Stranded assets and reduced profits: Analyzing the economic underpinnings of the fossil fuel industry's resistance to climate stabilization

Hansen, T.A.

Published in:
Renewable and Sustainable Energy Reviews

Link to article, DOI:
10.1016/j.rser.2022.112144

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

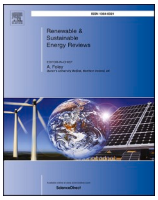
Citation (APA):
Hansen, T. A. (2022). Stranded assets and reduced profits: Analyzing the economic underpinnings of the fossil fuel industry's resistance to climate stabilization. *Renewable and Sustainable Energy Reviews*, *158*, [112144]. https://doi.org/10.1016/j.rser.2022.112144

Renewable and Sustainable Energy Reviews 158 (2022) 112144

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



Stranded assets and reduced profits: Analyzing the economic underpinnings of the fossil fuel industry's resistance to climate stabilization

T.A. Hansen

Department of Wind Energy, Technical University of Denmark, Roskilde, Denmark

ARTICLE INFO

Keywords:
Fossil fuel industry
Stranded assets
Profitability
Climate change
Climate strategy

ABSTRACT

Governments have failed to act at the scale and pace necessary to avert the climate crisis. This paper explores one key constraint on global action to combat climate change: resistance mounted by the fossil fuel industry. The economic losses that the fossil fuel industry is likely to incur as a result of climate stabilization include stranded assets and reduced profits. Using a methodology that emulates the expectations and valuation procedures used by fossil fuel firms, I estimate the magnitude and distribution of wealth losses from stranded assets for the upstream fossil fuel industry (i.e., firms and governments involved in fossil fuel extraction) under 1.8 °C and 1.5 °C climate stabilization scenarios. I also explore the timing of expected future profit losses and compare historical profit margins between fossil fuel and renewable energy firms. Results show that fossil fuel reserves will suffer a devaluation of 37%–50%, amounting to $13-$17 trillion. This implies a strong incentive for fossil fuel producers to continue resisting climate stabilization. Over half (51%–63%) of the reserve devaluation stems not from fuels left in the ground but from price decreases for fuels that will still be extracted and sold during climate stabilization, indicating that even low-cost producers stand to bear large losses. Three-quarters of stranded assets belong to governments, implying formidable political obstacles in nations with nationalized fossil fuel ownership. The profitability analysis reinforces these findings. My results point to strategic demand reduction of fossil fuels as a key strategy for overcoming industry resistance.

1. Introduction

Governments have thus far failed to deliver on the Paris Agreement, which commits them to limit the rise in global average temperature to "well-below 2 °C" above preindustrial levels while striving for 1.5 °C [1,2]. One reason for this failure is the resistance mounted by the fossil fuel industry, including climate change disinformation campaigns [3,4], anti-climate political lobbying [5], fossil fuel promotional activities [6], and a general refusal to invest substantially in low-carbon technologies [7].,[1,2] The industry's motivations are economic [8–12]. While climate change poses an existential threat to organized human society, climate stabilization poses an existential threat to fossil fuel wealth. In this paper, I consider two questions:

1. What does the fossil fuel industry stand to lose economically from climate stabilization?
2. What does the answer to question (1) imply for how to overcome the industry's resistance?

The economic losses the fossil fuel industry is likely to incur from climate stabilization include stranded assets (i.e., assets that suffer unexpected and sustained reductions in market value) and reduced profits. Assets at risk include fossil fuel reserves (i.e., the oil, gas, and coal still in the ground) and the capital goods used to extract, process, and transport those reserves. Prior estimates of stranded assets and reduced profits are ill-suited to answer the questions above. None of these studies estimate wealth or income in the way fossil fuel firms do, and due to variation in methods and data, the estimates cover an enormous range: $3-$185 trillion [13–18].

Abbreviations: CPS, Current Policies Scenario; EIA, U.S. Environmental Information Administration; E&P, exploration and production; IEA, International Energy Agency; SDS, Sustainable Development Scenario; SDS1.8, 1.8°C Sustainable Development Scenario; SDS1.5, 1.5°C Sustainable Development Scenario; STEPS, Stated Policies Scenario; US$, United States dollars; WEO, World Energy Outlook; ° C, degrees Celsius.

E-mail address: tylha@dtu.dk.

[1] There are rare exceptions. Most notably, DONG (Danish Oil and Natural Gas) transformed itself into Ørsted, the world's largest offshore wind developer.

[2] See supplementary material for an overview of this literature.

https://doi.org/10.1016/j.rser.2022.112144
Received 21 October 2021; Received in revised form 17 December 2021; Accepted 12 January 2022
Available online 19 January 2022

Using methods and data that emulate the valuation procedures and expectations used by fossil fuel firms themselves, I estimate the magnitude of wealth losses from stranded assets for the upstream fossil fuel industry (i.e., firms and governments involved in fossil fuel extraction), and how those losses are distributed across the industry. Consistent with the goals of the Paris Agreement, I consider climate stabilization scenarios that limit global warming to 1.8 °C and 1.5 °C. I also explore the timing of future profit losses, and compare profit margins between the fossil fuel and renewable energy industries for the period 2011–2020.

Results show that in these climate stabilization scenarios, fossil fuel reserves will suffer a devaluation of 37%–50%, amounting to $13-$17 trillion, while losses due to stranded investments in capital goods will be comparatively trivial. These losses imply a strong economic incentive for the industry to continue on the path of resistance to climate stabilization. Over half (51%–63%) of the reserve devaluation stems not from fuels left in the ground but from price decreases for fuels that will still be extracted and sold during climate stabilization, implying that all fossil fuel producers, including those with the lowest production costs, stand to bear large losses. Three-quarters of stranded assets belong to governments, implying formidable political obstacles to climate stabilization in nations with nationalized fossil fuel ownership. The profitability analysis reinforces these findings, showing that fossil fuel firms have remained significantly more profitable than renewable energy firms, and that fossil fuel firms will face significant profit losses even in the short-term from climate stabilization. My results point to the importance of strategic demand reduction to overcome the industry's resistance to climate stabilization.

This paper is organized as follows: Section 2 presents the stranded assets analysis, Section 3 presents the profitability analysis, and Section 4 concludes with a discussion on strategies to overcome the fossil fuel industry's resistance to climate stabilization.

2. Stranded assets analysis

2.1. Literature review

Three studies provide high-level surveys of the stranded fossil fuel assets literature [19–21]. Each includes a list of stranded assets estimates. Using these lists as a starting point, I narrowed my review to studies that estimated wealth or income losses from climate stabilization for the entirety of the global upstream fossil fuel industry.[3] Six studies met this criterion. Two measure cumulative forgone profits with estimates of $12 trillion [14] and $25 trillion [15]. Four measure cumulative forgone revenue with estimates of $3-$4 trillion [13], $185 trillion [18], $100 trillion [17], and $28 trillion [16]. This section explores their methodologies and data sources to understand why they vary so widely and to inform the analysis in this paper.

All six studies employ scenario comparison to estimate stranded assets (or foregone income), shown in Eq. (1).

$$SA_i = VA_{i,BS} - VA_{i,CSS} \tag{1}$$

For each fuel (i), the value of wealth losses from stranded assets (SA_i) equals the value of fossil fuel assets in a baseline scenario ($VA_{i,BS}$) minus the value of assets in a climate stabilization scenario ($VA_{i,CSS}$). Beyond this general approach, the methodologies and data sources are quite varied, as summarized in Table 1.

Each estimate includes a metric of measurement (revenue or profits); an estimation timeframe; a discount rate, which determines the present value of future cash flows; and scenario projections of future fossil fuel supply, production costs, and prices. Estimation timeframes ranged from 18 to 100 years, discount rates ranged from 0% to 10%, and each study used a different source of projections.

In general, measuring revenue, which ignores production costs, over a long timeframe and at a low discount rate results in a higher estimate. Much of the variation, however, stems from differing sources of scenario projections. Three studies used the International Energy Agency's (IEA) World Energy Outlook (WEO). The WEO, published annually, includes three scenarios: The Current Policies Scenario (CPS), the Stated Policies Scenario (STEPS) (formerly called the New Policies Scenario), and the Sustainable Development Scenario (SDS) (formerly called 450S). CPS assumes that no new climate policies will be implemented in the future, STEPS assumes governments will follow through on announced climate policies, and SDS assumes climate stabilization consistent with the 1.5–2 °C warming target. For the baseline scenario, two studies used CPS and one used STEPS. Other projection sources used include the E3ME-FTT-GENIE and REMIND models. Channell et al. [17] used a back-of-the-envelope approach, multiplying the magnitude of fossil fuel reserves expected to be left in the ground in a 2 °C scenario (from McGlade and Ekins [24]) with fossil fuel prices at the time of analysis. To get a sense of the differences across sources, Table 2 displays oil prices for the years 2020 and 2040 in the baseline and 2 °C scenarios. I included pricing used in the present study as well, discussed further in Sections 2.2.2 and 2.2.5.

Given these methodological and data differences, the wide variation in estimates becomes clear. Linquiti and Cogswell's [18] $185 trillion estimate is nearly two times the next highest estimate—$100 trillion from Channell et al. [17]. While both studies measure forgone revenue using long timeframes and low discount rates, Linquiti and Cogswell use substantially higher fossil fuel price projections. Mercure et al. [13] provide the lowest estimates: $3-$4 trillion. Even though they measure forgone revenue, they use the shortest timeframe, highest discount rate, and exceptionally low oil and gas price projections.[4]

The wide variation across the estimates illustrates the importance of carefully developing a methodology and choosing scenario projections based on the goals of the analysis. In the context of this paper, that means emulating the expectations and valuation procedures used by fossil fuel firms, so the results can be used to understand these firms' incentives.

2.2. Methods and data

2.2.1. General methodology

Wealth losses from stranded assets (SA) are equal to the sum of wealth losses from stranded fossil fuel reserves (hereafter, "stranded reserves") (SR) and stranded fossil fuel capital (hereafter, "stranded capital") (SC). Subscript i refers to fuel type (oil, gas, or coal).

$$SA_i = SR_i + SC_i \tag{2}$$

Following the stranded assets literature, I estimate stranded reserves and stranded capital through scenario comparison, shown in Eqs. (3) and (4).

$$SR_i = VR_{i,BS} - VR_{i,CSS} \tag{3}$$

$$SC_i = VC_{i,BS} - VC_{i,CSS} \tag{4}$$

I estimate the value of reserves (VR) and capital goods (VC) in baseline and climate stabilization scenarios, denoted with subscripts BS and CSS, respectively. The baseline scenario represents a future in which current trends in fossil fuel supply and demand continue with minimal changes, whereas the climate stabilization scenario represents a future that is consistent with the 1.5–2 °C climate stabilization target.

---

[3] It is important to note that the stranded assets literature is much broader than this. In addition to literature already mentioned, see Ref. [22] for a literature review of stranded assets from a developing country perspective and [23] for an analysis and discussion of investor impacts.

[4] Their 2040 baseline oil price of $42 per barrel, for example, is similar to crude oil prices throughout the first year of the COVID-19 pandemic [28].

Table 1
Methodology and data comparison across six global estimates of wealth and income losses.

Study	Estimate (metric)	Timeframe	Baseline projections	Climate stabilization projections	Discount rate
Mercure et al. [13]	$3-$4 T (revenue)	2018–2035	E3ME-FTT-GENIE	E3ME-FTT-GENIE (2 °C)	10%
Bauer et al. [14]	$12 T (profits)	2010–2100	REMIND	REMIND (2 °C)	5%
Nelson et. al [15]	$25 T (profits)	2015–2035	CPS from 2013 WEO [25]	450S from 2013 WEO [25] (2 °C)	8%
Lewis [16]	$28 T (revenue)	2013–2035	NPS[a] from 2013 WEO [25]	450S from 2013 WEO [25] (2 °C)	0%
Channell et al. [17]	$100 T (revenue)	Unk.[b]	McGlade/Ekins [24]	McGlade/Ekins (2015) (2 °C)	0%
Linquiti/Cogswell [18]	$185 T (revenue)	2016–2115	CPS from 2015 WEO [26]	450S from 2015 WEO [26] (2 °C)	3.18%

[a] Equivalent to STEPS in the 2019 WEO.
[b] Likely similar to Linquiti and Cogswell.

Table 2
Comparison of oil prices across studies (2018 US$ per barrel).

Source	Baseline		2 °C	
	2020	2040	2020	2040
Mercure et al. [13]	$38[a]	$42[a]	$36[a]	$27[a]
Bauer et al. [14]	$71	$89	Unk.	Unk.
Nelson et al. [15]	$132	$169[a]	$121	$106[a]
Lewis [16]	$124	$149[a]	$121	$106[a]
Channell et al. [17]	$70	$70	$70	$70
Linquiti/Cogswell [18]	$88	$159	$82	$101
Present study (STEPS-SDS1.8)	$56	$88	$52	$51
Present study (CPS-SDS1.8)	$59	$115	$52	$51

Values adjusted for inflation using BLS [27].
[a] Linear extrapolation used.
Sources: Studies cited in the table; [25,26].

As the prior section shows, estimating stranded assets is not an exact science. It requires making simplifying assumptions and forecasting possible energy futures based on present expectations, leading to inevitable uncertainties. The remainder of this section discusses the methodological and data choices made for this paper and shows how they are broadly representative of the fossil fuel industry's perspective.

2.2.1.1. Stranded reserves. Estimating stranded reserves requires valuing fossil fuel reserves. Given the highly disproportionate size of stranded reserves relative to stranded capital—especially for the oil and gas industry—this is the most important task of estimating stranded assets. Researchers and practitioners alike agree that the market value of a quantity of fossil fuel reserves is equivalent to the present value of expected cumulative net income from producing them [29–33]. This is captured in the discounted cash flow (DCF) model in Eq. (5).

$$VR_i = \sum_{t=0}^{T} \frac{(P_{t,i} - MC_{t,i}) Q_i S_{t,i} - CE_{t,i}}{(1+d)^t} \tag{5}$$

Variables are defined as follows

- VR_i: Value of fossil fuel reserves for fuel i.
- $P_{t,i}$: Market price of fuel i in year t.
- $MC_{t,i}$: Marginal cost of production per unit of reserves for fuel i in year t.
- Q_i: Total quantity of proved reserves (i.e., reserves with a 90–100% probability of being profitably extracted under current technologies) for fuel i.
- S_t: Share of proved reserves expected to be extracted for fuel i in year t.
- $CE_{t,i}$: Capital expenditures for fuel i in year t.
- d: Discount rate.
- T: Time period—the number of years it will take to fully extract the resource in question.

Under the DCF model, the net income from producing fossil fuel reserves is determined for each year, discounted at rate d (explained in detail in Section 2.2.3), and summed over the entire time period. The key to valuing fossil fuel reserves in the way fossil fuel firms do is in choosing the parameters and energy projections used in Eq. (5). I describe and justify my choices in Sections 2.2.2-2.2.6.[5]

2.2.1.2. Stranded capital. Stranded capital (E. (4)) can be further disaggregated into losses from stranding existing capital goods and losses from stranding investments in future capital goods. If industry refrains from overinvesting in the future, stranded capital from climate stabilization is limited to the existing capital goods left unused. The magnitude of future capital expenditures at risk is difficult to quantify. If the world transitions from the baseline scenario to the climate stabilization scenario, firms will transition their future capital expenditures accordingly. One way to assess future capital expenditures at risk is in terms of the potential time lag between when governments implement climate stabilization measures, and when industry transitions capital expenditures to be consistent with those measures. In other words, if governments shift policies from the baseline scenario to a climate stabilization scenario—either 1.5 °C or 2 °C—it may take some time before industry follows suit. I call this the "government-industry time lag". Wealth losses from future capital expenditures are equal to the excess capital expenditures made during this time.

The value of losses from stranded capital (*SC*) shown in Eq. (4) can thus be reformulated into Eq. (6).

$$SC_i = EC_{i,BS} - EC_{i,CSS} + \sum_{t=1}^{L} \frac{(CE_{t,i,BS} - CE_{t,i,CSS})}{(1+d)^t} \tag{6}$$

EC is the value of existing capital goods, *CE* is the value of future capital expenditures, *d* is the discount rate, *L* is the length of the time lag, and *t* is the specific year of the time lag. In the case of future capital expenditures, the losses are discounted to convert future cash flows into present value terms. The discount rate is discussed in depth in Section 2.2.3.

2.2.2. Scenarios and timeframe

Following the lead of prior estimates, my main source for scenario projections is the IEA's 2019 World Energy Outlook (hereafter, "WEO" refers to the 2019 WEO) [34]. Prior estimates, however, used either CPS or STEPS as their baseline scenarios. CPS, which assumes no new climate policies, is pessimistic from the perspective of clean energy. STEPS, which assumes governments will follow through on announced climate policies and targets, is too optimistic—announced policies are not automatic, especially given the industry's resistance to them.[6] Thus, industry and market expectations likely lie somewhere in between CPS and STEPS. I therefore estimate stranded assets for each and use the average of the two for my central estimates. My choice of taking the average is supported by the 2020 Global Energy Outlook [36], which compares energy and climate projections from eight energy organizations and corporations, including the IEA, U.S. Energy Information

---

[5] A more in-depth discussion of valuation methods is included in the supplementary material.

[6] The IEA [35] agrees with this assessment.

Administration (EIA), Organization for Petroleum Exporting Countries, Institute of Energy Economics Japan, BP, ExxonMobil, Shell, and Equinor. Among the eight baseline scenarios compared for carbon emissions, STEPS and CPS generally constitute the upper and lower bounds, with the others dispersed in-between—some closer to CPS and others closer to STEPS.

SDS—the WEO's climate stabilization scenario—entails a two-thirds chance of limiting global warming to 1.8 °C above preindustrial levels, which is consistent with the language of the Paris Agreement (limiting warming to "well-below 2 °C"). I also include a 1.5 °C scenario in which I adjust SDS to entail a 50% chance of achieving the 1.5 °C target.[7] To distinguish between the climate stabilization scenarios, I use SDS1.8 (identical to SDS) and SDS1.5 (adjusted for the 1.5 °C target).

The WEO provides projections from 2020 to 2040, which is the timeframe I use for the analysis. During this time, only a fraction of the world's known fossil fuel reserves will be extracted, even in the baseline scenario. However, post-2040 reserves are worth little in present value terms due to high production costs [14] and high discount rates, the latter of which is discussed in detail in the following section.

2.2.3. *Discount rate*

The basic idea of discounting is that a dollar earned today is worth more than a dollar earned in, for example, ten years. This stems from the nature of investing. A dollar earned today, if invested, will likely generate interest and dividends, and thereby grow over time. This concept is actualized through the discount rate, which decreases future cash flows on account of the forgone interest and dividends. The higher the discount rate, the less valuable future cash flows are in the present. The present value of $1 million received in 20 years, for example, is $1 million at a 0% discount rate, and $150,000 at a 10% discount rate. A firm only invests if its expected rate of return is higher than the discount rate. To select a discount rate, I reviewed the literature on how fossil fuel firms—both private and state-owned—discount future cash. All rates discussed are in real terms (i.e., account for inflation).

According to a 2013 survey of oil and gas valuation practitioners, 75% of practitioners use rates of 8–12%, with 60% using 10%, which is known as the industry standard [37–39]. Coal assets are discounted similarly from 8% to 10% [40–42]. Franc-Dąbrowska et al. [43] estimated the cost of capital—often used to calculate a firm's discount rate—of a sample of private fossil fuel firms, with results ranging from 7% to 11%. More general surveys on how private corporations discount future cash flows suggest rates of 12%–13% [44–46]. Overall, the 10% industry-standard discount rate provides a good midpoint between the rates surveyed.

Most fossil fuel production, however, is controlled by governments. One of the studies reviewed in Section 2.1—Linquiti and Cogswell [18]—argue that state-owned firms use lower discount rates. They do not say why, but their choice likely reflects the notion that governments prioritize providing public services over profit-making.

Hartley and Medlock [47] explore this issue theoretically and argue the opposite—discount rates for state-owned oil companies are likely higher. State-owned firms "[face] the same geologic, technological and market environments as the private firm" and are subject to the "political discount premium," whereby politicians are especially short-sighted in their attempts to stay in power. They assume the political discount premium to be in the range of 5–10% but offer no evidence.

To get a sense of how state-owned fossil fuel firms discount future cash flows, I examined the financial statements of five large publicly traded, state-owned fossil fuel firms, which reveal discount rates used for asset acquisitions or impairments. Rosneft used a discount rate of 16%, Gazprom 5–14%, Saudi Aramco 8%, CNPC 6–12%, and Sinopec 10% [48–52]. The average among the five firms is 10.5%. Thus, I see no reason to change the discount rate for state-owned firms. For my analysis, I use a discount rate of 10% for private and state-owned firms alike.

2.2.4. *Projecting fossil fuel supply*

There are two methods for obtaining fossil fuel supply projections. The first is to simply use yearly regional production projections from the WEO or some other energy model (hereafter, the "scenario projection method"). This is the method used by the stranded assets studies reviewed in Section 2.1, and it is the method I use to project coal supply. Oil and gas valuation practitioners, however, use a different method. They assume oil and gas reserves will enter production as soon as possible, and then use production decline curves to estimate the quantity of reserves that will be produced each year (hereafter, the "practitioner method"). The practitioner method is better suited for valuing reserves. The market value of reserves reflects immediate use of the reserves, not when a specific firm plans to use them. Thus, I use the practitioner method for my oil and gas analysis.

Production decline curves were first formulated by J.J. Arps [53]. Production rates from oil and gas wells are governed by the physical properties of reservoirs. In general, wells are most productive in their first days. Production then declines at a declining rate for the lifetime of the well, generally 15–30 years [54,55]. Production generally follows one of three decline curves: exponential, hyperbolic, or harmonic.[8] Following the oil and gas valuation literature [56–58], I assume an exponential curve with a 10% production decline rate, shown in Eq. (7). Q is the quantity produced, D is the annual production decline rate (10%), and t is the year. Appendix 1 provides further details on actualizing the practitioner method.

$$Q_t = Q_0(1-D)^t \tag{7}$$

As noted earlier, I use the scenario projection method to project coal supply. Unlike oil and gas, production from coal mines varies little from year to year [59]. In addition, I did not find an alternative method for projecting coal supply in the fossil fuel valuation literature.

2.2.5. *Projection data*

2.2.5.1. *Stranded reserves.*

The model to value fossil fuel reserves is reproduced here.

$$VR_i = \sum_{t=0}^{n} \frac{(P_{t,i} - MC_{t,i})Q_i S_{t,i} - CE_{t,i}}{(1+d)^t}$$

Supply projections (Q) for the baseline and 1.8 °C scenarios are from the WEO [34],[9] and for the 1.5 °C scenario from Huppmann et al. [64]. Table 3 reports the total supply for each scenario (i.e., reserves produced from 2020 to 2040) along with total proved and unproved (i.e., probable + possible) reserves, which includes reserves that will not be

---

[7] Adjustments described in Section 2.2.5.1.

[8] A more in-depth discussion of production decline curves is included in the supplementary material.

[9] The IEA released the 2020 World Energy Outlook [35] in October 2020, after conducting my analysis. I did not incorporate the new projections for two reasons. (1) The 2020 WEO excluded the Current Policies Scenario, which I need for my baseline scenario (see Section 3.3). (2) The 2020 WEO was released during a particularly grim moment in modern human history. COVID-19 daily death tolls were rising despite economic shutdowns, vaccine prospects were at best uncertain, and the global economy was in the worst economic crisis since the Great Depression. Unsurprisingly, 2020 WEO projections of fossil fuel prices, supply, and investments were revised downward relative to the 2019 WEO. In early-to mid-2021, however—with the introduction of several effective vaccines—major economies began to reopen, and economic prospects have significantly improved. As of July 2021, fossil fuel prices exceed both pre-pandemic levels and 2020 WEO projections [28,60,61]. In addition, after releasing the 2020 WEO, the IEA significantly increased its energy demand projections [62,63].

Table 3
Fossil fuel reserves.

	Reserves by Scenario (2020–2040)				Total Known Reserves		
	CPS	STEPS	SDS1.8	SDS1.5	Proved Developed	Proved	Probable + Possible
Oil (billions of barrels)	830	780	633	462	296	1700	6165
Gas (trillions of cubic feet)	104	99	87	55	38	225	803
Coal (billions of metric tons)	125	115	75	62	N/A	1043	23,014

Sources [34,64].

extracted from 2020-2040.[10]

Fossil fuel price projections (P) for the baseline and 1.8 °C scenarios come from the WEO. For oil, WEO projections for 2019 are higher than actual 2019 prices. Thus, I supplement them with baseline oil price projections from the EIA [65], which start at about $9 per barrel lower.[11] I use the EIA baseline scenario projections in place of STEPS, as prices increase at about the same rate in both scenarios. I then adjust the other scenarios proportionately.[12] I use linear interpolation to fill in the missing years.

None of the sources provides SDS1.5 price projections. Precise modeling of how prices will change from SDS1.8 to SDS1.5 is out of the scope of this paper. Nonetheless, SDS1.5 prices should be lower than SDS1.8 prices. To strike a balance between these two concerns, I adjust SDS1.5 prices downward, erring on the side of caution. Methods are described in Appendix 2.

I use the WEO for projections of future capital expenditures (CE) and amortize them equally over the 2020–2040 time period.[13] For marginal costs of production (MC), I use the EIA [66], Statista [67], and WSJ [68]. For oil, I average the three sources. For gas, I use EIA, as the other sources only consider oil.[14] I assume these costs remain constant over the timeframe of estimation, as the vast majority of reserves to be produced are conventional.[15]

Data on marginal cost for coal production are unavailable publicly. Thus, I extrapolate from oil and gas, assuming that the ratio of the marginal cost of production to the market price for coal is equivalent to the average of these ratios for oil and gas for the year 2020.

2.2.5.2. Stranded capital. Estimating wealth losses from stranded capital includes the devaluation of existing capital goods and the potential devaluation of future capital expenditures. Future capital expenditure projections are taken from the WEO, which provides projections for 2020–2030 and 2031–2040. I assume that capital expenditures are spread equally across each time period.

Estimates of losses from existing capital goods are based on the IEA [7], which estimates that $250 billion of existing oil and gas infrastructure will be stranded in the 1.8 °C scenario.[16] I extrapolate the $250 billion figure to coal under the assumption that the ratio of losses from existing capital goods to losses from future capital expenditures is equal across industries.[17] I then extrapolate from 1.8 °C to 1.5 °C based on the assumption that losses from existing capital goods increase proportionately to the change in future capital expenditures between the two scenarios.

2.2.6. Distributional analysis

The WEO provides projections for fossil fuel supply and future capital expenditures by region. Huppmann et al. [64]—used for the 1.5 °C scenario—provide only aggregate projections. I create regional projections by assuming that production from each region relative to world production for each year is proportionate between the 2 °C and 1.5 °C scenarios. I map price and marginal cost data onto the WEO regions as described in Appendix 3. To estimate the shares of fossil fuel reserves controlled by governments and private firms for each region, I use data from several sources including the IEA [7], the National Oil Company Database [69], and PwC [70] (further details on data and methods are in Appendix 4).

2.3. Results

This section presents the main results and implications of the stranded assets analysis. As discussed in Section 2.2., stranded assets estimation requires making simplifying assumptions and utilizing energy forecasts. These results, thus, should not be seen as exact, but rather as broadly representative of the fossil fuel industry's perspective on stranded assets. The sensitivity analysis (Section 2.3.5) provides more detail on how specific methodological and data choices impact the overall results.

2.3.1. Aggregate results

Table 4 displays the magnitude of wealth losses from stranded reserves for the 1.8 °C and 1.5 °C scenarios.[18] Overall, reserves suffer a devaluation of 37%–50%, amounting to $12.9-$17.2 trillion. The bulk of

Table 4
Wealth losses from stranded reserves (percentage loss in parentheses) (2018 US $, B=Billion, timeframe: 2020–2040).

	1.8 °C	1.5 °C
Stranded oil + gas reserves	$11,628 B (−37%)	$15,448 B (−49%)
Stranded oil reserves	$9920 B (−46%)	$11,640 B (−54%)
Stranded gas reserves	$1708 B (−17%)	$3808 B (−39%)
Stranded coal reserves	$1258 B (−32%)	$1777 B (−53%)
Total stranded reserves	$12,886 B (−37%)	$17,225 B (−50%)

Source: Author's calculations (data and methods described in Section 2.2).

---

[10] I estimate proved developed reserves according to the method described in Appendix 1.

[11] I take the average of the West Texas Intermediate and Brent Crude oil prices.

[12] For example, to obtain the adjusted CPS oil price for each year, I multiplied the EIA baseline price by the ratio of the WEO CPS price to WEO STEPS price.

[13] Projections for oil and gas are combined in the WEO. In the text they provide the annual average capital expenditures for gas development for STEPS. Under the assumption that the ratio of gas to oil capital expenditures is constant across all scenarios, I separate the expenditure data into oil expenditures and gas expenditures.

[14] To account for low gas prices in the U.S., I adjust marginal costs for the U.S. downward by a factor of 0.5, and allocate 20% of the U.S. natural gas capital costs to oil.

[15] See Table A1 in the WEO. Tight oil and extra-heavy oil and bitumen constituted 10% of oil production in 2018 and are projected to account for 18% in 2040.

[16] I split this up into oil expenditures and gas expenditures as described in footnote 13.

[17] I do not have evidence supporting this assumption. However, its impact on overall SFFA is insignificant.

[18] As discussed in Section 2.2.2, these results are the average of two stranded reserves estimations, each with a different baseline scenario (STEPS and CPS). The individual estimations (from which the average is taken) can be found in the supplementary material.

stranded reserves—68%-77%—comes in the form of oil, as oil is the most widely used fossil fuel and generally the most profitable. When also considering natural gas, about 90% of stranded reserves fall on the oil and gas industry.

The results for stranded capital are presented in Table 5, organized by length of government-industry time lag (t). For $t = 0$ (i.e., only a portion of past investments are stranded) stranded capital is limited to $303-$364 billion. While large in absolute terms, these figures represent just 33%–39% of the fossil fuel industry's typical capital expenditures for a single year between 2014 and 2018 [34]. For lags of one or two years (i.e., industry fails to adjust investments immediately, resulting in over-investment), stranded capital rises to $539-$908 billion. It is important to note, however, that even if industry over-invests for one or two years, those investments could still be utilized. The IEA projects substantial capital investments for all three fossil fuels, even in the climate stabilization scenarios. This is especially true for oil and gas due to the production decline curves discussed in Section 2.2.4. Fig. 1 compares oil and gas demand under 1.8 °C and 1.5 °C scenarios with oil and gas supply from existing wells with no new capital investments.[19] In both the 1.8 °C and 1.5 °C scenarios, substantial oil and gas investments are needed.

These aggregate stranded assets estimates can be understood as the reduction in market value of fossil fuel reserves and capital, which are owned by private firms and governments, if the world chooses the path of climate stabilization. The $13-$17 trillion in stranded reserves are substantial by any measure. They provide an incentive for industry to expend resources on delaying climate stabilization for as long as possible. Stranded capital is relatively small, strengthening the incentive to resist climate stabilization. Producers can continue investing in fossil fuel production knowing that the risk of stranding these investments is small, especially in comparison to the stranded reserves that would occur from climate stabilization.

2.3.2. *The price effect vs. the carbon budget effect*

The magnitude of wealth losses from stranded reserves can be disaggregated into the price and carbon budget effects. They are best described through an example. In the 1.8 °C scenario, 172 billion barrels of oil will remain in the ground relative to the baseline scenario. The value of these reserves drops to zero, constituting the carbon budget effect. 633 billion barrels of oil will still be extracted and sold in the 1.8 °C scenario. However, due to the drop in demand for oil, these reserves will be sold at a significantly lower price, leading to lower profits and, thus, a lower market value. This is the price effect.[20]

Table 6 shows the percentages of stranded reserves that can be attributed to each effect. In both scenarios, the price effect outweighs the carbon budget effect. The carbon budget effect increases under the 1.5 °C scenario, as more reserves are left in the ground, but the price effect still dominates overall. For coal, the carbon budget effect dominates, as more coal will be left in the ground in both scenarios. Nonetheless, the price effect is still significant: 29%–45%. Producers could attempt to combat the price effect by cutting supply. Major oil producers have done this in the past quite regularly. However, in the past, decreases in demand were temporary. In a clean energy transition, demand would decrease permanently. Thus, if major producers were to cut supply, they would risk giving market share to others. In other words, they would be volunteering to leave more fossil fuels in the ground, the value of which would drop to zero. Some researchers argue that a more likely scenario is for low-cost producers to increase supply in the short-term to use up their reserves [13,72]. This would depress fossil fuel prices even further, leading to even greater stranded assets.

Table 5
Wealth losses from stranded capital by length of government-industry time lag (t) (2018 US$, B=Billion).

Fuel	1.8 °C			1.5 °C		
	$t = 0$ yr	$t = 1$ yr	$t = 2$ yrs	$t = 0$ yr	$t = 1$ yr	$t = 2$ yrs
Oil + Gas	$250 B	$445 B	$623 B	$306 B	$545 B	$762 B
Oil	$163 B	$290 B	$406 B	$192 B	$343 B	$479 B
Gas	$87 B	$155 B	$217 B	$113 B	$202 B	$283 B
Coal	$53 B	$94 B	$131 B	$59 B	$104 B	$146 B
Total	$303 B	$539 B	$754 B	$364 B	$649 B	$908 B

Source: Author's calculations (data and methods described in Section 2.2).

The substantial price effect shows that even the lowest-cost producers, such as those in the Middle East, which can produce oil for less than $10 per barrel, will bear significant losses. It is not just high-cost producers that have an incentive to resist climate stabilization in the short-term. The price effect also shows the importance of strategic demand reduction of fossil fuels for weakening the industry's economic and political power. I discuss this in more depth in the conclusion.

2.3.3. *Distribution between governments and private firms and by region*

Globally, governments—like those of Saudi Arabia, Russia, and China—control most fossil fuel production. Additionally, private firms must pay a portion of their profits to governments in the form of taxes and royalties. The result is that 76% of stranded reserves belong to governments, as shown in Table 7. The percentages displayed are the average of the two climate stabilization scenarios.[21] The implication here is that the climate movement will likely face more formidable political obstacles in nations with nationalized fossil fuel ownership. In these countries, the political leaders themselves have a major, direct stake in the continuation of fossil fuel production.

2.3.4. *Region*

As shown in Fig. 2, the three regions with the greatest shares of stranded reserves are the Middle East (33%), North America (19%), and Eurasia (17%), accounting for nearly 70% of total stranded reserves. Table 8 displays the regional distribution for each industry. For the oil and gas industry, stranded reserves are concentrated in the three regions mentioned above. In the coal industry, 81% of stranded reserves are in China. The location and concentration of stranded assets provide insights into where climate stabilization policies will be most successful in the short-term. I discuss this in detail in the conclusion.

2.3.5. *Sensitivity analysis*

This section presents a sensitivity analysis of the aggregate stranded reserves results, exploring how stranded reserves estimates change from alternative methodological and data choices.

Table 9 compares estimates for the 1.8 °C scenario. The estimates vary by method of projecting supply (practitioner method vs. scenario projection method), discount rate (0%, 3%, 5%, 8%, and 10%), and sources for price and supply projection data (Present study, WEO – STEPS, WEO – CPS, and Mercure/STEPS). "WEO - STEPS" and "WEO - CPS" refer to projections from the STEPS and CPS scenarios in the WEO. "Mercure/STEPS" refers to price projections from Mercure et al. [13] combined with supply projections for STEPS. The estimates that most closely resemble the methods and data used in the studies reviewed in Section 2.1 are in bold font and denoted with superscripts.

These estimates are not exact replications of studies reviewed. All estimates in Table 9 use the 2020–2040 timeframe and the capital and marginal cost projections used in the stranded assets estimation of this paper. This differs from Mercure et al. [13], Lewis [16], and Linquiti and Cogswell [18] who estimated revenue only. Additionally, all WEO

---

[19] See IEA [7] for a similar exercise using an 8% exponential decline curve.

[20] van der Ploeg and Rezai [71] use similar categories.

[21] Results were nearly identical between the two scenarios. This is due mostly to the way I modeled the 1.5 °C regional distribution, as explained in Section 2.2.6.

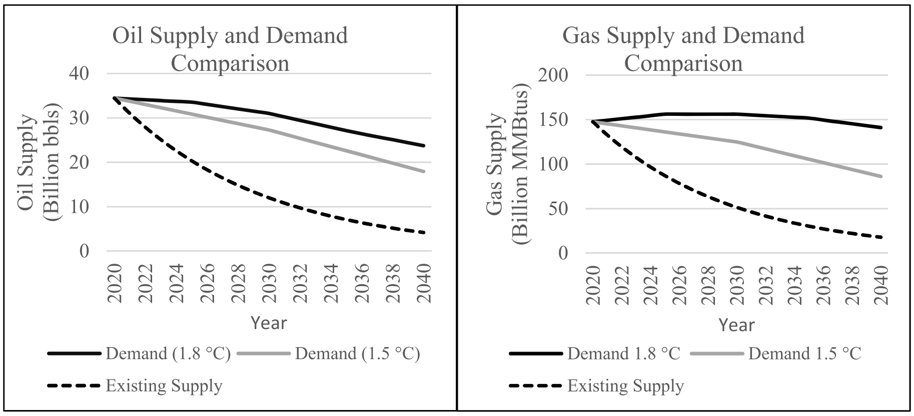


Fig. 1. Supply from existing wells vs. demand under climate stabilization.
Sources: [34]; Author's calculations (see text for details).

Table 6
Wealth losses from stranded reserves disaggregated into the price effect and carbon budget effect (timeframe: 2020–2040).

	1.8 °C		1.5 °C	
	Price Effect	Carbon Budget Effect	Price Effect	Carbon Budget Effect
Stranded oil + gas reserves	65%	35%	54%	46%
Stranded oil reserves	66%	34%	57%	43%
Stranded gas reserves	62%	38%	44%	56%
Stranded coal reserves	45%	55%	29%	71%
Total stranded reserves	63%	37%	51%	49%

Source: Author's calculations based on the results in Table 4.

Table 7
Distribution of stranded reserves between governments and private firms (timeframe: 2020–2040).

	Governments	Private Firms
Stranded oil + gas reserves	76%	24%
Stranded oil reserves	75%	25%
Stranded gas reserves	81%	19%
Stranded coal reserves	73%	27%
Total stranded reserves	76%	24%

Source: Author's calculations (data and methods described in Section 2.2.6 and Appendix 4).

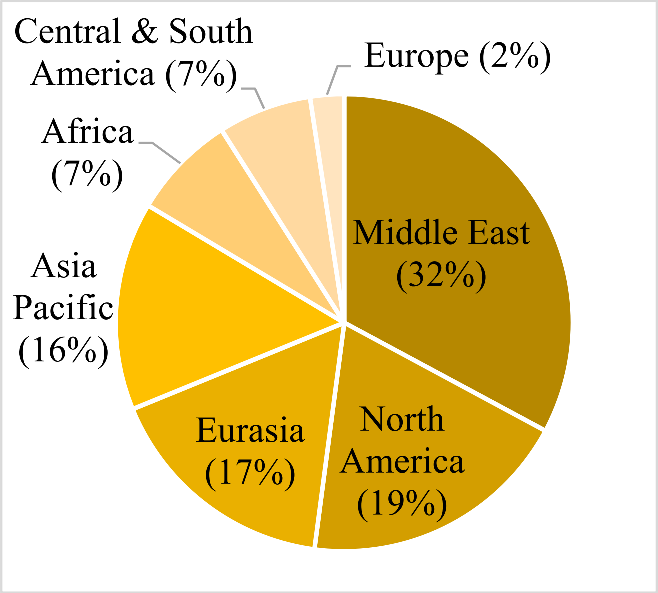


Fig. 2. Stranded reserves by region (timeframe: 2020–2040) Source: Table 8.

Table 8
Stranded reserves by region (timeframe: 2020–2040).

	Oil + Gas	Coal	Total
North America	21%	5%	19%
Central & South America	7%	1%	7%
Europe	2%	3%	2%
Africa	8%	3%	7%
Middle East	36%	0%	32%
Eurasia	18%	8%	17%
Asia Pacific	8%	81%	16%

Sources: Author's calculations (See Section 2.2.6 and Appendix 3).

projections are from the 2019 edition of the WEO [34], while Lewis [16], Linquiti and Cogswell [18], and Nelson et al. [15] used previous editions. Mercure et al. [13] provide incomplete price projection data, so I used linear interpolation to fill in the missing years. Finally, I do not have access to sufficient price and supply data from Bauer et al. [14]. I represent their estimate using STEPS.

Table 10 displays estimates of the value of stranded reserves for the 1.5 °C scenario using alternative discount rates. None of the prior studies modeled the 1.5 °C scenario, so I only consider the methods and data used in the main analysis of this paper.

The estimates of wealth losses are highly sensitive to the discount rate and sources used for projections. The estimates that are representative of Lewis and Bauer et al. for example, are identical in every way except the discount rate. Lewis' 0% rate leads to an estimate two times that of Bauer et al.'s 5% rate. Estimates for STEPS and the present study are quite similar.[22] The estimates using CPS are significantly higher while those using Mercure/STEPS are significantly lower. The practitioner and scenario projection methods of projecting oil and gas supply generally did not lead to substantial differences in estimates, the exceptions being the 0% and 10% discount rates.

These results highlight the importance of carefully selecting the parameters and scenario projections based on the goals of the analysis.

---

[22] While I used the average of STEPS and CPS for my estimation, I updated the oil prices using the EIA [65]. See Section 2.2.5.1 for more details.

Table 9
Alternative estimates of wealth losses from stranded reserves in the 1.8 °C scenario (d = discount rate, values in billions of 2018 US$, timeframe: 2020–2040).

	Practitioner method					Scenario projection method				
	d = 0%	3%	5%	8%	10%	d = 0%	3%	5%	8%	10%
Oil										
Present study	23,471	17,589	14,737	11,536	**9920**[a]	27,233	18,394	14,417	10,266	8323
WEO - STEPS	21,424	16,141	13,573	10,685	9223	**24,210**[b]	16,465	**12,971**[c]	9315	7599
WEO - CPS	37,028	27,796	23,316	18,287	15,746	42,618	**28,926**[d]	22,752	**16,295**[e]	13,266
Mercure/STEPS	5225	3981	3365	2659	2296	5930	3887	2977	2038	**1604**[f]
Gas										
Present study	3914	2977	2513	1981	**1708**[a]	4596	2900	2157	1403	1061
WEO - STEPS	2811	2156	1829	1454	1260	**3230**[b]	2022	**1495**[c]	965	726
WEO - CPS	5016	3798	3196	2508	2156	5962	**3778**[d]	2819	**1842**[e]	1397
Mercure/STEPS	599	463	391	303	255	841	424	248	79	**7**[f]
Coal										
Present study	N/A	N/A	N/A	N/A	N/A	3758	2603	2077	1522	**1258**[a]
WEO - STEPS	N/A	N/A	N/A	N/A	N/A	**2893**[b]	1988	**1577**[c]	1142	937
WEO - CPS	N/A	N/A	N/A	N/A	N/A	4622	**3218**[d]	2578	**1901**[e]	1579
Mercure/STEPS	N/A	N/A	N/A	N/A	N/A	154	67	30	−6	**−21**[f]
Total*										
Present study	31,143	23,169	19,327	15,039	**12,886**[a]	35,587	23,898	18,651	13,191	10,642
WEO - STEPS	27,129	20,285	16,979	13,282	11,420	**30,333**[b]	20,475	**16,043**[c]	11,422	9262
WEO - CPS	46,667	34,812	29,090	22,696	19,481	53,203	**35,923**[d]	28,148	**20,038**[e]	16,243
Mercure/STEPS	5979	4511	3786	2956	2530	6925	4378	3256	2111	**1589**[f]

* 'Total' values for the 'practitioner method' incorporate the 'scenario projection method' values for coal.

[a] Identical to results in Section 2.3.1.

[b] Method analogous to Lewis [16].

[c] Method analogous to Bauer et al. [14].

[d] Method analogous to Linquiti and Cogswell [18].

[e] Method analogous to Nelson et al. [15].

[f] Method analogous to Mercure et al. [13].

Source: Author's calculations (see text for details on methods and data).

Table 10
Alternative estimates of wealth losses from stranded reserves in the 1.5 °C scenario (d = discount rate, values in billions of 2018 US$, timeframe: 2020–2040).

	Practitioner method					Scenario projection method				
	d = 0%	3%	5%	8%	10%	d = 0%	3%	5%	8%	10%
Oil	27,122	20,437	17,178	13,504	11,640	30,873	20,930	16,443	11,746	9541
Gas	8371	6447	5487	4381	3808	9099	5993	4607	3172	2507
Coal	5068	3564	2872	2132	1777	5068	3564	2872	2132	1777
Total	40,561	30,448	25,537	20,018	17,225	45,040	30,487	23,921	17,051	13,825

Source: Author's calculations (see text for details on methods and data).

3. Profitability analysis

In addition to wealth, the fossil fuel industry will bear reduced profits. I explore this in two ways. First, timing. Recall that fossil fuel reserves are valued based on the profits they are expected to create. The $13-$17 trillion in stranded reserves, thus, stems from the expectation that fossil fuel production will create substantially lower profits in a climate stabilization scenario. The timing of these losses is important. If they mostly occur closer to 2040, for example, industry can expect to continue accumulating high profits for more than a decade, even in a climate stabilization scenario. Second, I compare profit margins between the fossil fuel and renewable energy industries. If renewable energy is as profitable as fossil fuel production, fossil fuel firms have a greater incentive to begin transitioning to renewable energy production and can minimize profit losses.

3.1. Timing

To estimate cumulative forgone profits from fossil fuel production for each year, I follow the same method as for estimating the value of fossil fuel reserves, with one exception: I use the scenario projection method for projecting annual fossil fuel supply (details in Section 2.2.4). The results are shown in Table 11.

Nearly half of forgone profits ($4.7-$6.5 trillion) occur from 2020 to 2030, with 15%–16% ($1.6-$2.3 trillion) occurring from 2020 to 2025. Thus, while just over half of forgone profits occur from 2031 to 2040, the fossil fuel industry will bear significant losses in the short-term in a climate stabilization scenario. Thus, once climate stabilization begins, fossil fuel firms will have little to no time before suffering economic losses in terms of both income and wealth. The short-term profit losses are due mainly to the price effect.

Table 11
Present value of forgone profits over time, assuming a 10% discount rate (percent of the total in parentheses) (2018 US$, T = Trillion).

Time period	Forgone Profits	
	1.8 °C	1.5 °C
2020–2025	$1.6 T (15%)	$2.3 T (16%)
2026–2030	$3.1 T (29%)	$4.2 T (30%)
2031–2035	$3.2 T (30%)	$4.0 T (29%)
2036–2040	$2.8 T (26%)	$3.4 T (24%)
Total	$10.6 T	$13.8 T

Sources: Author's calculations (data and methods described in Section 2.2).

3.2. Profit margin comparison

For the profit margin comparison, I used data from Bloomberg L.P

[73]. for 2011–2020. The Bloomberg database includes financial data for publicly traded firms from all countries. For each firm, I exclude data for years in which profit margins were not definable (i.e., profit or revenue data were missing, or revenue was zero). I collected data for three sectors within the fossil fuel industry: integrated oil and gas (i.e., firms that operate along the entire fossil fuel supply chain), oil and gas exploration and production (E&P), and coal mining) and three sectors within the renewable energy industry (equipment manufacturers, project developers,[23] and biofuels), classified according to the Bloomberg Industry Classification Standard (BICS). There is no overlap between the sectors.

Table 12 displays annual average profit margins and revenue for each sector as a whole and the top ten firms (based on revenue) of each sector for the period 2011–2020.[24] The revenue figures provide insight into the relative size of the firms of each sector. Integrated oil and gas firms are the largest by a wide margin, and renewable energy firms are the smallest. Overall, the fossil fuel industry, in general, was considerably more profitable than the renewable energy industry over the 2011–2020 period. The renewable energy industry recorded profits of just 0.1%, suggesting that it generally was not profitable. It is important to note, however, that the sector with the lowest profit margin was oil and gas E&P. For every sector, the largest ten firms performed better than the sector in general. This is due to major oil price crises in 2015–2016 and 2020.

Figs. 3 and 4 display profit margins over time. In general, the fossil fuel industry records the highest highs and the lowest lows. The one exception is the renewable energy project developers in 2018, which nearly matched the oil and gas E&P sector for the highest profit margin. Note that the oil and gas E&P sector recorded both the highest and lowest profit margin. The lows, however, outweighed the highs. In 2015, 2016, and 2020, oil and gas E&P recorded margins of −51%, −52%, and −37%, respectively. It appears as if there is a slight upward trend in profit margins for the renewable energy industry in general and an even greater trend for the top ten renewable energy firms. Fossil fuel industry profit margins show neither an upward nor downward trend. However, given the year-to-year variability and relatively short timeframe, it is impossible to say anything definitive about trends.

What one can say from this data is that the fossil fuel industry, in general, has enjoyed substantially greater profit margins than the renewable energy industry over the past decade, and there is little reason to think that the renewable energy industry will catch up in the near future, at least without a major change in energy policy. These findings are consistent with a recent report from the IEA [74]. The lower profit margins of renewable energy provide further incentive for fossil fuel firms to resist climate stabilization.

Table 12
Comparison of average annual profit margin, revenue, and market cap from 2011 to 2020 for fossil fuel and renewable energy firms (2018 US$, B=Billion).

Sector	Average Annual Profit Margin		Average Annual Revenue (per firm)	
	Entire Sector	Top 10 Firms	Entire Sector	Top 10 Firms
Fossil Fuels (n = 880)	3.8%	5.0%	$5.38 B	$248.85 B
Oil/Gas – Integrated (n = 39)	4.9%	5.0%	$86.47 B	$248.85 B
Oil/Gas E&P (n = 626)	−7.4%	2.0%	$0.73 B	$16.88 B
Coal mining (n = 215	4.9%	10.3%	$1.16 B	$10.78 B
Renewable Energy (n = 545)	0.1%	3.0%	$0.35 B	$5.10 B
Equipment Mfr. (n = 341)	−0.2%	3.4%	$0.40 B	$4.24 B
Project Developers (n = 148)	0.7%	2.2%	$0.24 B	$2.25 B
Biofuels (n = 56)	1.5%	2.3%	$0.32 B	$1.15 B

Sources: Author's calculations using data from Bloomberg L.P [73].

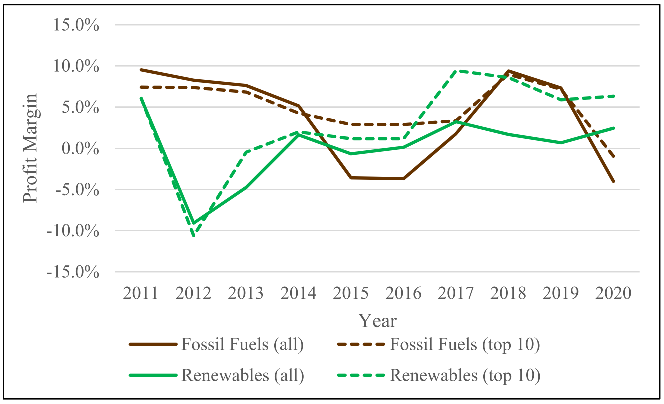


Fig. 3. Profit margins by industry, 2011–2020.
Sources: Author's calculations using data from Bloomberg L.P [73].

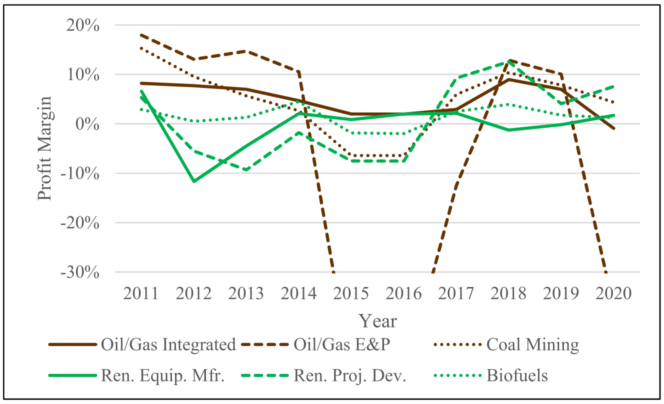


Fig. 4. Profit margins by industry (disaggregated), 2011–2020.
Sources: Author's calculations using data from Bloomberg L.P [73].

It is also important to note that this analysis does not consider medium- and long-term profitability in a clean energy transition. While wind and solar-based power generation are already cost-competitive with fossil fuel-based generation [75], several researchers point out that completely phasing out fossil fuels is not yet possible [76–78]. That is, clean energy will become prohibitively expensive—and thus unprofitable—as its share of the energy supply increases, at least without a continuation of substantial innovation in clean energy technologies.

Analyzing why the renewable energy industry is generally unprofitable at present as well as the longer-term issues just highlighted are out of the scope of this paper, but are important topics for further research.

4. Discussion and conclusions

The results from the stranded assets and profitability analyses suggest that the upstream fossil fuel industry—low-cost and high-cost producers alike—faces strong economic incentives to continue on the path of resisting climate stabilization. The main results include that climate stabilization will lead to a devaluation of fossil fuel reserves of 37–50%, or $13-$17 trillion. Most of this devaluation (51%–63%) stems from price decreases for fuels still extracted and sold during climate stabilization, and 76% will fall on governments. Fossil fuel firms have

---

[23] I added Ørsted A/S to this sector (Ørsted is the largest offshore wind developer in the world), as Bloomberg excluded them.

[24] The earliest year of data available from Bloomberg L.P. was 2011.

also remained significantly more profitable than renewable energy firms and can expect to suffer major profit losses even in the short-term from climate stabilization. I conclude by considering the implications of these results for two approaches to overcoming this resistance: (1) appeasing the industry, and (2) defeating it.

The appeasement approach attempts to entice the industry to change, designing climate policies and international agreements so as to induce industry into taking a leading role in remaking the energy system. In addition to other incentives, this approach would likely require compensation, including for the $13-$17 trillion in stranded assets, and policies to ensure comparable profitability in renewable energy.[25]

In terms of compensation, it is instructive to consider the cases of the U.S. and the Middle East. Firms in North America—mostly the U.S.—face the prospect of $2-$3 trillion of stranded assets. This is less than the $3.5 trillion the U.S. Federal Government has spent on COVID-19 relief as of September 30, 2021 [82]. The U.S. is also home to ample clean energy resources, which provides U.S.-based fossil fuel firms with opportunities to transition investments to clean energy production. Compensation, thus, may be feasible in the U.S., at least economically.

In the Middle East, stranded assets amount to $4-$6 trillion in losses—about one-third of total stranded assets worldwide—a sum larger than the region's gross domestic product [83]. Governments control most fossil fuel production in the region and rely on it for government revenue. The fiscal breakeven oil prices across the region in 2020—that is, the crude oil price required for governments to balance their budgets—ranged from $46-$194 per barrel [84]. Compensation thus would have to come from the international community. International compensation at this level—$4-$6 trillion—is highly unlikely, especially without major strings attached. The appeasement approach on its own, therefore, is not economically feasible.

The second approach—defeating industry—aims to disempower the industry to the point that its resistance becomes ineffective. Geels [85] advocates for and describes this approach using a "David versus Goliath" metaphor. "[R]ather than following the normal 'David versus Goliath' storyline, in which heroic green innovations overthrow the giant," he argues for a shift in research and policy agendas to "better understand how 'Goliath' can be weakened, eroded and destabilized, to enhance the chances of green Davids" (p. 37).

My results suggest that the key strategy for this purpose is strategic demand reduction of fossil fuels. As discussed in Section 2.3.2, most stranded assets stem not from leaving fossil fuels in the ground, but from price decreases for fossil fuels still extracted and sold during climate stabilization. As shown in Section 3.1, industry will suffer significant losses, even in the short-term, once climate stabilization begins. Even modest decreases in demand can begin to erode the wealth and power of the fossil fuel industry—low-cost and high-cost producers alike. Policies can also target supply, such as putting a cap or tax on fossil fuel production. The ultimate goal, however, remains the same: reducing society's dependency on fossil fuels (i.e., demand reduction).[26] If society remains dependent on fossil fuels, the industry will likely retain significant wealth and leverage in the political realm.

Demand-reduction policies are exactly what the fossil fuel industry is resisting. Pahle et al. [81] propose a framework for how to ratchet up the stringency of climate policies where barriers—such as the resistance of fossil fuel interests—successfully prevent them. The basic idea is that policymakers should focus on passing less stringent policies that are feasible in the short-term, but which also address the barriers to the more stringent policies that are necessary for climate stabilization, thus enabling the more stringent policies to be passed in the future. Pahle et al. exemplify their framework through case studies on Germany and California, where less stringent climate policies were able to bring down the costs of renewables, enabling the more stringent climate policies and targets that exist today.

Demand reduction strategies will likely be most successful outside of major fossil fuel-producing countries, especially outside those with nationalized fossil fuel ownership. Countries like the U.S. and Canada are somewhat unique: they are major fossil fuel producers; however, their fossil fuel production is privately controlled, providing an opening for environmental movements to pressure policymakers to implement demand-reduction policies notwithstanding the interests of the fossil fuel industry.

Another popular strategy under this approach is to try to isolate the industry socially and politically. Environmentalist Bill McKibben, for example, helped spark the fossil fuel divestment movement with a 2012 article in *Rolling Stone* where he deemed the fossil fuel industry "a rogue industry, reckless like no other force on Earth," and "Public Enemy Number One to the survival of our planetary civilization" [86]. The main goal of the divestment movement is to remove the industry's "social license to operate." Another example is the "No Fossil Fuel Money Pledge," committing politicians to forsake fossil fuel money [87]. These strategies can help create the political space necessary for demand reduction policies.

The two approaches—appeasing industry and defeating industry—are not mutually exclusive, and indeed can be complementary. For example, demand curtailment would reduce the industry's bargaining power, which in turn would reduce the compensation necessary to appease industry. Given the clear economic incentives for the fossil fuel industry to continue resisting climate stabilization, some combination of the two approaches will be necessary to overcome the industry's resistance and stabilize the climate.

Data availability

Data for the stranded assets analysis are available from the WEO [34], EIA [65], Huppmann et al. [64], EIA [66], Statista [67], WSJ [68], IEA [7], and NRGI [69]. Data for the profitability comparison are available via Bloomberg Terminal [73] access. The model used to obtain the main stranded assets results is available at https://doi.org/10.11583/DTU.18357251.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

---

[25] For discussions on compensation, see Refs. [79–81].

[26] From the fossil fuel industry's perspective, the impact of upstream carbon pricing (i.e., a carbon tax, cap-and-auction, or cap-and-trade system imposed on fossil fuel producers based on the carbon content of their products) is the same as a reduction in demand, even in the short-term. Producers would sell less fossil fuels at a lower price, while consumers would pay a higher price. The difference between what consumers pay and what producers receive is the carbon price, which goes to the government. The exception is a cap-and-trade policy where the government gives away carbon permits for free. In that case, the extra carbon revenue generated from the carbon price would go directly to the producers.

[25] For discussions on compensation, see Refs. [79–81].

[26] From the fossil fuel industry's perspective, the impact of upstream carbon pricing (i.e., a carbon tax, cap-and-auction, or cap-and-trade system imposed on fossil fuel producers based on the carbon content of their products) is the same as a reduction in demand, even in the short-term. Producers would sell less fossil fuels at a lower price, while consumers would pay a higher price. The difference between what consumers pay and what producers receive is the carbon price, which goes to the government. The exception is a cap-and-trade policy where the government gives away carbon permits for free. In that case, the extra carbon revenue generated from the carbon price would go directly to the producers.

the work reported in this paper.

Acknowledgments

This article stems from my Ph.D. dissertation, titled "Three Essays on the Political Economy of Global inaction on Climate Change." I am indebted to my dissertation committee members—Robert Pollin, James K. Boyce, Michael Ash, and Kevin Young—for their feedback and guidance. I am also grateful to four anonymous reviewers for their useful comments and suggestions. This research was supported in part by a 2021 Political Economy Research Institute (PERI) Dissertation Fellowship from the University of Massachusetts Amherst.

Appendix 1. Further details on the practitioner method of projecting oil and gas supply

As noted in Section 2.2.2, I consider a 21-year timeframe for the stranded assets analysis. All reserves to be produced in this timeframe are "proved," meaning they have a 90–100% probability of being profitably extracted under current technologies. Actualizing the practitioner method of projecting oil and gas supply requires further categorization: "proved developed" and "proved undeveloped" reserves. Proved developed reserves require little to no capital expenditures to enter production, and proved undeveloped reserves require a significant level of capital expenditures and an average of three years before entering production [88]. Thus, I assume proved developed reserves enter production in year one and proved undeveloped reserves in year four.

To determine the level of proved developed reserves, I use a simple model. I assume that wells last 21 years, production from wells declines at 10% per year, and 1 unit of oil/gas is produced per year. This most closely resembles production in STEPS. Each year, new production is equivalent to the loss of old production. I assume that developed reserves will enter production within 1.5 years, given that undeveloped proved reserves take an average of three years to enter production. Based on these assumptions, proved developed reserves constitute 38% of oil and gas reserves produced in STEPS.

One way to test the efficacy of the practitioner method is to compare it to a simple industry rule-of-thumb. Practitioners have found that the value of proved oil or gas reserves in a reservoir under normal conditions is equal to approximately one-third of the market price of oil or gas, or one-half of the net price (i.e., market price minus marginal cost of production). Multiple empirical papers confirm the accuracy of the rule-of-thumb hypothesis [39,58,89–91]. In Table A1.1, I compare the value of oil and gas reserves between the practitioner, scenario projection, and rule-of-thumb methods.[27] As expected, the rule-of-thumb most closely resembles the practitioner method.

Table A1.1
Value of oil and gas reserves for different methods of projecting fossil fuel supply (2018 US$, B=Billion, timeframe: 2020–2040)

Method	Oil	Natural Gas
Practitioner	$21,425 B	$9863 B
Scenario projection	$18,408 B	$7763 B
Rule-of-thumb	$20,060 B	$10,769 B

Source: Author's calculations (data and methods described in Section 2.2).

Appendix 2. Price adjustments for SDS1.5

To make the adjustments, I used the concept of elasticity. Generally, elasticities are used to describe the responsiveness of demand to changes in price. In this case, I am measuring the responsiveness of price to changes in demand. Thus, I use the inverse elasticity: percent change in price divided by percent change in demand from one scenario to another scenario.

For oil price, the inverse elasticity from CPS to STEPS starts at 5.7 (in 2020) and decreases to 1.9 (in 2040). For STEPS to SDS1.8, the inverse elasticity starts at 2.4 in 2020 and declines to 1.1 in 2040. I assume relatively low inverse elasticities between SDS1.8 and SDS1.5, starting at 1.0 in 2020 and decreasing to 0.4 in 2040. I assume the year-to-year rate of decrease of inverse elasticity from SDS1.8 to SDS1.5 is equal to the average year-to-year rate of decrease for CPS to STEPS and STEPS to SDS1.8.

I followed the same process to adjust natural gas and coal prices. Because these prices vary regionally, I created a weighted average price for each (weighted by annual regional production). For SDS1.8 to SDS1.5, I assume inverse elasticities start at 1 for gas and 0.5 for coal in 2020 and decrease to 0.4 for gas and 0.2 for coal in 2040. After estimating SDS1.5 weighted average prices, I adjusted regional gas and coal prices proportionately.

The resulting prices are shown in Table A2.1.

Table A2.1
Fossil fuel price comparison for climate stabilization scenarios (2018 US$)

Year	Oil price (US$/barrel)		Natural gas price (weighted avg, US$/MMBtu)		Coal price (weighted avg., US$/metric ton)	
	SDS1.8	SDS1.5	SDS1.8	SDS1.5	SDS1.8	SDS1.5
2020	$52.21	$52.21	$6.93	$6.93	$92.82	$92.82
2030	$51.90	$47.66	$6.77	$5.96	$67.34	$56.63
2040	$50.62	$45.67	$7.07	$6.05	$70.76	$64.03

Sources: [34]; Author's calculations (see text for methods).

---

[27] Data are described in Section 2.2.5.1.

Appendix 3. Mapping data onto WEO regions and Additional adjustments

I map gas and coal prices onto the WEO regions as follows: for North America and Europe, I use the U.S. and EU prices, respectively; for the Asia Pacific, I average the prices for China and Japan; and for Africa, the Middle East, and Eurasia, I average the EU and Asia Pacific prices.

For the Asia Pacific, the coal price in STEPS drops significantly between 2018 and 2025 (by about $34 per ton). For SDS1.8, the WEO provides price projections for 2030, but not 2025. Using linear interpolation for the in-between years results in a lower coal price in STEPS than SDS1.8. To address this (for Asia Pacific only), I assume that the SDS1.8 coal price drops by the same rate as the STEPS coal price in 2025, plus 10%.

The EIA [66] provides combined marginal cost data for oil and natural gas production for the U.S., Canada, Europe, former Soviet Union, Middle East, "Other Eastern Hemisphere", and "Other Western Hemisphere." Statista [67] and WSJ [68] provide marginal cost data for oil production for a subset of oil-producing countries. I map these costs onto the WEO regions by taking an average of the countries for which data is available in each region, weighted by each country's production for STEPS (country-level data are unavailable for the other scenarios). For North America, for example, I take a weighted average of the costs for the U.S., Canada, and Mexico.

Appendix 4. Private Firm vs. Government Distribution by Region

Table A4.1 displays my estimates for the shares of fossil fuel reserves controlled by governments and private firms for each region. For oil and gas reserves, I begin with data from the IEA [7]. In 2018, governments—via state-owned firms—owned 66% of oil reserves and 60% of gas reserves, and controlled 58% of oil production and 51% of gas production. Private firms controlled the rest. I take the midpoint between the reserves and production shares for my analysis (i.e., I assume governments control 62% of oil reserves and 56% of gas reserves). I do this for two reasons. Most importantly, the IEA data include both proved reserves and a portion of unproved reserves, most of which are excluded from my analysis. Thus, control of production may be a more accurate metric for my purposes. However, it is also likely that governments will continue to increase their role in production, as they own the bulk of the lowest-cost reserves. The midpoint method accounts for both of these phenomena.

Table A4.1
Reserves distribution between governments and private firms

Region	Oil		Gas		Coal	
	Private	Gov.	Private	Gov.	Private	Gov.
North America	90%	10%	98%	2%	100%	0%
Central & South America	20%	80%	20%	80%	90%	10%
Europe	70%	30%	70%	30%	100%	0%
Africa	8%	92%	8%	92%	90%	10%
Middle East	5%	95%	5%	95%	5%	95%
Eurasia	50%	50%	50%	50%	90%	10%
Asia Pacific	5%	95%	5%	95%	25%	75%
World	38%	62%	44%	56%	41%	59%

Sources: Listed in Appendix 4.

To estimate the share of reserves owned by governments in each region, I divided the total reserves produced by state-owned firms in each region from the National Oil Company Database [69] by the total reserves produced in their respective countries. The exception was Africa, for which very little data was available. Thus, I estimated the government shares for the other regions first and then estimated Africa's government share so that the regional shares were consistent with the global share from the IEA [7]. This method is not exact, as data was missing for some firms, while other firms owned reserves in other countries. Thus, I used my best judgment where necessary, consulting other sources including Jones Day [92] and EIA [93].

For coal reserves, due to data limitations, I used a bottom-up approach. I researched coal production in the largest coal-producing countries, including China, India, Australia, Indonesia, Russia, the U.S., South Africa, and Colombia. Together, they account for 93% of global coal production.[28] Exact percentages were not available. Thus, I looked for evidence on whether the coal industry in these countries was mainly state-controlled or privately controlled. The most important country is China, which accounts for nearly 80% of global coal production on its own. Sources are listed below.

- China: IEA [94].
- India: IEA [34].
- Indonesia: Listiyorini [95].
- Russia: Vorotnikov [96].
- United States: EIA [97].
- South Africa: Africa Mining IQ [98].
- Colombia: Strambo and Velasco [99].

Finally, I transfer 29% of profits from private firms to governments to account for taxes and royalties. This is based on 2018 figures from PwC [70].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112144.

---

[28] Author's calculations based on 2018 production data from the WEO.

References

[1] UNFCCC. Paris agreement. 2016 [cited 2020 Sep 10]. Available from: https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf.

[2] UNFCCC. Nationally determined contributions under the Paris agreement. 2021. Sep [cited 2021 Sep 22]. Available from: https://unfccc.int/sites/default/files/resource/cma2021_08_adv_1.pdf.

[3] Mann ME. The new climate war: the fight to take back our planet. first ed. New York: PublicAffairs; 2021.

[4] Grasso M. Oily politics: a critical assessment of the oil and gas industry's contribution to climate change. Energy Res Social Sci 2019;50:106–15. https://doi.org/10.1016/j.erss.2018.11.017.

[5] Brulle RJ. The climate lobby: a sectoral analysis of lobbying spending on climate change in the USA, 2000 to 2016. Clim Change 2018;149(3–4):289–303. https://doi.org/10.1007/s10584-018-2241-z.

[6] Brulle RJ, Aronczyk M, Carmichael J. Corporate promotion and climate change: an analysis of key variables affecting advertising spending by major oil corporations, 1986–2015. Clim Change 2020;159(1):87–101. https://doi.org/10.1007/s10584-019-02582-8.

[7] IEA. The oil and gas industry in energy transitions: insights from IEA analysis. 2020. Available from: https://www.iea.org/data-and-statistics/charts/share-of-oil-reserves-oil-production-and-oil-upstream-investment-by-company-type-2018.

[8] Farrell J, McConnell K, Brulle R. Evidence-based strategies to combat scientific misinformation. Nat Clim Change 2019;9(3):191–5. https://doi.org/10.1038/s41558-018-0368-6.

[9] Banerjee N. Exxon's oil industry peers knew about climate dangers in the 1970s, too. InsideClimate News; 2015 Dec 22 [cited 2020 Oct 1]; Available from: http://insideclimatenews.org/news/22122015/exxon-mobil-oil-industry-peers-knew-about-climate-change-dangers-1970s-american-petroleum-institute-api-shell-chevron-texaco.

[10] Jennings K, Grandoni D, Rust S. How Exxon went from leader to skeptic on climate change research. LA Times; 2015 Oct 23 [cited 2020 Aug 3]; Available from: http://graphics.latimes.com/exxon-research/.

[11] Brulle RJ. Institutionalizing delay: foundation funding and the creation of U.S. climate change counter-movement organizations. Clim Change 2014;122(4):681–94. https://doi.org/10.1007/s10584-013-1018-7.

[12] Dunlap RE, McCright AM. Organized climate change denial. In: The oxford handbook of climate change and society; 2011. Available from: https://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780199566600.001.0001/oxfordhb-9780199566600-e-10.

[13] Mercure J-F, Pollitt H, Viñuales JE, Edwards NR, Holden PB, Chewpreecha U, et al. Macroeconomic impact of stranded fossil fuel assets. Nat Clim Change 2018;8(7):588–93. https://doi.org/10.1038/s41558-018-0182-1.

[14] Bauer N, Mouratiadou I, Luderer G, Baumstark L, Brecha RJ, Edenhofer O, et al. Global fossil energy markets and climate change mitigation – an analysis with REMIND. Clim Change 2016;136(1):69–82. https://doi.org/10.1007/s10584-013-0901-6.

[15] Nelson D, Hervé-Mignucci M, Goggins A, Szambelan SJ, Vladeck T, Zuckerman J. Moving to a low-carbon economy: the impact of policy pathways on fossil fuel asset values. Climate policy initiative. 2014. Available from: https://www.climatepolicyinitiative.org/publication/moving-to-a-low-carbon-economy/.

[16] Lewis M. Stranded assets, fossilised revenues: USD28trn of fossil-fuel revenues at risk in a 450-ppm world. Kepler Cheuvreux. 2014. Available from: https://www.longfinance.net/media/documents/kc_strandedassets_2014.pdf.

[17] Channell J, Curmi E, Nguyen P, Prior E, Syme AR, Jansen HR, et al. Energy darwinism II: why a low carbon future doesn't have to cost the Earth. Citi GPS; 2015. Available from: https://www.ourenergypolicy.org/resources/energy-darwinism-ii-why-a-low-carbon-future-doesnt-have-to-cost-the-earth/.

[18] Linquiti P, Cogswell N. The Carbon Ask: effects of climate policy on the value of fossil fuel resources and the implications for technological innovation. J Environ Stud Sci 2016;6(4):662–76. https://doi.org/10.1007/s13412-016-0397-2.

[19] Curtin J, McInerney C, Ó Gallachóir B, Hickey C, Deane P, Deeney P. Quantifying stranding risk for fossil fuel assets and implications for renewable energy investment: a review of the literature. Renew Sustain Energy Rev 2019;116. https://doi.org/10.1016/j.rser.2019.109402.

[20] Shimbar A. Environment-related stranded assets: an agenda for research into value destruction within carbon-intensive sectors in response to environmental concerns. Renew Sustain Energy Rev 2021;144. https://doi.org/10.1016/j.rser.2021.111010.

[21] IRENA. Stranded assets and renewables. IRENA; 2017. Available from: https://www.irena.org/publications/2017/Jul/Stranded-Assets-and-Renewables.

[22] Bos K, Gupta J. Stranded assets and stranded resources: implications for climate change mitigation and global sustainable development. Energy Res Social Sci 2019;56. https://doi.org/10.1016/j.erss.2019.05.025.

[23] Semieniuk G, Holden PB, Mercure J-F, Salas P, Pollitt H, Jobson K, et al. Stranded fossil-fuel assets translate into major losses for investors in advanced economies. PERI Work Pap Ser; 2021. Available from: https://peri.umass.edu/component/k2/item/1529-stranded-fossil-fuel-assets-translate-into-major-losses-for-investors-in-advanced-economies.

[24] McGlade C, Ekins P. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. Nature 2015;517(7533):187–90. https://doi.org/10.1038/nature14016.

[25] IEA. World energy Outlook 2013. 2013. Available from: https://www.iea.org/reports/world-energy-outlook-2013.

[26] IEA. World energy Outlook 2015. IEA; 2015. Available from: https://www.iea.org/reports/world-energy-outlook-2015.

[27] Bls. CPI inflation calculator. 2021 [cited 2021 Sep 6]. Available from: https://www.bls.gov/data/inflation_calculator.htm.

[28] FRED. Crude oil prices: west Texas intermediate (WTI). 2021 [cited 2021 Jul 20]. Available from: https://fred.stlouisfed.org/series/DCOILWTICO#0.

[29] Caldwell R, Chodorow D, Dorobantu F. Valuing natural resources investments. Contemp Emerg Issues Law Damages Valuat Int Invest Arbitr 2018:293–322. https://doi.org/10.1163/9789004357792_012.

[30] Schumann CP. Current update on oil & gas valuation. The San Antonio Bar Association Natural Resources Section Meeting; 2014 [cited 2020 Oct 1]. Available from: https://www.cpschumannco.com/assets/pdf-files/oil_gas_valuation.pdf.

[31] McGowen RM. Valuing oil and gas properties. 39th Annual Natural Resources Law Institute; 2000 [cited 2020 Oct 1]. Available from: https://scholarworks.uark.edu/cgi/viewcontent.cgi?article=1044&context=anrlaw.

[32] Weir JP. Valuation of coal mining properties. Energy and Fuels Research Center, The Pennsylvania State University; 1993 [cited 2020 Oct 1]. Available from: https://scholarsphere.psu.edu/concern/generic_works/0v838067q.

[33] PetroWiki. Valuation of oil and gas reserves. 2017 [cited 2020 Oct 1]. Available from: https://petrowiki.org/PEH:Valuation_of_Oil_and_Gas_Reserves.

[34] IEA. World energy Outlook 2019. 2019. Available from: https://www.iea.org/reports/world-energy-outlook-2019.

[35] IEA. World energy Outlook 2020. 2020. Available from: https://www.iea.org/reports/world-energy-outlook-2020.

[36] RFF. Global energy Outlook 2020: energy transition or energy addition. 2020. Available from: https://www.rff.org/publications/reports/global-energy-outlook-2020.

[37] Harden C (Jim). Discount rate development in oil and gas valuation. SPE; 2014.

[38] Mercer capital. PV-X: WACCs for E&P companies. 2016 [cited 2021 Jul 28]. Available from: https://mercercapital.com/energyvaluationinsights/pv-x-waccs-for-ep-companies/.

[39] Adelman MA, Watkins GC. Reserve asset values and the hotelling valuation principle: further evidence. South Econ J 1995;61(3):664–73. https://doi.org/10.2307/1060989.

[40] Kopacz M, Kulpa J, Galica D, Dyczko A, Jarosz J. Economic valuation of coal deposits – the value of geological information in the resource recognition process. Resour Pol 2019;63. https://doi.org/10.1016/j.resourpol.2019.101450.

[41] Saługa PW, Szczepańska-Woszczyna K, Miśkiewicz R, Chłąd M. Cost of equity of coal-fired power generation projects in Poland: its importance for the management of decision-making process. Energies 2020;13(18). https://doi.org/10.3390/en13184833.

[42] Simionescu A, Buşe F, Hodor P, Mangu S. On the valuation of coal property. Ann Univ Petroşani Econ; 2002 [cited 2021 Jul 29]; Available from: https://econpapers.repec.org/article/petannals/v_3a2_3ay_3a2002_3ap_3a180-189.htm.

[43] Franc-Dąbrowska J, Mądra-Sawicka M, Milewska A. Energy sector risk and cost of capital assessment—companies and investors perspective. Energies 2021;14(6). https://doi.org/10.3390/en14061613.

[44] Jagannathan R, Matsa DA, Meier I, Tarhan V. Why do firms use high discount rates? J Financ Econ 2016;120(3):445–63. https://doi.org/10.1016/j.jfineco.2016.01.012.

[45] Graham J, Harvey C. Duke/CFO magazine global business Outlook, U.S. Topline tables. Duke: The Fuqua School of Business; 2011 [cited 2020 Oct 1]. Available from: https://faculty.fuqua.duke.edu/cfosurvey/pastresults.htm.

[46] Poterba JM, Summers LH. A CEO survey of U.S. Companies' time horizons and hurdle rates. Sloan Manag Rev Camb 1995;37(1):43. Available from: https://sloanreview.mit.edu/article/a-ceo-survey-of-us-companies-time-horizons-and-hurdle-rates/.

[47] Hartley P, Medlock KB. A model of the operation and development of a National Oil Company. Energy Econ 2008;30(5):2459–85. https://doi.org/10.1016/j.eneco.2007.12.017.

[48] Rosneft. Consolidated financial statements rosneft oil Company for the year. ended December 31. 2020. 2021 [cited 2021 Jul 29]. Available from: https://www.rosneft.com/upload/site2/document_cons_report/Rosneft_IFRS_12m2020_eng.pdf.

[49] Gazprom. PJSC Gazprom financial report 2020. 2021 [cited 2021 Jul 29]. Available from: https://www.gazprom.com/f/posts/13/041777/gazprom-financial-report-2020-en.pdf.

[50] Aramco Saudi. Saudi arabian oil Company consolidated financial statements for the year ended december 31, 2020. 2021 [cited 2021 Jul 29]. Available from: https://www.aramco.com/-/media/publications/corporate-reports/saudi-aramco-fy-2020-full-financials-english.pdf.

[51] CNPC. PetroChina Company limited 2020 annual report. 2021 [cited 2021 Jul 29]. Available from: http://www.petrochina.com.cn/ptr/rdxx/202104/3b0df6d7415349d2baecea5b527ed6fc/files/be5031791a2e44959eedb9fab714bf15.pdf.

[52] Sinopec. 2020 annual report and accounts: Sinopec corp. 2021 [cited 2021 Jul 29]. Available from: http://www.sinopec.com/listco/Resource/Pdf/2021041502.pdf.

[53] Arps JJ. Analysis of decline curves. Trans AIME 1945;160(1):228–47. https://doi.org/10.2118/945228-G.

[54] Hyne NJ. Nontechnical guide to petroleum geology, exploration, drilling, and production. third ed. Tulsa, Okla: PennWell Corporation; 2012.

[55] CAPP. Life Cycle of a Well. [cited 2020 Sep 12]. Available from:: https://www.capp.ca/explore/life-cycle-of-a-well/.

[56] Anderson ST, Kellogg R, Salant SW. Hotelling under pressure. J Polit Econ 2018;126(3):984–1026. https://doi.org/10.1086/697203.

[57] Adelman MA. Mineral depletion, with special reference to Petroleum. Rev Econ Stat 1990;72(1):1–10. https://doi.org/10.2307/2109733.

[58] Cairns RD, Davis GA. Adelman's rule and the Petroleum firm. Energy J 2001;22(3). https://doi.org/10.5547/ISSN0195-6574-EJ-Vol22-No3-2.

[59] Mining Technology. The ten biggest coal mines in the world. 2020 [cited 2021 Aug 31]. Available from: https://www.mining-technology.com/features/feature-the-10-biggest-coal-mines-in-the-world/.

[60] EIA. Natural gas spot and futures prices (NYMEX). 2021 [cited 2021 Jul 20]. Available from: https://www.eia.gov/dnav/ng/NG_PRI_FUT_S1_D.htm.

[61] Trading Economics. Coal. 2021 [cited 2021 Jul 20]. Available from: https://tradingeconomics.com/commodity/coal.

[62] IEA. Global electricity demand is growing faster than renewables, driving strong increase in generation from fossil fuels. 2021 [cited 2021 Jul 20]. Available from: https://www.iea.org/news/global-electricity-demand-is-growing-faster-than-renewables-driving-strong-increase-in-generation-from-fossil-fuels.

[63] IEA. Global electricity demand to rebound modestly in 2021 after historic shock from pandemic. 2020 [cited 2021 Jul 20]. Available from: https://www.iea.org/news/global-electricity-demand-to-rebound-modestly-in-2021-after-historic-shock-from-pandemic.

[64] Huppmann D, Kriegler E, Krey V, Riahi K, Rogelj J, Rose S, et al. IAMC 1.5°C scenario explorer and data hosted by IIASA. IIASA; 2018 [cited 2020 Jun 10].

[65] EIA. Annual energy Outlook 2020. 2020. Available from: https://www.eia.gov/outlooks/aeo/data/browser/.

[66] EIA. Performance profiles of major energy producers 2009. 2011. Available from: https://www.eia.gov/finance/performanceprofiles/.

[67] Statista. Average cost to produce one barrel of oil in top oil producing countries worldwide in 2015. 2015 [cited 2020 Jun 10]. Available from: https://www.statista.com/statistics/597669/cost-breakdown-of-producing-one-barrel-of-oil-in-the-worlds-leading-oil-producing-countries/.

[68] WSJ. Barrel Breakdown: the cost of producing a barrel of oil and gas varies widely across the world, setting up winners and losers as the price of crude fluctuates at historically low levels. 2016 [cited 2020 Jun 10]. Available from: http://graphics.wsj.com/oil-barrel-breakdown/.

[69] NRGI. National oil Company database. 2020 [cited 2020 Oct 1]. Available from: https://www.nationaloilcompanydata.org/.

[70] PwC. Mine 2019: resourcing the future. 2019. Available from: https://www.pwc.com/gx/en/industries/energy-utilities-resources/publications/mine-2019.html.

[71] van der Ploeg F, Rezai A. Stranded assets in the transition to a carbon-free economy. Annu Rev Resour Econ 2020;12(1):281–98. https://doi.org/10.1146/annurev-resource-110519-040938.

[72] Semieniuk G, Campiglio E, Mercure J-F, Volz U, Edwards NR. Low-carbon transition risks for finance. WIREs Clim Change 2021;12(1). https://doi.org/10.1002/wcc.678.

[73] Bloomberg LP. Accessed Bloomberg terminal. 2021 [cited 2021 Aug 31].

[74] IEA. Clean energy investing: global comparison of investment returns. 2021. Available from: https://www.iea.org/reports/clean-energy-investing-global-comparison-of-investment-returns.

[75] IRENA. Renewable power generation costs in 2020. Abu Dhabi; 2021. Available from: https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020.

[76] Heard BP, Brook BW, Wigley TML, Bradshaw CJA. Burden of proof: a comprehensive review of the feasibility of 100% renewable-electricity systems. Renew Sustain Energy Rev 2017;76:1122–33. https://doi.org/10.1016/j.rser.2017.03.114.

[77] Moriarty P, Honnery D. Can renewable energy power the future? Energy Pol 2016;93:3–7. https://doi.org/10.1016/j.enpol.2016.02.051.

[78] Loftus PJ, Cohen AM, Long JCS, Jenkins JD. A critical review of global decarbonization scenarios: what do they tell us about feasibility? WIREs Clim Change 2015;6(1):93–112. https://doi.org/10.1002/wcc.324.

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

[80] Armstrong C. Decarbonisation and world poverty: a just transition for fossil fuel exporting countries? Polit Stud 2020;68(3):671–88. https://doi.org/10.1177/0032321719868214.

[81] Pahle M, Burtraw D, Flachsland C, Kelsey N, Biber E, Meckling J, et al. Sequencing to ratchet up climate policy stringency. Nat Clim Change 2018;8(10):861–7. https://doi.org/10.1038/s41558-018-0287-6.

[82] USASpending.gov. The federal response to COVID-19. 2021 [cited 2021 Dec 7]. Available from: https://usaspending.gov/disaster/covid-19.

[83] World Bank. GDP (current US$) - Middle East & North Africa. 2021 [cited 2021 Sep 22]. Available from: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=ZQ.

[84] Knoema. Cost of oil production by country. 2020 [cited 2020 Nov 12]. Available from: https://knoema.com//infographics/vyronoe/cost-of-oil-production-by-country.

[85] Geels FW. Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective. Theor Cult Soc 2014;31(5):21–40. https://doi.org/10.1177/0263276414531627.

[86] McKibben B. Global warming's terrifying new math. Rolling Stone. 2012 Jul 19 [cited 2020 Oct 1]; Available from: https://www.rollingstone.com/politics/politics-news/global-warmings-terrifying-new-math-188550.

[87] No Fossil Fuel Money Pledge. No Fossil Fuel Money Pledge. [cited 2021 Dec 7]. Available from:: http://nofossilfuelmoney.org.

[88] IEA. World energy investment 2019. 2019. Available from: https://www.iea.org/reports/world-energy-investment-2019.

[89] Miller MH, Upton CW. The pricing of oil and gas: some further results. J Finance 1985;40(3):1009–18. https://doi.org/10.1111/j.1540-6261.1985.tb05030.x.

[90] Adelman MA. The economics of petroleum supply: papers by M. A. Adelman. The MIT Press; 1993.

[91] Davis GA, Cairns RD. Simple analytics of valuing producing Petroleum reserves. Energy J 1998;19(4). https://doi.org/10.5547/ISSN0195-6574-EJ-Vol19-No4-6.

[92] Jones Day. Saudi Arabia's Oil and Gas Sector—An Update: Part 1. [cited 2020 Oct 1]. Available from: https://www.jonesday.com/en/insights/2015/08/saudi-arabias-oil-and-gas-sectoran-update-part-1.

[93] EIA. Country analysis brief: Ecuador. 2017 [cited 2020 Oct 1]. Available from: https://www.eia.gov/international/content/analysis/countries_long/Ecuador/Ecuador.pdf.

[94] IEA. Chinese companies energy activities in emerging Asia – analysis. 2019. Available from: https://www.iea.org/reports/chinese-companies-energy-activities-in-emerging-asia.

[95] Listiyorini E. Indonesia plans to cut coal output to bolster prices. Revenue: Bloomberg News.; 2020 [cited 2020 Oct 1]; Available from: https://www.bloomberg.com/news/articles/2020-01-09/indonesia-plans-to-cut-coal-output-to-bolster-prices-revenue.

[96] Vorotnikov V. Russian coal producers invest in operations. Engineering and mining journal. 2013 [cited 2020 Oct 1]; Available from: https://www.e-mj.com/features/russian-coal-producers-invest-in-operations/.

[97] EIA. Table 10. Major U.S. Coal producers, 2018. 2018. Available from: https://www.eia.gov/coal/annual/pdf/table10.pdf.

[98] Africa Mining IQ. Coal Mining Companies in South Africa. [cited 2020 Oct 1]. Available from: http://www.projectsiq.co.za/coal-mining-companies-in-south-africa.htm.

[99] Strambo C, Velasco AJP. The changing politics of coal extraction in Colombia. Stockholm Environment Institute; 2017 [cited 2020 Oct 1]. Available from: http://www.jstor.org/stable/resrep02786.