing	√		√
	Use of Sold Products (combustible)	√	√	√
	Use of Sold Products (non-combustion)			
Midstream	Transport, Storage, and Trading			√
	Petrochemicals			
	Refining			√
Downstream	Use of Sold Products (e.g. gasoline and petrol)		√	√
	logistics and retail			√
	Energy efficiency services			√
Upstream/Midstream/Downstream	CCS, Natural CO2 Removal, and Enhanced Oil Recovery		√	√
	Renewables and electricity production, distribution, and retail		√	√

Supplementary Table 5. Upstream, midstream and downstream accounting. The upstream, midstream and downstream items included for fossil fuel companies from existing carbon accounting methods.

	Allocation approach	Principles	Assumptions	Outputs
Sectoral Decarbonisation Approach (SDA)	Grandfathering	Cost-optimization; Physical production intensity Convergence	All companies in a sector will converge towards a common emission intensity in 2050	Intensity reduction trajectories
Revised SDA (Dietz et al. [8])	Grandfathering	Cost-optimization; Emission intensity benchmark	Normalize and project companies' targets with scope 1,2 and 3 emissions from use of sold products	Binary answers to alignment against benchmarks (aligned or not aligned, no budget or trajectory allocation)
Absolute Contraction Approach ("ACA")	Grandfathering	Historical emissions	Constant annual absolute emission reduction rate	Absolute emissions reduction trajectories
Greenhouse gas emissions per unit of value added ("GEVA")	Grandfathering	Historical economic contribution	Constant annual economic intensity reduction rate	Economic intensity reduction trajectories
This Study	Grandfathering	Historical production share	All fossil companies will share the production budget based on historical production share	Production reduction trajectories

Supplementary Table 6. Main SBT methods and allocation principles.

	SDA	Revised SDA	LCM	BFFA	This study
Data inputs required	Scope 1, 2 and 3 USP	Scope 1, 2 and 3 USP; company targets	Asset-level supply data with associated costs	Sold products (operations) converted to energy and non-energy use	Upstream sold products
Fossil fuel types	Oil & Gas	Oil & Gas	Oil & Gas	Oil & Gas	Oil & Gas & Coal
Allocation principles	Sectoral carbon budget and market share	None	Future market projections and cost optimization	Production or reserves in base year	Current geopolitical factors and market share (average production since base year of underlying decarbonisation pathway until 2018 compared to world)
Benchmark Models	IPCC/IAMs 1.5°C Scenario IEA WEO 2019 and ETP 2017;	IPCC/IAMs 1.5°C Scenario	IEA sectoral budget; 1.6°C B2DS benchmark scenario; 1.7-1.8°C SDS benchmark scenario	McGlade & Ekins [1] (TIAM) and Welsby et al. [2]	IEA Net Zero Roadmap and IAMs SSPs-1.9 scenarios
Output Metrics	Intensity convergence	Intensity	Capital expenditure; production budget	Production budget	Production trajectories; production budget
Pros	Flexible; easy-applicable	Flexible; easy-applicable	Market-oriented;	Transparent; accountable;	Transparent; accountable

Cons	No guarantee for absolute emission reduction; data intensive	No guarantee for absolute emission reduction; data intensive	No consideration of geopolitical factor; data intensive	No reward mechanism for scope 1-2 emissions mitigation; no consideration of efficiency	No reward mechanism for scope 1-2 emissions mitigation; no consideration of efficiency
Organisations	SBTi	Transition Pathway Initiative	Carbon Tracker Initiative; SBTi	-	-
Base year	2018	2014 (for benchmarks)	2019	2010 or 2020	2010 for IAMs SSPs-1.9 scenarios

Supplementary Table 7. Comparison of climate target setting methods with this study. Note: the benchmark models and the base year are adjustable based on the up-to-date models in all methods.