Energy Policy 166 (2022) 112950

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

"Carbon Bombs" - Mapping key fossil fuel projects

Kjell Kühne [a,b,*], Nils Bartsch [c], Ryan Driskell Tate [d], Julia Higson [e], André Habet [f]

[a] University of Leeds, School of Geography, Leeds, UK
[b] Leave it in the Ground Initiative, Radebeul, Germany
[c] Urgewald, Berlin, Germany
[d] Global Energy Monitor, USA
[e] University of British Columbia, Canada
[f] Syracuse University, USA

ARTICLE INFO

Keywords:
Supply side mitigation
Carbon bombs
Carbon budget
Harvest mode
Fossil fuels
Climate change

ABSTRACT

Meeting the Paris targets requires reducing both fossil fuel demand and supply, and closing the "production gap" between climate targets and energy policy. But there is no supply-side mitigation roadmap yet. We need criteria to decide where to focus efforts.

Here, we identify the 425 biggest fossil fuel extraction projects globally (defined as >1 gigaton potential CO_2 emissions). We list these "carbon bombs" by name, show in which countries they are located and calculate their potential emissions which combined exceed the global 1.5 °C carbon budget by a factor of two. Already producing carbon bombs account for a significant percentage of global fossil fuel extraction. But 40% of carbon bombs have not yet started extraction.

Climate change mitigation efforts cannot ignore carbon bombs. Defusing them could become an important dimension of climate change mitigation policy and activism towards meeting the Paris targets. So far, few actors, mainly from civil society, are working on defusing carbon bombs, but they are focussing on a very limited number of them. We outline a priority agenda where the key strategies are avoiding the activation of new carbon bombs and putting existing ones into "harvest mode".

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) negotiations have framed climate change mitigation as a demand-side challenge for the past three decades, avoiding an explicit focus on fossil fuel extraction (Aykut and Castro, 2017; SEI et al., 2019). The IPCC has warned in its special report on the 1.5° target that swift reductions in emissions from fossil fuels are necessary and business as usual emissions would take us past the mark in less than two decades (IPCC et al., 2018). However, additional fossil fuel extraction projects are still being planned by energy companies, including state-owned enterprises (SOEs). These add to the overhang of "unburnable carbon". While mechanisms to untangle this situation are already being discussed (Asheim et al., 2019; e.g. Newell and Simms, 2020; Pellegrini et al., 2021; van Asselt, 2014; West, 2020), they have not seen a breakthrough at the international policy level.

Potential emissions from fossil fuel reserves exceed admissible emissions by a factor of four to seven (Intergovernmental Panel on Climate Change, 2014). Because the overhang in unburnable carbon is so huge, in the dwindling time frame to meet the Paris targets, we need to be able to identify priorities for supply-side mitigation activities, the "next step in climate policy" (Erickson et al., 2018). Non-governmental organizations have identified and criticized a number of large scale fossil fuel expansion plans (Berman, 2019; Voorhar and Myllyvirta, 2013). But so far we lack a comprehensive and detailed map of specific fossil fuel extraction projects that are relevant to the global greenhouse gas emissions roadmap.

We aim to contribute to the characterization of the global supply-side mitigation landscape by answering some questions about the biggest fossil fuel projects globally, which we call "carbon bombs". We define a carbon bomb as a proposed or existing fossil fuel extraction project (a coal mine, oil or gas project) that would result in more than 1 gigaton of CO_2 emissions if its reserves were completely extracted and burnt. Where are they located? What is their combined size? What is their status? How easy is it to find information on them? Is their role in disrupting the climate being questioned nationally?

* Corresponding author. University of Leeds, School of Geography, Leeds, UK.
E-mail address: kjell.kuehne@gmail.com (K. Kühne).

https://doi.org/10.1016/j.enpol.2022.112950
Received 15 September 2021; Received in revised form 16 February 2022; Accepted 25 March 2022
Available online 12 May 2022

In order to answer these questions, the first step is to establish the identity of these projects. We therefore provide a complete global dataset of carbon bombs. We use a simple method for estimating potential emissions, based on reserve data and average emissions factors.

This global list of carbon bombs is a first step towards defusing more of them. In the discussion section, we suggest an agenda for defusing carbon bombs which starts by cancelling new projects first and putting existing ones into "harvest mode", thus avoiding stranded assets.

2. Background

The idea that we need to regulate fossil fuel projects and analyze their potential emissions is not new. Even before the UNFCCC was established, the issue had already been identified and a global budget for fossil fuels had been proposed by Krause et al. (1990) to deal with climate change. To provide a background for our research, we will briefly outline how the topic of foregoing extraction for climate reasons has been dealt with in academia, civil society and government.

2.1. Academia

Grubb identified non-conventional fossil fuels as a future key arena at the intersection of climate and energy policy in 2001 (Grubb, 2001). Meinshausen et al. charted a global carbon budget for temperature targets against proven fossil fuel reserves (Meinshausen et al., 2009).

In 2015, McGlade and Ekins detailed which fossil fuel reserves would stay in the ground for a 2° target, based on economic considerations (McGlade and Ekins, 2015). In 2021, Welsby et al. updated this analysis. These analyses paint an outline of the global supply-side mitigation picture (Welsby et al., 2021). We believe it is useful to further expand this picture, based on the following considerations.

Firstly, the authors list much coal (~2000 Gigatons worth of CO_2). This might be an overly optimistic scenario, as recent work has shown that coal is not available in as large quantities as previously assumed (Ritchie and Dowlatabadi, 2017). Additionally, coal is quickly losing competitiveness against renewables, to the point that half the global coal power plant fleet could already be profitably replaced by renewables plus storage (Bodnar et al., 2020). Therefore we tend towards the view that much of the coal in their scenario is not likely to get extracted. By using a dataset that identifies existing projects, we intend to help focus supply-side mitigation efforts where they may make a difference, i.e. in places that are arguably close to extraction. Secondly, while economics provides an important perspective on fossil fuel reserves, uneconomic projects are often enabled through subsidies (see e.g. Erickson et al., 2017). We therefore believe that mapping carbon bombs independently of economic considerations is admissible and in fact useful. And lastly, Welsby at al.'s analysis provides data at the regional level without naming individual projects. Policy decisions are typically taken at the national level, and movements tend to center on specific projects. Providing detail down to the project level would be useful to practitioners.

After NGOs took the lead for a while in spearheading keep-it-in-the-ground efforts (see the following section), calls from the scientific community have intensified over the last years to address climate change mitigation from the supply side (Erickson et al., 2018; Green and Denniss, 2018). Scientists of the Stockholm Environment Institute have published a series of papers and briefs (Erickson et al., 2017; Erickson et al., 2018; Erickson and Lazarus, 2014; Lazarus and van Asselt, 2018; Piggot et al., 2018) and organized several international conferences on supply-side mitigation. In 2018, Newell and Simms proposed a fossil fuel non-proliferation treaty (Newell and Simms, 2020), a vision that has since galvanized research and activism alike along the lines of anti-fossil-fuel norms (Green, 2018).

Academic contributions have also examined equity considerations, which pose additional challenges beyond purely technical questions (Gambhir et al., 2018; Kartha et al., 2018; Le Billon and Kristoffersen, 2019), the movement against fossil fuel projects (Benedikter et al., 2016; Cheon and Urpelainen, 2018; Gaulin and Le Billon, 2020; Klein, 2014; Piggot, 2018) national and subnational *first movers*, some of which are described in the "government" section below (Carter and McKenzie, 2020), and methods to quantify the emissions impacts of the movement (Kühne, 2021).

A related topic of academic inquiry has been into *stranded assets*. In the context of our question, they refer to those fossil fuel assets that become worthless because of global climate action. The concept was introduced by the Carbon Tracker Initiative (2011) and has found its way into the mainstream of the financial community. Academics have subsequently used the framing to look at a number of fossil fuel and other sectors globally and in different countries (e.g. Caldecott et al., 2016, 2015, 2013a, 2013b; Dietz et al., 2016). These analyses help flag the companies and projects most exposed to potential asset stranding for investors. This perspective is an interesting complement to the carbon bombs lens, because it can help identify those projects that could be disastrous from an economic perspective on top of the climate one. On the other hand, it can help understand which projects are economically so solid that stopping them might be challenging.

2.2. Civil society

A number of contributions - conceptual and more tangible - have come from environmental non-governmental organizations (NGOs) and other activists. These include the concept of *carbon bombs*, which has been used by civil society at least since 2013 (Voorhar and Myllyvirta, 2013) and alludes to the close link between a fossil fuel based energy model and climate change related casualties.

A growing *Keep it in the Ground (KING) Movement* against fossil fuel infrastructures (Kühne, 2021) has used different tactics ranging from publishing reports over lawsuits to civil disobedience (Benedikter et al., 2016; Gaulin and Le Billon, 2020; Klein, 2014; Piggot, 2018). Multiple 'frontline struggles' are being waged across the planet against fossil fuel extraction (e.g. tar sands, fracking, new coal mining) and associated infrastructures (e.g. airports, motorways, pipelines and corporate headquarters). As an example, the German direct action coalition *Ende Gelände* regularly stages actions of mass civil disobedience to shut down coal mines in Germany (Bosse, 2017), including both carbon bombs on our list (Appendix 1). Fracking is another activity that faces increasing opposition. In 2015, more than 1000 organizations called for a global ban on fracking (PowerShift, 2015). These are just two examples of the resistance of the KING movement.

In a more conceptual line of work, in 1997, Greenpeace published a report named "The Carbon Logic", adding detail to the connection between fossil fuels and different climate targets (Hare, 1997). Almost 20 years later, Oil Change International's report "The Sky's Limit" showed that existing coal mines and oil and gas fields can take us past the carbon budget after the Paris Agreement (Muttitt, 2016), providing a factual basis for the argument against new approvals of additional fossil fuel projects. This evaluation has been validated by the International Energy Agency in 2021 (Bouckaert et al., 2021). Organizations that started with tracking all coal power plants (Global Energy Monitor, 2020; Shearer et al., 2018, 2019) are now moving on to monitoring all coal mines and oil and gas projects globally (Global Energy Monitor, 2021, n.d.). A global registry for all fossil fuel reserves has been called for (Byrnes, 2020) in connection with the proposal of a fossil fuel non-proliferation treaty mentioned above, and a methodology is now under construction (Byrnes, personal communication). Once published, this may help standardize the way fossil fuel reserves and resources are reported and identified globally.

A very influential NGO has been the Carbon Tracker Initiative, which in 2011 published its first "Carbon Bubble" report which looked at the financial aspect of private companies owning rights to exploit "unburnable" carbon that exceeds the global 2° carbon budget. Since then, many sectoral and other reports have followed, and the danger of fossil

fuel investments becoming stranded assets is recognized in the financial community. Following their lead, the Carbon Underground 200, publishes a list of fossil fuel reserves of publicly traded companies (FFI Solutions, 2020) which however does not cover most SOEs.

Complementary to this work, 350.org started a fossil fuel divestment movement in 2011 under the "keep it in the ground" banner (Alexander et al., 2014). By the end of 2018, 8 trillion US dollars had been committed to not be invested in fossil fuels any more (Hanley, 2018). This is relevant for the availability of capital for fossil fuel extraction projects, including carbon bombs.

From the mentioned examples it is clear that civil society has been watching the fossil fuel industry and its plans closely and there are a number of published reports singling out some of the biggest planned fossil fuel projects which also appear on the carbon bombs list (Berman, 2019; Bingler, 2020; Cimons, 2016; Voorhar and Myllyvirta, 2013). However, these reports are not the result of a systematic, global approach towards identifying the biggest fossil fuel projects, but rather respond to the needs and dynamics of campaign-driven organizations. They characterize "hot spots" of current struggles against fossil fuels so to say. This is helpful for understanding how the struggles to defuse carbon bombs unfold in real life. But it leaves a gap in terms of gaining a complete global overview of which projects are already active and which ones are in preparation, especially in countries without ongoing NGO campaigns. We aim to close that gap with the current research, aiming at policy makers and activists both on a global and on a national level.

2.3. Governments

The UNFCCC so far uses a decidedly non-fossil fuel framing, thanks to the efforts of Saudi Arabia and other allies with strong fossil fuel interests (Aykut and Castro, 2017, pp. 185–191). Different commentators have decried this (McKibben et al., 2012; Monbiot, 2007, 2015) without much impact. However, there are other fronts where the framing has taken root. The IPCC's 5th Assessment Report mentions explicitly that we have 4 to 7 times more fossil fuel reserves than can be burned (IPCC, 2014 Section 2.2.5.). Also according to the IPCC, the 1.5 °C target requires limiting global emissions to no more than 420 Gt CO_2 from 2017 (IPCC et al., 2018, p. 12), and fossil fuel extraction could only occupy part of that carbon budget. In 2019, UNEP and partners published the first "Production Gap Report", listing national extraction reduction policies and calculating the gap between fossil fuel extraction plans and the Paris temperature targets (SEI et al., 2019). While the Paris Agreement was silent on fossil fuels (Piggot et al., 2017), it did set a date for "net zero" emissions in the second half of the century. Subsequently, the needle has shifted orientation towards a 2050 deadline for fossil fuels (Bouckaert et al., 2021; United Nations Secretary-General, 2020).

In 2007, Ecuador proposed the Yasuní-ITT Initiative where close to a billion barrels of oil would be left in the ground in one of the most biodiverse corners of the planet - in exchange for the international community giving financial help amounting to half of the expected income from the oil, to be used for changing the Ecuadorian economy onto a post-carbon course (Larrea and Warnars, 2009). The initiative ultimately failed, but raised the profile of the question about appropriate mechanisms for keeping fossil fuels in the ground on the international level - a question that still remains unanswered.

In 2015, President Tong of Kiribati called on other leaders to establish a moratorium on new coal mines and coal mine extensions. Later that year, the Suva Declaration by Pacific Island leaders called on governments to initiate a dialogue on a moratorium on fossil industry development, especially coal mines. So far, the call remains unanswered.

Other nations have also taken action: Costa Rica has a moratorium on oil exploration in place until 2050 (Sequeira, 2014), some countries and states have banned fracking (France, Bulgaria, Germany, Ireland, Québec and New York State) and thus stopped extraction of oil and gas from shale formations that cannot otherwise be recovered. Greenland recently became the first country to ban oil and gas exploration for climate reasons (Buttler, 2021). Spain and New Zealand have also stopped giving further oil & gas licenses and California intends to end oil & gas extraction by 2045 (Lo, 2021). Both the Powering Past Coal Alliance launched in 2017 and the Beyond Oil and Gas Alliance launched in 2021 have formed coalitions around the common agenda of phasing out these fossil fuels. These *first movers* are setting precedents for other countries to follow, even if policies and proposals sometimes fail, are temporary, or get rolled back - as in the United States, where the Trump administration promoted drilling for oil and gas in protected areas and offshore, rolling back previous measures against extraction.

Between the top-down approach of global climate targets and the bottom-up efforts of first movers, there is currently little connection. With the carbon bombs analysis we hope to cover some of the middle ground, bridging the two, and showing where progress needs to be made for arriving at globally relevant numbers.

2.4. Defusing carbon bombs

In order to identify especially worthwhile objectives for supply-side mitigation efforts, we provide a list of the biggest individual units of potential fossil fuel emissions: carbon bombs. Framing climate change mitigation as "defusing carbon bombs" can capture the highly abstract challenge of managing global CO_2 emissions in a concrete way and offers a "collective action frame" (Benford and Snow, 2000) that builds a bridge between the global level of the climate system and concrete energy policy and activism choices by establishing a middle level of discrete and discernible projects that are on a scale that can be influenced through the actions of small groups of people. At the same time the wording implies the urgency of the matter.

3. Method and data

For calculating potential emissions of carbon bombs we use average IPCC emissions factors for direct CO_2 emissions from burning the fossil fuels in question (Eggleston et al., 2006). For projects already in operation, we include them in the list if they still have more than 1 gigaton worth of CO_2 emissions in remaining reserves. The method is purposefully straightforward: our aim is not to project the precise amount of emissions that would be generated over the lifetime of each project, but rather give an estimate of the potential climate impact from the largest projects.

We only include extraction projects, but not transport infrastructure (LNG terminals, pipelines, ports), nor demand-side pieces of infrastructure such as power plants in our analysis. This avoids double counting in our global analysis. Drawing on additional datasets, future work could conceptualize such pieces of infrastructure as carbon bombs as well. *Oil and gas pipelines* could be considered carbon bombs if they allow for the additional extraction and transport of oil or gas that results in over 1 Gt CO_2 emissions. This is the case for many pipelines, assuming a 40 year lifetime and use at full capacity, any pipeline with a capacity over 200,000 bpd of oil or 10 bcm of gas per year qualifies for that status. *LNG terminals* with a capacity bigger than 15 mtpa can be carbon bombs over a 40 year lifetime. As an example, the South Korean Incheon LNG terminal has a processing capacity of 38 mtpa, resulting in a potential of 1 Gt CO_2 emissions over less than 12 years (see Kühne, 2021 for a quick method to estimate emissions of such projects). *Coal power plants* could theoretically reach the size, but the Global Coal Plant Tracker (Global Energy Monitor, 2020) lists only two canceled projects worldwide with lifetime CO2 emissions over 1 Gt CO2.

3.1. Reserves data

The sources presented in Table 1 were screened for carbon bombs, identifying projects that are already in operation or planned.

Table 1
Data sources for identifying carbon bombs.

Fuel	Database/Publication	Identification criterion	Year of publication
Coal	BP Statistical Review of Energy	countries with >375 million tons reserves	2020
	US EIA	mines with >10 million tons annual production, reserves bigger than: 385 mt anthracite 375 mt coking coal 410 mt bituminous 500 mt coal (general) 555 mt sub-bituminous 835 mt lignite	various
	Global Energy Monitor Global Coal Mine Tracker	Reserves bigger than thresholds above	2021
Oil & Gas	Rystad UCube	>2,500 million bbl oil equivalent reserves	2020

For oil & gas reserves, we used the Rystad UCube database, a commercial database and identified all projects, existing and planned, with more than 2.5 billion barrels of oil equivalent reserves or 400 bcm of gas equivalent reserves. A project is defined as follows in the Rystad database: "*Project is a practical aggregation of assets. Typically a Project consists of assets to be developed as one industry project. For US onshore Project corresponds to all assets in same basin in same state, or same shale.*" After performing the calculation with the emissions factors described below, projects with less than 1 Gt CO_2 potential emissions were discarded from the list.

For coal reserves, in a first step we identified all countries over a threshold of 375 million tons of coal reserves in the BP Statistical Review of Energy (BP, 2019). Only countries individually listed were considered. The sources provided by the US Energy Information Administration for its estimates of coal reserves (EIA, 2021) were then consulted to identify individual coal mines above the carbon bomb threshold. Government and company reports, and in the absence of these, industry news reports were used to identify the latest available reserve figures. Sources are given in column L of the Coal sheet of the dataset (Appendix 2). In a final step, the resulting list was compared with Global Energy Monitor's Global Coal Mine Tracker (Global Energy Monitor, 2021) to identify further mines or more up-to-date information.

Coal reserves are defined in this dataset as "recoverable reserves": the amount of coal at a mine that is considered economically mineable with the highest degree of confidence. Recoverable reserves include measured resources that are sufficiently "proved" and indicated/measured resources that are "probable." This approach enabled us to estimate carbon bombs at the mine-level, where extraction is ongoing or proposed. The use of recoverable reserves also provides a more consistent approach to global reserve figures, which can vary based on local standards of measurement and reporting, although currently national reserve estimates are being unified into a single framework by the Committee for Mineral Reserves International Reporting Standards (Expert Group on Resource Classification, 2015). When recoverable reserve figures were unavailable, we collected data on coal resources and indicated those in the dataset in column H "Reserve category." Those mines likely have smaller recoverable reserve sizes than indicated, but without data on drilled and sampled measurements, this is the best available information for our analysis.

3.2. Production data

Production data stem from Rystad (Rystad Energy, 2020) in the case of oil and gas and the German Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources, 2021) in the case of coal.

3.3. Emissions factors

For estimating the average emissions of different fossil fuel reserves, we build on the work of the Production Gap Report (SEI et al., 2019) which uses adjustments for fugitive emissions and non-energy uses of coal, oil and gas for their projections. In our approach, we have not included those adjustments which work in opposite directions. Our numbers are therefore labeled as *potential emissions* - the emissions that would result if all reserves were burnt. By excluding methane leakage, we slightly underestimate the global warming potential, particularly of the gas carbon bombs. By excluding non-energy uses (e.g. plastics, fertilizer, etc.) where the products are not burnt and the carbon may not reach the atmosphere in the form of CO2 - we slightly overestimate the emissions in a real-life use case. The emissions factors used are described in the tab "Emissions Factors" of Appendix 2. We opted for such a simplified approach towards emissions factors, because we are concerned with giving a global picture of the biggest fossil fuel projects, and establishing the identity of those projects. A more precise accounting of potential emissions would change the overall position of a carbon bomb on the list only in a small number of cases and only in border cases where adapting the formula pushes individual projects above or below the limit, the composition of the list would be modified at all through such methodological fine-tuning. SEI et al. (2019, Annex B3) have also shown that the difference between a top-down approach with just one global emissions factor vs. a bottom-up approach using individual country data tends to be relatively small. We therefore opted for the top-down approach. Additionally, comparability and future efforts to update the carbon bomb inventory will be facilitated by a simpler methodology. Our aim is to contribute to the "defusing" of carbon bombs. If successful, emissions will be zero for projects that have not started yet or much lower for those already in operation. Therefore a very precise quantification of emissions defeats the purpose of our work.

3.4. Harvest mode analysis

To explore the potential results of a policy of stopping further investments into carbon bombs, we ran a scenario of putting all existing carbon bombs into "harvest mode". This means naturally declining output of producing oil and gas fields, a scenario that is described by the International Energy Agency as a "no new investment" scenario (International Energy Agency, 2020a Figure 7.3, 2018, p. 158). As a proxy, we used a 8% annual decline in output from existing fields for oil and gas. We did not differentiate between conventional and fracked wells, although the second have much higher decline rates (Peters, 2021), because they account for a minor portion of global oil and gas supply. This is a simplification of the picture, because there are big differences in decline rates between different unconventional and conventional oil and gas fields and also between ramp-up, legacy and post-peak fields (International Energy Agency, 2018, pp. 159–160).

For coal, we performed a simpler harvest mode analysis, based on the assumption that once coal mines have reached an annual extraction capacity they can run at that level with limited further investments. We simply assumed that all existing mines continued extraction at 2019 levels until 2050. For 13 of 137 operating mines this meant they would exhaust their resources. The rest of them still had reserves remaining at 2050. To establish the validity of our harvest mode analysis, we compared it with two IEA scenarios from the 2019 World Energy Outlook (International Energy Agency, 2019, Fig. 5.13): A "strict" scenario without new investment, which shows a global roughly linear decline of 4% of current global extraction capacity going offline each year, resulting in zero coal extraction in the year 2043.[1] A "softer" scenario with a 2% annual linear decline was derived from the IEA estimate

[1] The graph ends in 2040. Continuing the trend from 2018 in a linear fashion meets zero in 2043.

for production going forward under continued "brownfield investment", but no investment in new "greenfield" mines. Note that the IEA figures are for all global coal extraction, and our figures only for the 137 biggest projects globally.

4. Results and discussion

We have identified 425 carbon bombs. 195 oil and gas projects fall into this category, 76 of which are new projects that had not started production in 2020. We identified 230 coal mines with over 1 gigaton of potential CO_2 emissions, 93 of which had not been producing yet in 2020. Table 2 gives an overview of the numbers of projects in the different categories and their potential emissions.

Fig. 1 shows the global map of carbon bombs with combined potential emissions given for each country. The complete list with all project names, ordered by country, can be found in Appendix 1.

There are only 10 countries with more than 10 carbon bombs: China (141), Russia (41), United States (28), Iran (24), Saudi Arabia (23.5),[2] Australia (23), India (18), Qatar (13), Canada (12) and Iraq (11). Together, they account for three quarters of the emissions potential of all carbon bombs.

In terms of current production, carbon bomb projects in operation were responsible for 45% of global oil and gas production and 25% of global coal production in 2019 (see Appendix 2, "production share"). A focus on these projects thus has the potential to address a significant portion of global fossil fuel emissions.

The potential emissions of the sum of all carbon bombs are roughly double the remaining 1.5 °C budget (IPCC et al., 2018, p. 12)(see Fig. 2), an important climate policy benchmark.

A number of carbon bombs have not started extraction yet. In some cases, the required infrastructure has not yet been built. The combined potential emissions of new carbon bombs are 419 Gt CO_2 (225 Gt from coal, 194 Gt from oil & gas).

Our harvest mode analysis leads to a combined production until 2050 of 318 billion barrels of oil equivalent (113 Gt CO_2) and 64.2 billion tons of coal (128 Gt CO_2), resulting in a combined 241 Gt CO_2 over the period 2019–2050 - a figure much more compatible with a 1.5 °C carbon budget. Our simple harvest mode model only offers a very limited view of global fossil fuel markets. More detailed models with refined assumptions are needed to give a better picture on potentially stranded assets among carbon bombs.

When comparing our results with findings of previous research, a few reference points are helpful.

The Production Gap report has pointed to the difference between governments' climate pledges and supply side energy policies (SEI et al., 2019), resulting in a gap that is 50% as wide as permissible production under a 2 °C pathway and 120% as wide under a 1.5 °C pathway in 2030. Our perspective on carbon bombs coincides in identifying a large overhang of potential emissions coming from the supply side, and helps refine this production gap picture by naming the biggest projects that would be responsible for a significant part of this excess production.

The Sky's limit report (Muttitt, 2016) identified the potential emissions from existing oil and gas fields and coal mines and compared them with 1.5° and 2° carbon budgets, arriving at the conclusion that existing infrastructure would be enough to take us past those thresholds. Again, our findings are consistent with this, in that existing carbon bombs have more reserves than would be compatible with 1.5° and no new fossil fuel infrastructure is admissible from a climate perspective.

A third line of work looks at the lock-in of emissions from demand-side fossil fuel infrastructure, such as power plants, internal combustion engine cars (Smith et al., 2019; Tong et al., 2019). This research indicates that with near-term action in the sense of ceasing to build new fossil fuel infrastructure, the 1.5° and 2 °C targets would be reachable. Our research focuses on the supply side and thus complements this demand-side picture with some new insights from the supply side of fossil fuels and priorities for bringing it in line with the global climate targets.

As discussed in the literature review section, we provide a more detailed perspective on previous regional overviews of unburnable carbon (McGlade and Ekins, 2015; Welsby et al., 2021).

Our results furthermore agree with authors that have pointed out the importance of climate change mitigation efforts to focus on fossil fuel extracting countries (Johnsson et al., 2019). These countries must be part of an ambitious conversation, else mitigation efforts might fail to reach their global objective.

Taken together, two thirds of carbon bombs are located either in China, Russia or the Middle East and North Africa regions. These regions have so far received very limited attention in terms of efforts to stop fossil fuel extraction. A closer look at Chinese coal (130 projects, including 48 new ones) and Middle Eastern oil & gas projects (82 projects, including 24 new ones) are urgently needed to avoid locking in an overshoot of the Paris targets. Other hotspots of carbon bombs are in the United States, Australia, India and Canada. These countries will have to be more actively engaged in searching for ways to meet the Paris targets, and the likely path leads via defusing some of their carbon bombs.

China interestingly has a history of striving to close small coal mines, leaving only major, more efficient ones (Cao, 2017). The average mine capacity is now over 1 million tons per annum (Fitch Ratings, 2020). The Chinese coal mining sector deserves more focussed attention from the climate policy community because it makes up the largest number of carbon bombs globally and more studies such as Shi et al.'s (2018) examination of the Chinese capacity cut policy would be useful.

Some existing carbon bombs may have escaped our method where exploration activities are still taking place. Reserve numbers also see changes when prices change and the oil price depression in 2020 may have made the extraction of some carbon bombs unviable, leaving fewer carbon bombs to defuse. On the other hand, a rebound in fossil fuel prices could add more projects to the carbon bombs list by increasing the reserves in individual projects beyond the threshold.

Table 2
Number of total and new carbon bombs and their potential emissions.

Category	Coal total	Oil & Gas total	Carbon bombs total	*Coal new*	*Oil & Gas new*	*New Carbon bombs total*
# of projects	230	195	425	*93*	*76*	*169*
Potential emissions (Gt CO_2)	536.2	646.0	1182.3	*225.2*	*193.8*	*419.0*

5. Conclusions and policy implications

We have mapped the biggest fossil fuel projects worldwide, 425 carbon bombs, with a CO_2 emissions potential exceeding 1 Gigaton in each project. The potential emissions from these projects exceed the 1.5 °C carbon budget by a factor of two. We showed that there is a high concentration of these projects in countries that have so far received little attention by those looking at the supply side of climate change mitigation: China, Middle Eastern countries and Russia. This is a major gap in mitigation policy and urgently needs to be addressed. There are over a hundred new carbon bombs currently being planned. As a direction for dealing with carbon bombs, in the following we discuss some strategic options.

[2] The Khafji project in the Neutral Zone between Saudi Arabia and Kuwait that is operated jointly by both countries has been assigned to 50% to each country in our list.

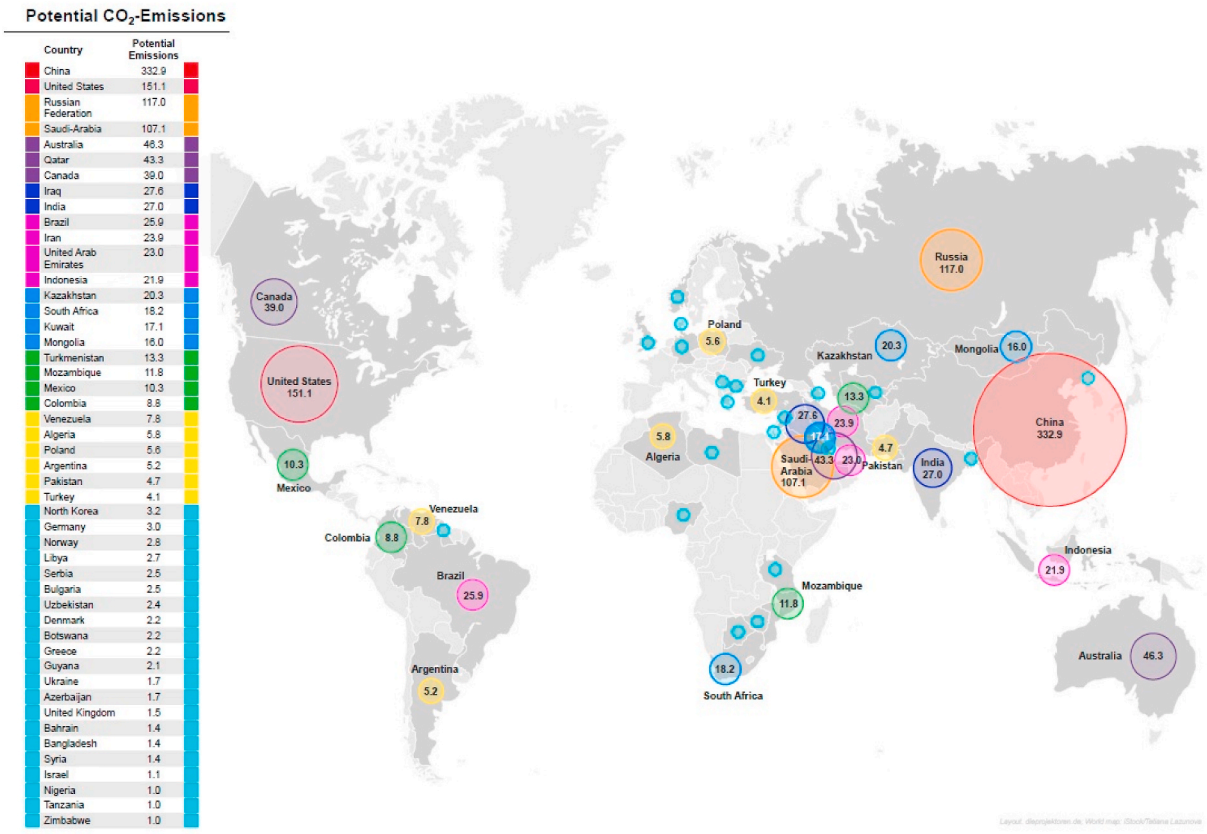

Fig. 1. Potential CO_2 emissions from carbon bombs per country Source: Own data.

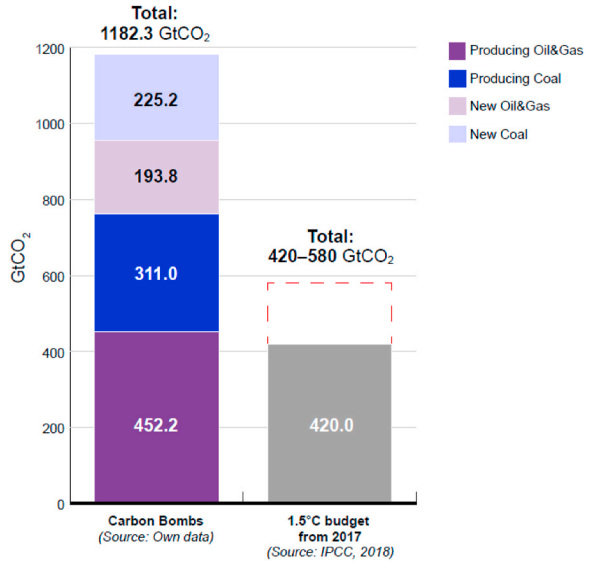

Fig. 2. Combined potential emissions of all carbon bombs versus 1.5 °C carbon budget.
Sources: Own data, based on Rystad Energy, 2020, Global Energy Monitor, 2021 (Carbon bombs), and IPCC et al., 2018 (1.5° carbon budget).

5.1. *No new projects*

Our results on "new" carbon bombs indicate that a moratorium on new carbon bombs could avoid about a third of potential emissions from carbon bombs.

Coal mines and oil & gas fields, especially of the size considered in this article, have long lead times and require years for planning, regulatory approvals and acquiring financial backing in the billions of US dollars. The time until a project recovers its initial investment ("break-even"), tends to be over ten years for such big projects (Muttitt, 2016, p. 35 Figure 12). Because investments in fossil fuel projects need to compete with other alternative uses of the capital, the return on investment is critical. Companies internally often apply so-called hurdle rates, where an investment will not go forward if it does not meet the hurdle rate, typically 10% as an internal rate of return (Erickson et al., 2020). Erickson et al. (2017) have analyzed how many fossil fuel projects in the US are pushed over the hurdle rate through fossil fuel subsidies. Implementing the long-standing G20 commitment to eliminate fossil fuel subsidies could thus result in a shortening of the list of carbon bombs.

In today's energy context, with an ongoing energy transition towards renewables and ambitious climate policy targets adopted at the global level by all countries through the UNFCCC and on a national level in a stepwise fashion, there are strong question marks over the reliability of decades-long forecasts of revenue for fossil fuel projects (Atanasova and Schwartz, 2019; Krane, 2017). The least risky strategy under these circumstances is to forego the investment. A strictly economic analysis (such as Welsby et al., 2021) does not adequately capture the dynamics of a market with a significant percentage of actors not mainly driven by economic incentives, but rather responding to a range of political factors. If further carbon bomb projects are started, the relevant actors must seriously consider the danger of generating a stranded asset. Failing to act accordingly and exercising prudence can often be explained by misaligned incentives and political economy analyses have been used to shine light on these dynamics (e.g. Brauers and Oei, 2020).

The recent IEA roadmap for net zero by 2050 which arrived at the conclusion that no new oil and gas fields nor coal mines are needed (Bouckaert et al., 2021) aligns well with the argument. Increasingly, oil and gas exploration is also questioned in courts on the grounds of its

incompatibility with global climate change mitigation (Médici Colombo, 2020). Therefore, further inquiry into the potential emissions impacts of carbon bombs projects and their compatibility with global climate change mitigation pathways, both on an aggregate and a project level are needed, especially where investments are still considered. The UN Secretary General has stated in August 2021 that countries should not explore for more fossil fuels nor start new extraction projects (United Nations Secretary-General, 2021). Our analysis points in the same direction and outlines a priority list of projects that could be questioned.

5.2. Harvest mode

During the COVID-19 pandemic, most oil and gas companies found themselves in a situation of low oil prices and little capital for investments and exploration. Some privately-owned companies ceased to pay dividends. In 2021, prices were on the increase again, and these same companies were under pressure to reestablish dividends and align their plans with the Paris Agreement, rather than withholding the money from their shareholders and investing in further extraction which is incompatible with the Paris Agreement. Applying a "harvest mode" strategy, which consists of continuing extraction without new investments, is one possible response to the challenge. It could be combined with a shift in focus of a business towards other sectors within or beyond energy (see Harries and Annex, 2018 for a successful example; and Harrigan and Porter, 1989 for general strategies). Applying a harvest mode strategy can stabilize a fossil fuel business and reduce its risks, because it continues to provide returns, as no investment needs to be made while fossil fuels are still harvested. This property of a harvest mode strategy might make it a useful ingredient of the conversation about a "managed decline" of fossil fuels (Erickson et al., 2018). It provides a potential alignment of different interests: firstly, central banks focused on stability of the financial system, which would be threatened by the collapse of big companies (Baer, 2020); secondly, governments focused on a strong economy and stable jobs; thirdly, investors focused on financial returns; and lastly climate-vulnerable countries and young generations focused on a swift reduction in fossil fuel emissions.

Different fossil fuel sectors have different decline rates when applying a harvest mode strategy, with unconventional oil and gas extracted through fracking having much steeper declines than conventional oil and gas or coal. Our analysis indicates that this strategy might make a contribution to aligning fossil fuel supply with climate goals. On the demand side, the work of Millward-Hopkins et al. (2020) indicates that there is also potential for a bigger alignment, while meeting the basic needs of the global population.

5.3. Early closure

The major part of coal globally today is used for electricity (International Energy Agency, 2020b). Levelized cost of electricity analyses show that renewables are replacing coal as the cheapest source of electricity in most major countries (Ram et al., 2018). However, coal-fired electricity is often shielded from market competition, meaning that it can persist even when it is effectively more expensive than cleaner energy sources (Bodnar et al., 2020). This situation, where consumers pay more for coal power which is not only high in emissions, but also highly polluting, may change soon. Finance mechanisms have been proposed that could unlock benefits of cost, emissions and health (Bodnar et al., 2020; Kanak, 2020). The necessity of early closure due to climate constraints has already been examined for coal power plants (Kefford et al., 2018), and for coal mines (Auger et al., 2021; Caldecott et al., 2016; Lucas, 2016).

China dominates the global coal picture, and a wave of coal mine retirements expected in the mid-2020s (International Energy Agency, 2019, p. 244) provide an opportunity for a shift. Opening new coal mines as replacements may increase the need for early closure of existing coal mines. If and how the list of 48 new Chinese coal carbon bombs we have identified is being planned to start operations in this decade is an urgent question to be tackled, in order to identify alternatives.

What early closure would mean for oil and gas carbon bombs needs to be investigated. Today, only when operating costs fall below revenue levels, projects tend to close down. However, this creates the issue of "stranded liabilities" when clean-up obligations are not sufficiently covered through guarantees during the operational phase (Schuwerk and Rogers, 2020). When bankruptcies occur, as has been the case in the coal sector in recent years, these liabilities are absorbed by the public. Several scenarios are possible in this "fossil endgame": a big crash, destabilizing financial markets, or intervention through central banks which absorb potentially stranded assets and liabilities in a proactive manner and allow a managed decline (Kroll, 2018).

5.4. Defusing carbon bombs

As shown, there are too many carbon bombs being activated, so an obvious question raised by our analysis is: how can carbon bombs be defused?

In theory, some policies, such as a "No New Coal Mines" policy (Denniss, 2015) or a "Coal Elimination Treaty" (Burke and Fishel, 2020) propose to automatically eliminate a significant number of them. A global fracking ban, as called for by a coalition of NGOs, or an offshore drilling ban could eliminate an additional amount. While outright banning fossil fuels (Green, 2018) seems appropriate in the face of the climate emergency, the list of countries with a large number of carbon bombs indicates the challenge of a rather entrenched fossil fuel model with governments and corporations with very tangible interests in pushing the projects forward - a situation that has been called carbon entanglement (Gurría, 2013).

Therefore, in practical terms, political economy concerns (Zhao and Alexandroff, 2019) are key for achieving a swift phase-out, and poorer countries who are especially vulnerable (Cust et al., 2017) might require some dedicated support.

In the absence of government action to limit fossil fuel supply, a growing number of social movement actors have taken to blocking fossil fuel infrastructure, such as pipelines, coal mines or ports through actions of civil disobedience over the past years (Gaulin and Le Billon, 2020; Piggot, 2018). While they are illegal in many cases, they have increasingly been justified in court as based on the necessity to avoid greater harm (McGraw, 2018).

Some important regions and their extractive sectors however are currently almost unattended by the climate movement, namely the Middle East, China and Russia. Given the size of the carbon bombs' potential emissions, this is a gap that needs to be closed urgently by the climate movement, because without defusing a sufficient number of carbon bombs, meeting the Paris targets will be impossible.

While some non-governmental actors are already engaged in trying to defuse a small subset of carbon bombs, official climate change mitigation policy must not ignore the issue either. In order to defuse a significant amount of carbon bombs, a serious supply-side discussion among big fossil fuel producer states is needed. Especially China, Russia and Middle Eastern countries, along with the United States urgently need to start exploring non-extraction options. The discussion could start with identifying global principles for a managed decline and create a priority list of carbon bombs that can easily be defused. Reverse auctions have also been proposed (Pellegrini et al., 2021). Coal carbon bombs would likely be the first to be pledged by countries to be defused, followed by marginal oil & gas projects (see Collier and Venables, 2014 for a proposal of a similarly staged approach). With the proposal of a Fossil Fuel Non-Proliferation Treaty (Newell and Simms, 2020) some detailed thinking is already available on how this process could be structured, using the successful process in nuclear arms control as point of departure.

A dialogue on limiting fossil fuel extraction would not only be useful for avoiding carbon lock-in and a very volatile market situation for fossil fuel exporting countries - as has been the case in the early 2020s, but it would also be a way to minimize the amount of additional stranded assets being created. Managing the transition away from fossil fuels in coordination could be a stabilizing force in a world in energy transition and reduce the risk of emissions leakage which reduces the attractivity of unilateral action.

5.5. The way forward

The carbon bombs framing translates the rather abstract and intractable challenge of mitigating climate change to a very concrete and specific task of defusing a number of carbon bombs in each country. As an example, in Germany there are two carbon bombs, both lignite mines. Shutting them down should be a priority for climate change mitigation. However, to consider defusing those 425 projects as a new or different mitigation agenda would be too simplistic. The size of potential emissions is just one of many perspectives under which a fossil fuel project can be viewed. Some other factors that influence the views of political, economic and social movement decision makers are cost, location, emissions intensity (as opposed to overall size), available alternatives, fiscal revenue, jobs, and whether it is an existing or a new project. Studying and understanding the individual carbon bombs of our list will be essential for developing useful approaches tailored to each context. Some defusing may be negotiated internationally, some may be tackled mainly at a national policy level, some may be struggles of movements with lawsuits and blockades. The concentration of two thirds of potential emissions of carbon bombs in just ten countries potentially makes the targeting of multilateral efforts easier, as only a limited number of governments need to participate in an initial dialogue. The lack of an effective civil society pursuing climate ambition in several of these countries means that such government-focused efforts are even more important. Defusing carbon bombs will be essential for keeping temperatures below 1.5° warming and new strategies are needed for designing effective measures that will result in their non-extraction - an area so far neglected by mainstream mitigation policy (Verkuijl et al., 2019).

Identifying coal carbon bombs to a common standard has proven challenging (see the Methods section), and for oil and gas we had to resort to a commercial, paid service (Rystad) to get reliable data with global coverage. This illustrates the need for more transparency in the sector, and the global fossil fuel registry (Byrnes, 2020) could be a step forward in bringing it about. The list of carbon bombs can also be used as an *indicator of progress* of global mitigation efforts. If demand-side mitigation measures are effective towards the ultimate UNFCCC goal of avoiding dangerous anthropogenic interference with the climate system, they will have an impact on the list of carbon bombs, limiting their full exploitation.

In this article, we have introduced a new methodology to identify the world's biggest potential fossil fuel emissions sources. Our list of carbon bombs brings much clarity to the question of where the climate crisis can be addressed from the supply side. The list can assist activists and policymakers alike in setting priorities and preparing the next step of defusing carbon bombs. A number of jurisdictions have recently declared climate emergencies. Defusing carbon bombs could be a priority in response to the emergency, to meet the Paris targets and avoid planetary run-away climate change.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2022.112950.

References

Alexander, S., Nicholson, K., Wiseman, J., 2014. Fossil Free: the Development and Significance of the Fossil Fuel Divestment Movement (No. Paper No. 3), MSSI Issues. Melbourne Sustainable Society Institute, The University of Melbourne.

Asheim, G.B., Fæhn, T., Nyborg, K., Greaker, M., Hagem, C., Harstad, B., Hoel, M.O., Lund, D., Rosendahl, K.E., 2019. The case for a supply-side climate treaty. Science 365, 325–327. https://doi.org/10.1126/science.aax5011.

Atanasova, C., Schwartz, E.S., 2019. Stranded Fossil Fuel Reserves and Firm Value (Working Paper No. 26497), Working Paper Series. National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w26497.

Auger, T., Trüby, J., Balcombe, P., Staffell, I., 2021. The future of coal investment, trade, and stranded assets. Joule 5, 1462–1484. https://doi.org/10.1016/j.joule.2021.05.008.

Aykut, S.C., Castro, M., 2017. The end of fossil fuels? : understanding the partial climatisation of global energy debates. In: Aykut, S.C., Foyer, J., Morena, E. (Eds.), Globalising the Climate: COP21 and the Climatisation of Global Debates. Routledge, London. https://doi.org/10.4324/9781315560595-10.

Baer, M., 2020. The Impact of Stranded Fossil Fuel Assets on International Financial Institutions: a financial exposure analysis and implications for European central banks and financial regulators. SSRN J. https://doi.org/10.2139/ssrn.3844406.

Benedikter, R., Kühne, K., Benedikter, A., Atzeni, G., 2016. Keep it in the ground." the Paris agreement and the renewal of the energy economy: toward an alternative future for globalized resource policy? Challenge 59, 205–222. https://doi.org/10.1080/05775132.2016.1171665.

Benford, R.D., Snow, D.A., 2000. Framing processes and social movements: an overview and assessment. Annu. Rev. Sociol. 26, 611–639. https://doi.org/10.1146/annurev.soc.26.1.611.

Berman, T., 2019. World Oil and Gas Markets. IEEFA Energy Finance Training, New York. June 17, 2019.

Bingler, J., 2020. Five Years Lost. How Finance Is Blowing the Paris Carbon Budget. Urgewald, Germany.

Bodnar, P., Gray, M., Grbusic, T., Herz, S., Lonsdale, A., Mardell, S., Ott, C., Sundaresan, S., Varadarajan, U., 2020. How to Retire Early: Making Accelerated Coal Phaseout Feasible and Just. Rocky Mountain Institute, US.

Bosse, J., 2017. Analyse: „Zurück in der Grube. Ende Gelände 2"1 – die Anti-Kohlebewegung in der Lausitz im Mai 2016. Forschungsjournal Soziale Bewegungen 30. https://doi.org/10.1515/fjsb-2017-0011.

Bouckaert, S., Fernandez Pales, A., McGlade, C., Remme, U., Wanner, B., Varro, L., D'Ambrosio, D., Spencer, T., 2021. Net Zero by 2050 - A Roadmap for the Global Energy Sector. International Energy Agency, Paris.

BP, 2019. BP Statistical Review of World Energy 2019. BP, London.

Brauers, H., Oei, P.-Y., 2020. The political economy of coal in Poland: drivers and barriers for a shift away from fossil fuels. Energy Pol. 144, 111621 https://doi.org/10.1016/j.enpol.2020.111621.

Burke, A., Fishel, S., 2020. A coal elimination treaty 2030: fast tracking climate change mitigation, global health and security. Earth Syst. Govern., 100046 https://doi.org/10.1016/j.esg.2020.100046.

Buttler, M., 2021. Greenland Bans Future Oil Exploration over Climate Concerns. Time.

Byrnes, R., 2020. A Global Registry of Fossil Fuels. Fossil Fuel Non-Proliferation Treaty Initiative.

Caldecott, B., Dericks, G., Mitchell, J., 2015. STRANDED ASSETS AND SUBCRITICAL COAL: the Risk to Companies and Investors. SMITH SCHOOL OF ENTERPRISE, Oxford.

Caldecott, B., Howarth, N., McSharry, P., 2013a. Stranded Assets in Agriculture: Protecting Value from Environment-Related Risks. Stranded Assets Programme. Smith School of Enterprise and the Environment, University of Oxford, Oxford.

Caldecott, B., Kruitwagen, Lucas, Dericks, Gerard, Tulloch, Daniel J., Kok, Irem, Mitchell, James, 2016. Stranded Assets and Thermal Coal: an Analysis of Environment-Related Risk Exposure. Stranded Assets Programme, SSEE, University of Oxford, Oxford.

Caldecott, B., Tilbury, J., Ma, Y., 2013b. Stranded Down under? Environment-Related Factors Changing China's Demand for Coal and what This Means for Australian Coal Assets. Stranded Assets Programme, Smith School of Enterprise and the Environment, University of Oxford, Oxford.

Cao, X., 2017. Policy and regulatory responses to coalmine closure and coal resources consolidation for sustainability in Shanxi, China. J. Clean. Prod. 145, 199–208. https://doi.org/10.1016/j.jclepro.2017.01.050.

Carbon Tracker Initiative, 2011. Unburnable Carbon – Are the World's Financial Markets Carrying a Carbon Bubble? Carbon Tracker Initiative.

Carter, A.V., McKenzie, J., 2020. Amplifying "keep it in the ground" first-movers: toward a comparative framework. Soc. Nat. Resour. 1–20. https://doi.org/10.1080/08941920.2020.1772924.

Cheon, A., Urpelainen, J., 2018. Activism and the Fossil Fuel Industry. Routledge, Taylor & Francis Group, London ; New York.

Cimons, M., 2016. Keep it in the Ground. Sierra Club, 350.org, Greenpeace.

Collier, P., Venables, A.J., 2014. Closing coal: economic and moral incentives. Oxf. Rev. Econ. Pol. 30, 492–512. https://doi.org/10.1093/oxrep/gru024.

Cust, J., Manley, D., Cecchinato, G., 2017. Unburnable Wealth of Nations: Successful Action to Address Climate Change Would Diminish the Value of Fossil Fuel Resources in Many of the World's Poorest Countries. Finance & Development. https://doi.org/10.5089/9781475577150.022.A016, 0054.
Denniss, R., 2015. When You Are in a Hole - Stop Digging! the Economic Case for a Moratorium on New Coal Mines. The Australia Institute, Canberra (Discussion paper).
Dietz, S., Bowen, A., Dixon, C., Gradwell, P., 2016. 'Climate value at risk' of global financial assets. Nat. Clim. Change 6, 676–679. https://doi.org/10.1038/nclimate2972.
Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, Chikyū Kankyō Senryaku Kenkyū Kikan, Kanagawa.
EIA, 2021. International - coal and coke [WWW document]. URL. U.S. Energy Information Administration, 3.30.21. https://www.eia.gov/international/data/world/coal-and-coke/coal-reserves.
Erickson, P., Down, A., Lazarus, M., Koplow, D., 2017. Effect of subsidies to fossil fuel companies on United States crude oil production. Nat. Energy 2, 891. https://doi.org/10.1038/s41560-017-0009-8.
Erickson, P., Lazarus, M., 2014. Impact of the Keystone XL pipeline on global oil markets and greenhouse gas emissions. Nat. Clim. Change 4, 778–781. https://doi.org/10.1038/nclimate2335.
Erickson, P., Lazarus, M., Piggot, G., 2018. Limiting fossil fuel production as the next big step in climate policy. Nat. Clim. Change 8, 1037–1043. https://doi.org/10.1038/s41558-018-0337-0.
Erickson, P., Mulvey, K., Davis, S.J., Trout, K., Muttitt, G., 2018. In: Enough Already: Committed CO2 Emissions from Developed Fossil Fuel Reserves and the Case for a Managed Decline of Production. American Geophysical Union, Fall Meeting 2018, 2018, PA41A-01.
Erickson, P., van Asselt, H., Koplow, D., Lazarus, M., Newell, P., Oreskes, N., Supran, G., 2020. Why fossil fuel producer subsidies matter. Nature 578, E1–E4. https://doi.org/10.1038/s41586-019-1920-x.
Expert Group on Resource Classification, 2015. BRIDGING DOCUMENT BETWEEN THE CRIRSCO TEMPLATE AND UNFC-2009.
Federal Institute for Geosciences and Natural Resources, 2021. BGR Energy Data 2019 - German and Global Energy Supplies [WWW Document]. Bundesanstalt für Geowissenschaften und Rohstoffe. https://doi.org/10.25928/es-2019-tab-en.
FFI Solutions, 2020. The Carbon Underground 200, 2.15.21 [WWW Document]. URL. https://www.ffisolutions.com/research-analytics-index-solutions/research-screening/the-carbon-underground-200/.
Fitch Ratings, 2020. Chinese Provincial Coal SOEs Accelerate Consolidation, 8.8.21 [WWW Document]. URL. https://www.fitchratings.com/research/corporate-finance/chinese-provincial-coal-soes-accelerate-consolidation-24-07-2020.
Gambhir, A., Green, F., Pearson, P.J.G., 2018. Towards a Just and Equitable Low-Carbon Energy Transition. Imperial College London, London. Grantham Institute Briefing paper No 26.
Gaulin, N., Le Billon, P., 2020. Climate change and fossil fuel production cuts: assessing global supply-side constraints and policy implications. Clim. Pol. 1–14. https://doi.org/10.1080/14693062.2020.1725409.
Global Energy Monitor, 2021. Global Coal Mine Tracker, 3.30.21 [WWW Document]. URL. https://globalenergymonitor.org/projects/global-coal-mine-tracker/.
Global Energy Monitor, 2020. Global Coal Plant Tracker, 1.21.21 [WWW Document]. URL. https://globalenergymonitor.org/projects/global-coal-plant-tracker/.
Global Energy Monitor, n.d. Global Fossil Infrastructure Tracker [WWW Document]. GGON. URL https://greeninfo-network.github.io/fossil_tracker/(accessed 7.21.19).
Green, F., 2018. Anti-fossil fuel norms. Climatic Change 150, 103–116. https://doi.org/10.1007/s10584-017-2134-6.
Green, F., Denniss, R., 2018. Cutting with both arms of the scissors: the economic and political case for restrictive supply-side climate policies. Climatic Change 150, 73–87. https://doi.org/10.1007/s10584-018-2162-x.
Grubb, M., 2001. Who's afraid of atmospheric stabilisation? Making the link between energy resources and climate change. Energy Pol. 29, 837–845. https://doi.org/10.1016/S0301-4215(00)00128-2.
Gurría, Á., 2013. The Climate Challenge: Achieving Zero Emissions, 2.9.22. Lecture by the OECD Secretary-General London, 9 October 2013. [WWW Document]. OECD. URL. http://www.oecd.org/about/secretary-general/the-climate-challenge-achieving-zero-emissions.htm.
Hanley, S., 2018. Fossil Fuel Divestment Movement Exceeds $8 Trillion. CleanTechnica.
Hare, B., 1997. Fossil Fuels and Climate Protection: the Carbon Logic. Greenpeace International, Amsterdam.
Harries, T., Annex, M., 2018. Orsted's Profitable Transformation from Oil, Gas and Coal to Renewables [WWW Document], 9.10.21. Powering Past Coal Alliance (PPCA). URL. https://www.poweringpastcoal.org/insights/economy/orsteds-profitable-transformation-from-oil-gas-and-coal-to-renewables.
Harrigan, K.R., Porter, M.E., 1989. End-game strategies for declining industries. In: Asch, D., Bowman, C. (Eds.), Readings in Strategic Management. Macmillan Education UK, London, pp. 219–233. https://doi.org/10.1007/978-1-349-20317-8_16.
Intergovernmental Panel on Climate Change, 2014. In: Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.
International Energy Agency, 2020a. World Energy Outlook 2020. IEA, Paris.
International Energy Agency, 2020b. Coal – Global Energy Review 2020 – Analysis, 8.26.21 [WWW Document]. IEA. URL. https://www.iea.org/reports/global-energy-review-2020/coal.
International Energy Agency, 2019. World Energy Outlook 2019. IEA, Paris.
International Energy Agency, 2018. World Energy Outlook 2018, World Energy Outlook. IEA, Paris. https://doi.org/10.1787/weo-2018-en.
IPCC, 2014. In: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland.
IPCC, 2018. Summary for policymakers. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. IPCC, Geneva, Switzerland.
Johnsson, F., Kjärstad, J., Rootzén, J., 2019. The threat to climate change mitigation posed by the abundance of fossil fuels. Clim. Pol. 19, 258–274. https://doi.org/10.1080/14693062.2018.1483885.
Kanak, D.P., 2020. How to Replace Coal with Renewables in Developing Countries, 8.26.21 [WWW Document]. World Economic Forum. URL. https://www.weforum.org/agenda/2020/05/how-to-replace-coal-and-accelerate-the-energy-transition-in-developing-countries/.
Kartha, S., Caney, S., Dubash, N.K., Muttitt, G., 2018. Whose carbon is burnable? Equity considerations in the allocation of a "right to extract. Climatic Change 150, 117–129. https://doi.org/10.1007/s10584-018-2209-z.
Kefford, B.M., Ballinger, B., Schmeda-Lopez, D.R., Greig, C., Smart, S., 2018. The early retirement challenge for fossil fuel power plants in deep decarbonisation scenarios. Energy Pol. 119, 294–306. https://doi.org/10.1016/j.enpol.2018.04.018.
Klein, N., 2014. This Changes Everything: Capitalism vs. The Climate. Alfred A. Knopf Canada, Toronto, Ont.
Krane, J., 2017. Climate change and fossil fuel: an examination of risks for the energy industry and producer states. MRS Energy Sustain. 4 https://doi.org/10.1557/mre.2017.3.
Krause, F., Bach, W., Koomey, J., 1990. Energy Policy in the Greenhouse: from Warming Fate to Warming Limit. Earthscan, London.
Kroll, D.M., 2018. How to Convert Fossil Fuel Stranded Assets into Renewable Energy Investments. The 'Climate Bailout'. (Policy Brief). World Future Council, Hamburg.
Kühne, K., 2021. Big numbers for bold activists: a quick method for estimating potential emissions of fossil fuel projects. Energy Res. Social Sci. 79, 102172 https://doi.org/10.1016/j.erss.2021.102172.
Larrea, C., Warnars, L., 2009. Ecuador's Yasuni-ITT Initiative: avoiding emissions by keeping petroleum underground. Energy Sustain. Dev. 13, 219–223. https://doi.org/10.1016/j.esd.2009.08.003.
Lazarus, M., van Asselt, H., 2018. Fossil fuel supply and climate policy: exploring the road less taken. Climatic Change 150, 1–13. https://doi.org/10.1007/s10584-018-2266-3.
Le Billon, P., Kristoffersen, B., 2019. Just cuts for fossil fuels? Supply-side carbon constraints and energy transition. Environ. Plann.: Econ. Space. https://doi.org/10.1177/0308518X18816702, 0308518X1881670.
Lo, J., 2021. California Is the Biggest Producer in the World Planning to Go beyond Oil [WWW Document]. URL. Climate Home News, 8.10.21. https://www.climatechangenews.com/2021/05/07/california-biggest-producer-planning-go-beyond-oil/.
Lucas, A., 2016. Stranded assets, externalities and carbon risk in the Australian coal industry: the case for contraction in a carbon-constrained world. Energy Res. Social Sci. 11, 53–66. https://doi.org/10.1016/j.erss.2015.08.005.
McGlade, C., Ekins, P., 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. Nature 517, 187–190. https://doi.org/10.1038/nature14016.
McGraw, S., 2018. Trial Will Test New Weapon against Climate Change: the Necessity Defense. Climate Liability News.
McKibben, B., Bassey, N., Solon, P., 2012. Open letter: to really address climate change UNFCCC-COP18 should decide to leave under the soil more than 2/3 of the fossil reserves, 4.15.19, URL. http://www.envjustice.org/2012/11/open-letter-to-really-address-climate-change-unfccc-cop18-should-decide-to-leave-under-the-soil-more-than-23-of-the-fossil-reserves/.
Médici Colombo, G.A., 2020. Presupuesto de carbono y autorización de proyectos de producción de combustibles fósiles: el caso "Gloucester Resources Ltd. v. Minister for Planning. Revista Catalana de Dret Ambiental 11. https://doi.org/10.17345/rcda2781.
Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., Allen, M.R., 2009. Greenhouse-gas emission targets for limiting global warming to 2 °C. Nature 458, 1158–1162. https://doi.org/10.1038/nature08017.
Millward-Hopkins, J., Steinberger, J.K., Rao, N.D., Oswald, Y., 2020. Providing decent living with minimum energy: a global scenario. Global Environ. Change 65, 102168. https://doi.org/10.1016/j.gloenvcha.2020.102168.
Monbiot, G., 2015. Keep Fossil Fuels in the Ground to Stop Climate Change. The Guardian.
Monbiot, G., 2007. Leave it in the Ground. The Guardian.
Muttitt, G., 2016. The Sky's limit: why the Paris climate goals require a managed decline of fossil fuel production. Oil Change Int.
Newell, P., Simms, A., 2020. Towards a fossil fuel non-proliferation treaty. Clim. Pol. 20, 1043–1054. https://doi.org/10.1080/14693062.2019.1636759.

Pellegrini, L., Arsel, M., Orta-Martínez, M., Mena, C.F., Muñoa, G., 2021. Institutional mechanisms to keep unburnable fossil fuel reserves in the soil. Energy Pol. 149, 112029 https://doi.org/10.1016/j.enpol.2020.112029.

Peters, E., 2021. US Shale Oil & Gas Production Data | Update through April 2021, 8.8.21. ShaleProfile. URL. https://shaleprofile.com/blog/us/us-update-through-april-2021/.

Piggot, G., 2018. The influence of social movements on policies that constrain fossil fuel supply. Clim. Pol. 18, 942–954. https://doi.org/10.1080/14693062.2017.1394255.

Piggot, G., Erickson, P., Asselt, H.van, Lazarus, M., 2018. Swimming upstream: addressing fossil fuel supply under the UNFCCC. Clim. Pol. 18, 1189–1202. https://doi.org/10.1080/14693062.2018.1494535.

Piggot, G., Erickson, P., Lazarus, M., van Asselt, H., 2017. How to Address Fossil Fuel Production under the Paris Agreement [WWW Document], 8.11.19. SEI. URL. https://www.sei.org/publications/fossil-fuel-production-paris-agreement/.

PowerShift, 2015. Global Frackdown to Paris: Über 1.200 Organisationen Weltweit Fordern Fracking-Verbot, 8.10.21. PowerShift. URL. https://power-shift.de/global-frackdown-to-paris-ueber-1-200-organisationen-weltweit-fordern-fracking-verbot/.

Ram, M., Child, M., Aghahosseini, A., Bogdanov, D., Lohrmann, A., Breyer, C., 2018. A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030. J. Clean. Prod. 199, 687–704. https://doi.org/10.1016/j.jclepro.2018.07.159.

Ritchie, J., Dowlatabadi, H., 2017. The 1000 GtC coal question: are cases of vastly expanded future coal combustion still plausible? Energy Econ. 65, 16–31. https://doi.org/10.1016/j.eneco.2017.04.015.

Rystad Energy, 2020. UCube [WWW document], 10.28.20, URL. https://www.rystadenergy.com/energy-themes/oil–gas/upstream/u-cube/.

Schuwerk, R., Rogers, G., 2020. It's Closing Time: the Huge Bill to Abandon Oilfields Comes Early. Carbon Tracker Initiative, London.

SEI, IISD, ODI, Climate Analytics, CICERO, UNEP, 2019. The Production Gap: the Discrepancy between Countries' Planned Fossil Fuel Production and Global Production Levels Consistent with Limiting Warming to 1.5°C or 2°C. Stockholm Environment Institute, Stockholm.

Sequeira, A., 2014. Luis Guillermo Solís extiende moratoria a explotación petrolera hasta el 2021. La Nación.

Shearer, C., Mathew-Shah, N., Myllyvirta, L., Yu, A., Nace, T., 2019. Boom and Bust 2019: TRACKING the GLOBAL COAL PLANT PIPELINE. Global Energy Monitor, Greenpeace Environmental Trust, Sierra Club.

Shearer, C., Mathew-Shah, N., Myllyvirta, L., Yu, A., Nace, T., 2018. Boom and Bust 2018: TRACKING the GLOBAL COAL PLANT PIPELINE. CoalSwarm. Sierra Club, Greenpeace USA.

Shi, X., Rioux, B., Galkin, P., 2018. Unintended consequences of China's coal capacity cut policy. Energy Pol. 113, 478–486. https://doi.org/10.1016/j.enpol.2017.11.034.

Smith, C.J., Forster, P.M., Allen, M., Fuglestvedt, J., Millar, R.J., Rogelj, J., Zickfeld, K., 2019. Current fossil fuel infrastructure does not yet commit us to 1.5 °C warming. Nat. Commun. 10, 101. https://doi.org/10.1038/s41467-018-07999-w.

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., Davis, S.J., 2019. Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. Nature 1. https://doi.org/10.1038/s41586-019-1364-3.

United Nations Secretary-General, 2021. Secretary-General's Statement on the IPCC Working Group 1 Report on the Physical Science Basis of the Sixth Assessment, 8.10.21. United Nations Secretary-General [WWW Document]. URL. https://www.un.org/sg/en/content/secretary-generals-statement-the-ipcc-working-group-1-report-the-physical-science-basis-of-the-sixth-assessment.

United Nations Secretary-General, 2020. Carbon Neutrality by 2050: the World's Most Urgent Mission [WWW Document], 8.10.21. URL. https://www.un.org/sg/en/content/sg/articles/2020-12-11/carbon-neutrality-2050-the-world%E2%80%99s-most-urgent-mission.

van Asselt, H., 2014. Governing the transition away from fossil fuels: the role of international institutions. SSRN Electron. J. https://doi.org/10.2139/ssrn.2531405.

Verkuijl, C., Jones, N., Lazarus, M., 2019. Untapped Ambition: Addressing Fossil Fuel Production through NDCs and LEDS, SEI Working Paper. Stockholm Environment Institute, Stockholm.

Voorhar, R., Myllyvirta, L., 2013. Point of No Return: the Massive Climate Threats We Must Avoid. Greenpeace International, Amsterdam.

Welsby, D., Price, J., Pye, S., Ekins, P., 2021. Unextractable fossil fuels in a 1.5 °C world. Nature 597, 230–234. https://doi.org/10.1038/s41586-021-03821-8.

West, J., 2020. Compensating Indebted Countries for Keeping Fossil Fuels in the Ground. A Proposal (Background Paper No. 6), Debt Relief for Green and Inclusive Recovery Project. Heinrich Böll Foundation, Center for Sustainable Finance (SOAS, University of London), and Global Development Policy Center (Boston University), Berlin.

Zhao, S., Alexandroff, A., 2019. Current and future struggles to eliminate coal. Energy Pol. 129, 511–520. https://doi.org/10.1016/j.enpol.2019.02.031.