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Potential emissions of CO_2 and methane from proved reserves of fossil fuels: An alternative analysis☆

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ABSTRACT

Scientists have argued that no more than 275 GtC (IPCC, 2013) of the world's reserves of fossil fuels of 746 GtC can be produced in this century if the world is to restrict anthropogenic climate change to ≤2 °C. This has raised concerns about the risk of these reserves becoming "stranded assets" and creating a dangerous "carbon bubble" with serious impacts on global financial markets, leading in turn to discussions of appropriate investor and consumer actions. However, previous studies have not always clearly distinguished between reserves and resources, nor differentiated reserves held by investor-owned and state-owned companies with the capital, infrastructure, and capacity to develop them in the short term from those held by nation-states that may or may not have such capacity. This paper analyzes the potential emissions of CO_2 and methane from the proved reserves as reported by the world's largest producers of oil, natural gas, and coal. We focus on the seventy companies and eight government-run industries that produced 63% of the world's fossil fuels from 1750 to 2010 (Heede, 2014), and have the technological and financial capacity to develop these reserves. While any reserve analysis is subject to uncertainty, we demonstrate that production of these reported reserves will result in emissions of 440 GtC of carbon dioxide, or 160% of the remaining 275 GtC carbon budget. Of the 440 GtC total, the 42 investor-owned oil, gas, and coal companies hold reserves with potential emissions of 44 GtC (16% of the remaining carbon budget, hereafter RCB), whereas the 28 state-owned entities possess reserves of 210 GtC (76% of the RCB). This analysis suggests that what may be needed to prevent dangerous anthropogenic interference (DAI) with the climate system differs when one considers the state-owned entities vs. the investor-owned entities. For the former, there is a profound risk involved simply in the prospect of their extracting their proved reserves. For the latter, the risk arises not so much from their relatively small proved reserves, but from their on-going exploration and development of new fossil fuel resources. For preventing DAI overall, effective action must include the state-owned companies, the investor-owned companies, and governments. However, given that the majority of the world's reserves are coal resources owned by governments with little capacity to extract them in the near term, we suggest that the more immediate urgency lies with the private sector, and that investor and consumer pressure should focus on phasing out these companies' on-going exploration programs.

1. Introduction

Anthropogenic climate change presents a serious threat to the health, prosperity, and stability of human communities, to the stability and existence of non-human species and ecosystems, and to international political and military stability (IPCC, 2013, 2014; World Bank, 2012; Center for Naval Analysis, 2014; Holy Father Francis, 2015). The United Nations Framework Convention on Climate Change commits its signatories to preventing "dangerous anthropogenic interference" (DAI) in the climate system, a level that has generally been thought to occur at about 2 °C (UNFCCC, 1992; IPCC, 2013). This has raised the question of what proportion of existing reserves of fossil fuels may be used without exceeding that 2 °C level. The International Energy Agency has concluded that "[n]o more than one-third of proved reserves of fossil fuels can be consumed prior to 2050 if the world is to achieve the 2 °C goal, unless carbon capture and storage (CCS) technology is widely deployed" (IEA, 2012). Carbon Tracker concludes that a "precautionary approach" would leave 80% of reserves in the ground (CTI,

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2013). These conclusions are based on the carbon content of global reserves of fossil fuels, based on BP data (BP, 2014b), and World Energy Council surveys (World Energy Council, 2013), which are in turn based on data from resource and reserve assessments as reported by national governments, geological surveys, coal ministries, petroleum directorates, national oil companies, and the like. A geographic and economic dispatch model also based on global reserves data concludes that one-third of oil, half of gas, and 82 to 88% of coal reserves must remain unused to 2050 (McGlade and Ekins, 2015).

Many of these reserves, however, are located in nations that lack the productive capacity to exploit them. From the perspective of disruptive climate change, the most pressing concern is not the total quantity of fossil fuel in the Earth's crust, which in any event is an unknown quantity, but the proved recoverable reserves reported by the largest producers around the world—i.e., the companies poised to produce, refine, and deliver those fuels to global markets in the near term. This paper addresses the questions: What are the reported proved reserves held by companies with the capacity to deliver them to world markets? What are the potential emissions from their expected production? What percentage of the remaining 2 °C carbon budget do they represent?

2. Potential emissions of CO_2 from proved reserves of oil, natural gas, and coal

The conclusion that a large portion of the world's reserves of fossil fuels must be left in the ground has led to concerns about the risk of these reserves becoming "stranded assets," and creating a dangerous"carbon bubble" with large impacts on global financial markets (CTI, 2013, 2014a,b; CERES 2012; Generation Foundation, 2013; The Economist, 2014; Leggett, 2013). Analysis of many oil and gas producers' capital expenditures highlights the vulnerabilities of highly valued assets if restrictions on carbon emissions are put in place (CTI, 2014a,b). The total cumulative anthropogenic carbon budget consistent with >66% probability of not exceeding a 2 °C target has been estimated at 1.0 trillion tons of carbon (TtC) (Allen et al., 2009; IPCC, 2013; Matthews et al., 2009; Matthews and Solomon, 2013; Meinshausen et al., 2009). If these figures are correct, they suggest that no more than 275 GtC remain to be emitted as carbon dioxide from fossil fuel use (see section on carbon budget below). How do these figures compare with the carbon that would be emitted if existing proved reserves of fossil fuels are produced and used? This paper attempts to answer that question by an analysis of reported proved reserves held by fossil fuel corporations with the technical and financial capacity to produce them in the near future. This includes investor-owned companies (IOC) such as BP and Peabody, state-owned Organization of Petroleum Exporting Countries (OPEC) producers such as Saudi Aramco and Sonatrach, and non-OPEC state-owned entities (SOE) such as Petrobras (Brazil), CNOOC (China), Statoil (Norway), and Gazprom (Russia). Our analysis does not forecast the rate of each entity's fossil fuel production, and therefore does not predict whether current reserves will be produced by 2050, 2100, or beyond. Clearly, the rate of production is relevant to emissions scenarios, and therefore to the rate at which climate change may occur (IPCC, 2014). However, investor-owned oil and gas companies have typical reserve-to-production ratios of 12 ± 5 years, coal producers 35 ± 15 years, and OPEC-member companies 150 ± 120 years. It is therefore reasonable to assume that absent policies to alter current trajectories, nearly all investor-owned reserves, and a lion's share of state-owned reserves, will be exploited before the end of the century.We also note that all fossil fuel reserve estimates are subject to considerable uncertainty arising from many diverse factors (Laherrère, 1999, 2011). Reserve estimates vary by source, year, and by fuel. They may also be subject to deliberate inflation; OPEC oil and gas reserves, for example, are not audited, but are widely reported by international sources. Clearly, any attempt to quantify greenhouse gas emissions that will result from the use of these reserves is subject to any uncertainty already embedded in reserve estimates. Moreover, in some sense the term "proved" is misleading, insofar as nothing is proved until a resource has actually been extracted and sold. Nonetheless, the term is used conventionally to refer to that portion of a resource that is known to exist, has been well delineated, and which companies are poised to develop. "Proved reserves" is also a standard category that companies report to shareholders and therefore is available to the public and researchers and subject to peer review. Our analysis uses this term in this conventional sense, and relies on publicly available data that have been reported under this rubric.

We also note that for purposes of this analysis all carbon emissions are viewed as equivalent, although we recognize that with respect to the question of "dangerous anthropogenic interference" (DAI) in the climate system, this is not strictly the case.

3. Methods

This analysis is based primarily on company self-reported estimates of proved reserves of recoverable oil, natural gas, and coal, reduced for global average non-energy uses, and multiplied by emission factors for each fuel type. Uncertainties arise regarding estimated reserves and data sources (discussed below). In addition, company operations, crude oil sources, operational emissions, and the disposition and use of extracted, refined, and marketed carbon products vary from company to company. In the section that follows, we explain what data and assumptions are used in the analysis; the interested reader is referred as well to Heede for further details (Heede, 2013, 2014).

Oil, natural gas, and coal companies report annual production and recoverable reserves to investors and the U.S. Securities and Exchange Commission (SEC) on the basis of SEC guidelines if the company is based in the United States, is listed on U.S. securities exchanges, or operates producing assets within the U.S. or its offshore areas. The reserves attributed to the seventy investor-owned and state-owned fossil fuel companies (plus the coal sector in eight nation-states – China, Czech Republic, Kazakhstan, North Korea, Poland, Russian Federation, Slovakia, and Ukraine – with limited participation by investor-owned companies) in this analysis are estimates based on international reporting standards (in the case of non-OPEC companies) and on unknown standards and limited transparency in the case of entities operating in OPEC-member states, such as Saudi Aramco, Petroleos de Venezuela, Sonatrach, and others. National Oil Companies that are partially privatized are classified in this study as state-owned if >50% of shares are owned by the government. This includes Statoil, at 67% government-owned, Petrobras, 55.6% state-owned, and Gazprom, 50.01% state-owned.

3.1. Data sources

Our analysis is based on reported reserves data, gathered chiefly from the statements published by the U.S.-based companies for year-end 2013 in Form 10-K (20-F or 40-F, by foreign and Canadian companies with assets in the United States, respectively) filed with the U.S. Securities and Exchange Commission. Additional sources include statistics in the *Oil & Gas Journal,* the National Mining Association, company websites, annual reports, and government sources. State-owned companies do not submit statements to the SEC (unless they own producing assets in the United States, such as

Statoil); for these companies we rely on reserve statements in company reports (if available) or collected by the *Oil & Gas Journal* (Xu and Bell, 2013; Xu and Kottungal, 2014). In cases where reserve estimates are disputed by other sources we use the more conservative estimate.

For example, the large reserves claimed by Coal India (Anand 2010) were disputed (Greenpeace India, 2013), and we adopted the lower reserve estimate for the purposes of this study. Similarly, estimated reserves of Russian oil and gas companies based on the Russian classification system leads to higher reserve estimates than the more conservative 1P reserve estimates for state-owned Gazprom and Rosneft that are based on the Society of Petroleum Engineers' Petroleum Resources Management System protocol (SPE, 2011). SEC submissions show "proved reserves" of crude oil, condensates, bitumen (heavy oil & oil sands), natural gas liquids (NGLs), natural gas, and coal. Reporting typically includes "developed" and "undeveloped" oil & gas reserves by geographic region (SEC, 2009). Coal reserves, unlike oil and gas reserves, combine proved and probable reserves, and often include coal rank or heating values, and mining method (underground or surface).

3.2. Emission factors and non-energy uses

The reserves data for each entity – in million bbl (Mb) of oil & NGLs, billion cubic feet (Gcf) of natural gas, and million tons (Mt) of coal – are multiplied by the emission factors developed in the Carbon Majors methodology (Heede, 2013, 2014) (Tables 1 and 2). The analysis deducts for non-energy uses of each fuel (8.02% for crude oil & NGLs, 1.71% for natural gas, and 0.016% for coal). This permits estimation of expected emissions from the production of the proved recoverable reserves for each entity.

Analyses of potential emissions incorporate assumptions that may vary over the timeframe of their extraction, processing, and consumption. International regulatory schemes, such as regional carbon taxes, will alter the value of carbon resources compared to non-carbon energy sources. Use of crude oil and natural gas may shift to higher-value petrochemicals or fertilizers than assumed in our analysis, leading to lower carbon fuel usage rates and emissions. We have not attempted to predict such future fluctuations in this study.

3.3. Analytical approach

The analytical approach developed in Heede (2014) is adopted here to estimate potential emissions from the combustion of reported proved recoverable reserves (less non-energy uses) declared by the 78 entities included in the analysis (Heede, 2013, 2014). The fossil fuel production entities were selected from leading producers of coal, oil, and natural gas, defined as producing 8 MtC or more in a recent year. Additional emissions from extraction and processing of the reserves – such as the venting of CO_2 from the processing of raw natural gas into marketable fuel, CO_2 from flaring of associated gas at well heads not linked to gas pipeline networks, and vented and fugitive methane from oil, natural gas, and coal production – are also estimated in order to capture the complete emissions resulting from the production and delivery of carbon fuels to end users. Other estimates of potential emissions from reserves (IPCC, IEA, Carbon Tracker) assume that all of the carbon in the fuel reserves is combusted to the atmosphere. This study makes the more realistic assumption that not all carbon in fuel reserves is burned; we deduct for carbon in the products used for non-energy purposes, such as waxes, lubricants, petrochemicals, carbon fibers, pigments, fertilizers, steelmaking, and road oil. The methodology also accounts for emissions from subsequent combustion of non-energy products, such as tyres, waxes, lubricants, and plastics. We calculate potential emissions from declared reserves published by each company based on prevailing commodity prices.

Every producing company's operational emissions differ, since coal mining depth, methane ventilation or utilization, leakage control, quantities of CO_2 entrained in raw natural gas (which varies from field to field), efficiencies in refineries and pipelines, and the flaring of associated gas vary by company and producing region (Gordon et al., 2015). Emission factors for these ancillary sources are taken from international sources such as IPCC, IEA, EIA, and EPA, as well as scientific organizations, engineering societies, and trade associations. Documentation of the methodology and emission factors is detailed in Heede (2013, 2014).

3.4. Caveats and sources of uncertainty

As noted above, reserve estimates are intrinsically uncertain: they vary by year on the basis of new discoveries, reserve additions, extensions of known reserves, reductions for produced quantities, fluctuating commodity prices, and new engineering estimates that shift reserves from the "probable" into the "proved" categorization. In this respect our analysis is conservative, insofar as rising prices in the future may lead to currently uneconomic resources becoming economic, thus expanding proved reserves.

In addition, many analysts believe that reserve statements by some state-owned oil and gas companies, notably Saudi Aramco and other OPEC members, are inflated by as much as 300 billion bbl

Table 1
Combustion emission factors (also account for non-energy uses).

Energy source	Carbon tC/unit	Carbon dioxide tCO_2/unit
Crude oil & NGLs	101.4 kgC/bbl	371.4 $kgCO_2$/bbl
Natural gas	14.6 kgC/kcf	53.4 $kgCO_2$/kcf
Lignite	328.4 kgC/t	1203.5 $kgCO_2$/t
Subbituminous	495.2 kgC/t	1814.4 $kgCO_2$/t
Bituminous	665.6 kgC/t	2439.0 $kgCO_2$/t
Anthracite	715.6 kgC/t	2621.9 $kgCO_2$/t
"Metallurgical coal"	727.6 kgC/t	2665.9 $kgCO_2$/t
"Thermal coal"	581.1 kgC/t	2129.3 $kgCO_2$/t

Crude oil: prior to non-energy deduction & adjustment for NGLs: 115.7 kgC/bbl, 423.8 $kgCO_2$/bbl; Gas: prior to non-energy deduction: 14.86 kgC/kcf,or 54.44 $kgCO_2$/kcf; (kcf = thousand cubic feet).

Table 2
Emission factors for vented, flared, and fugitive carbon dioxide & methane.

Entry	Combustion $kgCO_2/tCO_2$	Flaring $kgCO_2/tCO_2$	Vented $kgCO_2/tCO_2$	Methane $kgCH_4/tCO_2$	Methane $kgCO_2e/tCO_2$	Total $kgCO_2e/tCO_2$
Crude oil & NGLs	1000	15.94	3.83	1.92	40.39	1060.2
Natural gas	1000	1.74	28.53	9.88	207.44	1237.7
Coal	1000	ne	ne	4.03	84.73	1084.7

ne: not estimated. GWP factor for methane of 21 × CO_2 on 100-year time horizon, per IPCC SAR.

(Gb), or roughly one-quarter of OPEC reserves (Laherrère, 1999, 2011; Deffeyes, 2001; Sandrea, 2003; Mushalik, 2004; Simmons, 2005; Mearns, 2010; Tippee, 2010). OPEC reserve estimates are not audited, independent geological assessments are not available, uniform and transparent reserve protocols are not used, and most OPEC-member state-owned companies do not adjust reserves for annual production. Moreover, OPEC production quotas are tied to reserves, creating a strong incentive toward reserve inflation (Laherrère, 2011; Tippee, 2010). Reserve inflation may not be limited to state-owned entities. SEC guidance is explicit on the matter of reserve estimation and reporting, although companies have run afoul of reporting standards. For example, Royal Dutch Shell admitted "without . . . wrongdoing" to overstating reserves by 3.9 billion bbl (Gb), or 20%, and was subsequently fined $27 million and ordered to pay $353 million in compensation to shareholders (Anon., 2004; Treanor, 2009).

The present analysis does not attempt to second-guess the accuracy of reported reserves, nor to predict future fluctuations in exogeneous variables that may affect reserves. Rather it relies on reserve assessments by each considered entity – typically for year-end 2013 – as reported to shareholders and the SEC, or based on other publicly available estimates as described above. Reserves held in global Strategic Petroleum Reserves and commercial stocks have not been included in this analysis. Total storage is 4.1 Gb, of which 2.7 Gb is held by private industry and 1.4 Gb stored in government facilities. The largest reserve – the U.S. Strategic Petroleum Reserve – held 0.727 Gb at year-end 2010 (EIA, 2013). Storage of 4.1 Gb represents potential emissions of 0.42 GtC, a small figure relative to global totals.

4. World reserves

According to the BP global reserve assessment for 2013 (the same year for which we calculate emissions from company reserves), proved recoverable oil & NGL reserves total 1668 Gb, natural gas reserves total 6558 trillion cubic feet (Tcf), and 892 billion tons (Gt) of coal (BP, 2014b).

Full production of global fossil fuel reserves will lead to an estimated 746 GtC (2734 $GtCO_2$) of carbon emissions, based on the methodology adopted from Heede (2014) (Table 3). This includes emissions of CO_2 from flaring and venting associated with the production of marketed carbon fuels, and deducts for non-energy uses.

Table 3
World fossil fuel reserves by type and potential emissions, 2013.

Type	Reserves (units)	World GtC	World $GtCO_2$	Percent of total
Oil & NGLs	1688 Gb	171.1	626.9	22.9%
Natural gas	6558 Tcf	95.6	350.4	12.8%
Coal	892 Gt	479.5	1756.9	64.3%
Total	na	746.2	2734.2	100.0%

Reserves data: BP (2014b).

Table 4
Major carbon fuel producers & world reserves, 2013, by ownership.

Fuel	Major producers units	Major producers, percent of world
Crude Oil & NGLs	Gb	
Investor-owned	120	7.1%
State-owned	1265	74.9%
Total oil	1385	82.0%
Natural Gas	Tcf	
Investor-owned	433	6.6%
State-owned	4387	66.9%
Total natural gas	4820	73.5%
Coal	Gt	
Investor-owned	43	4.8%
State-owned	28	3.1%
Nation-states	347	38.9%
Total coal	418	46.9%

5. Carbon reserves and potential emissions

In the following analysis we focus on the reported proved reserves declared by 78 of the largest fossil fuel producers whose historic production of carbon fuels from as early as 1854 to 2010 contributed 63% of global emissions of carbon dioxide and methane since 1751 (Heede, 2014). Of the extant 78 entities that hold fossil fuel reserves, 70 are incorporated entities, of which 42 are investor-owned and 28 are state-owned companies. These companies possess 82% of oil, 73% of natural gas, and 8% of total world reserves of coal (Table 4). In addition, eight government-run industries in nation-states such Poland and China possess 39% of world coal reserves. This analysis focuses on the reserves held by the 70 investor- and state-owned companies.

The state-owned companies produce three-quarters of world oil and have been reported to possess 90% of the oil reserves (World Bank, 2011), although our analysis suggests state-owned companies control 75% of global reserves (Table 4).

The seventy incorporated investor-owned companies (IOC) and state-owned entities (SOE) have declared total proved recoverable reserves of 1385 Gb of crude oil and NGLs, 4820 Tcf of natural gas, and 71 Gt of coal (Table 4). The oil reserves are chiefly held by the 28 state-owned companies that are OPEC members, and by a small number of state-owned companies that are not OPEC members, such as Rosneft and Gazprom in Russia, Statoil in Norway, and Petrobras in Brazil. In contrast to oil and gas reserves, the majority of coal reserves are held by the eight nation-states, primarily China and the Russian Federation.

Table 5 summarizes estimated potential emissions by fuel type from fossil fuel products, flaring and venting of CO_2, and fugitive methane from operations of the 70 SOEs and IOCs (see Supplementary materials for emissions estimated for the 70

Table 5
Potential emissions of major carbon producers' reserves, by fuel.

Source	Product emissino GtC	Flaring & venting GtC	Total carbon GtC	Fugitive methane GtCe
Investor- & state-owned:				
Oil & NGLs	140.4	2.8	143.2	5.7
Natural gas	70.3	2.1	72.4	14.6
Coal	39.1	na	39.1	3.3
Subtotal	249.8	4.9	254.7	23.6
Nation-states:				
Coal	185.4	0.0	185.4	15.7
Total, all entities	435.2	4.9	440.1	39.3

Table 6
Potential emissions of major carbon producers' reserves, by ownership.

Source	Product emissions GtC	Flaring & Venting GtC	Total carbon GtC	Fugitive methane GtCe
Investor-owned	44.0	0.4	44.4	4.0
State-owned	205.8	4.5	210.3	19.6
Nation-states	185.4	0.0	185.4	15.7
Total	435.2	4.9	440.1	39.3

companies' reserves). Table 6 shows the same results by ownership category for investor- and state-owned entities, and potential emissions of 185 GtC from 347 Gt coal reserves declared by the eight nation-states, plus 15.7 GtCe of methane emissions associated with coal mining. Fig. 1 shows potential emissions estimated for the 42 investor-owned and the 28 state-owned oil, natural gas, and coal companies, and Fig. 2 shows potential emissions from the reserves declared by the 30 largest investor-owned and state-owned fossil fuel companies – and the dominance of the latter group in world reserves. The end use combustion of carbon fuels is the principal source of potential emissions from the production of reserves, accounting for ~90% of total estimated emissions, on average. The direct operational emissions from flaring, venting, and fugitive methane associated with the production, processing, and delivery of fuels (~10% of the total, on average) are also estimated. Methane emissions are not compared to the remaining carbon budget; see discussion below. Methane is a significant source of direct emissions from natural gas, coal, and oil production (see Table 2 for relative contributions), and while methane emissions are not compared to the remaining carbon budget, we present the results for context and future analysis. We use the 100-year global warming potential factor for methane of $21 \times CO_2$, adopting the standard for national greenhouse gas inventories using values in IPCC Second Assessment Report (IPCC Task Force on National Greenhouse Gas Inventories).

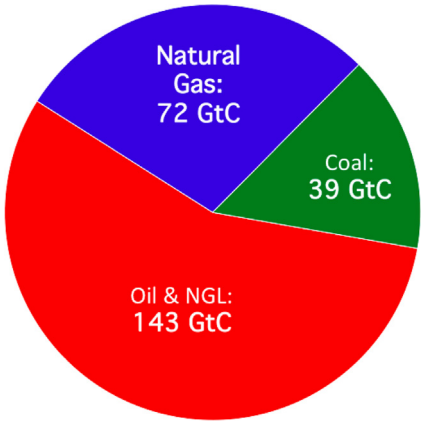

Fig. 1. Major producers' potential emissions from reserves (IOCs, SOEs).

6. Results: most reserves are in state-owned entities and nation-states

The results of our analysis show that the lion's share of potential emissions from proved reserves are not in the hands of publicly-traded, investor owned corporations, but in the hands of state-owned entities and nation-states. Even if OPEC reserves are inflated, as they may be, *there is no question that the majority of reserves of both oil and natural gas are held by state-owned companies.*

The state-owned companies hold the largest reserves of oil and gas, totaling 210 GtC of potential emissions from product end use, flaring, and venting, dominated by oil reserves: 131 GtC from oil, 66 GtC from natural gas, and 14 GtC from coal. The eight nation-

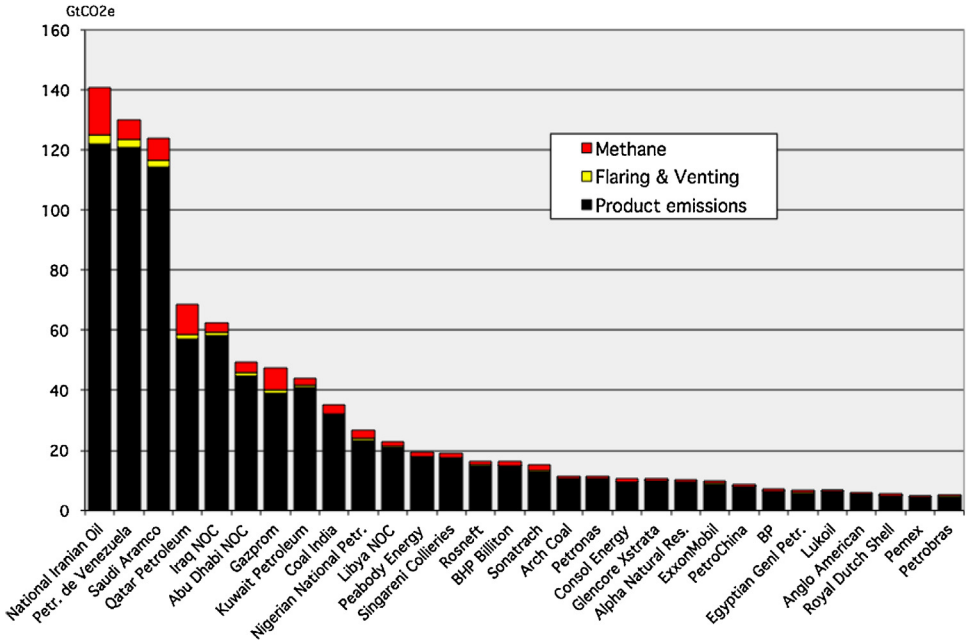

Fig. 2. Major producers' emissions from largest thirty investor- and state-owned companies' reserves.

Table 7
Major carbon producers by ownership compared to the IPCC remaining carbon budget.

Source	Major producers GtC	IPCC budget GtC	CM percent of IPCC budget
Investor-owned	44.4	275	16.1%
State-owned	210.3	275	76.4%
Nation-states	185.4	275	67.4%
Total	440.1	275	160.0%

Table 8
Major carbon producers by fuel compared to the IPCC remaining carbon budget.

Source	Major producers GtC	IPCC budget GtC	CM percent of IPCC budget
Oil & NGLs	143.2	275	52.1%
Natural gas	72.4	275	26.3%
Coal	224.5	275	81.6%
Total	440.1	275	160.0%

states with government-run coal industries possess reserves with potential emissions of 185 GtC. In contrast, the 42 investor-owned oil, natural gas, and coal companies hold reserves with potential emissions of 44.4 GtC, including 0.4 GtC from flaring and vented CO_2. Tables 7 and 8 and Figs. 3 and 4 compare our results with an estimated remaining carbon budget of 275 GtC (based on a cumulative carbon budget of 1000 GtC) (Allen et al., 2009; Meinshausen et al., 2009; Matthews et al., 2009; Matthews and Solomon, 2013; IPCC, 2013; see also CTI, 2013).

Reserves declared by the 42 investor-owned companies represent emissions equivalent to 16% of the remaining carbon budget, whereas the 28 SOE reserves are equivalent to 76%, and the coal reserves of the eight nation-states are equivalent to 67%. The reserves of the seventy IOCs and SOEs (255 GtC) are equivalent to 93% of the remaining carbon budget of 275 GtC (Fig. 3). Estimated potential emissions from the reserves held by all three ownership categories – 440 GtC – exceed the remaining carbon budget by 60% (Fig. 4).

7. Discussion

Our analysis confirms the results of prior studies that conclude that a substantial fraction of the world's fossil fuel reserves must remain unburned if the world is to achieve the goal of maintaining anthropogenic climate change below 2 °C (Allen et al., 2009; Meinshausen et al., 2009; Matthews et al., 2009; Matthews and Solomon, 2013; IPCC, 2013; CTI, 2011, 2013). However, it diverges from previous studies in two important respects. One widely cited study is Carbon Tracker's *Unburnable Carbon* (CTI, 2011). CTI estimates emissions from proved reserves of the 100 largest oil and gas companies and 100 largest coal companies listed on stock exchanges, but excludes most state-owned companies included in our analysis. Our study makes clear that consideration of state-owned companies is essential to understanding the threat of the use of existing proven reserves of fossil fuels. Because of the large proportion of reserves in the hands of state-owned entities, DAI cannot be prevented by focusing on private sector activity alone.

This conclusion has important implications for who needs to be "at the table" in climate negotiations. Victor (2011) has suggested that existing frameworks for international negotiation have erred by being too inclusive, and therefore difficult to manage and likely to fail. He argues that future negotiations should focus on creating a small club of key countries, by which he means the largest annual emitters: China, the United States, and the European Union. Should these countries become "enthusiastic" about a climate agreement, significant progress could be achieved, creating a positive incentive

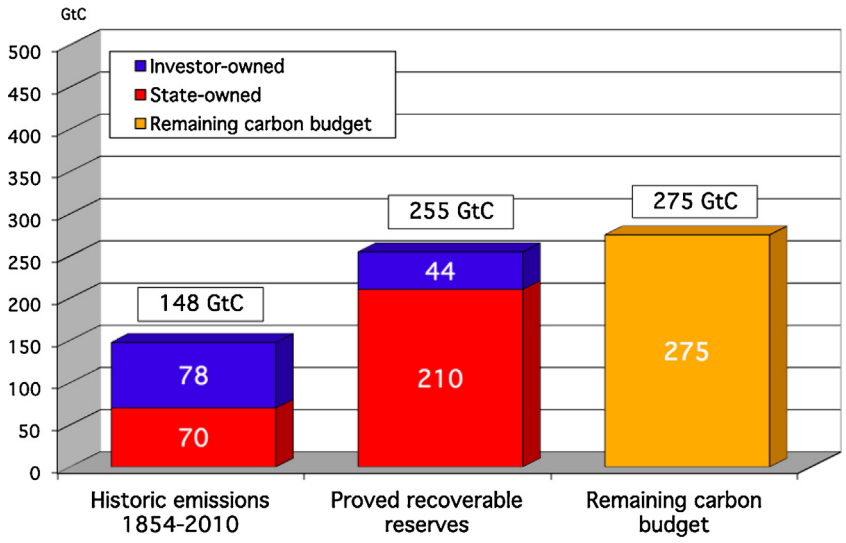

Fig. 3. Potential emissions from reserves vs. IPCC remaining carbon budget (IOCs and SOEs).

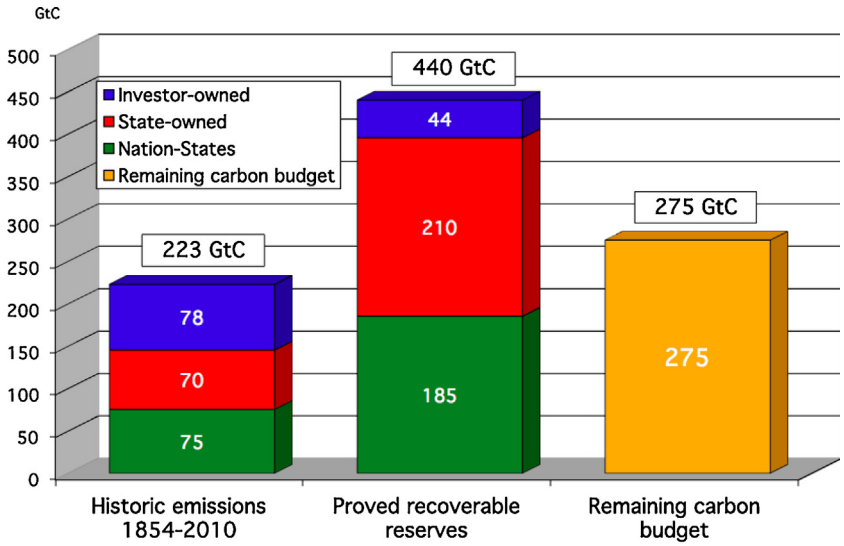

Fig. 4. Potential emissions from reserves vs. IPCC remaining carbon budget (IOCs, SOEs, and nation-states).

over time for other countries to come into the "club." While one can acknowledge the politically pragmatic quality of that suggestion, an analysis that takes into account the potential impact of future use of proved reserves suggests a different mix of essential parties. Table 9 compares the top ten emitting countries (both current and historic) with a list of the nations that hold the lion's share of reserves in the hands of state-owned entities, or in the hands of the states themselves. One immediately discerns that the top ten reserve holders are not the same as the top ten emitters. In the former group, Australia, Iran, Saudi Arabia, Venezuela, and Kazakhstan come to the fore. One may accept the argument that a focus on a smaller number of countries increases the odds of success, but come to a different conclusion about which countries need to be involved in those agreements. Negotiations to date have focused on the end users of fossil fuels, in effect, focusing on demand rather than on supply. The analysis presented here suggests the importance of attention to supply as well.

A second important difference between the analysis presented here and earlier studies involves the role of investor-owned entities. Forty-three companies are common to our study and Carbon Tracker's, such as Peabody, ExxonMobil, Rio Tinto, Chevron, BP, Shell, BHP Billiton, etc. Potential emissions from proved recoverable reserves held by all of the 43 companies estimated in both this and CTI's analyses total 72 GtC and 108 GtC, respectively (this study, and CTI, 2011). (The CTI analysis excludes state-owned oil and gas companies, except for those partially privatized, such as Statoil, Gazprom, and Petrobras.) Our respective estimates of potential emissions from coal reserves are in closer agreement than estimated emissions from oil reserves. CTI's estimates for some oil and gas companies (such as Chevron, BP, ExxonMobil, and Hess) exceed our estimates by a factor of four or more.

The primary reason for the differing results is that CTI did not quantify potential emissions from *reported* proved *oil reserves* but "extrapolated the oil reserves to maintain production to 2050" (Leaton, 2014). In other words, whereas our analysis is based solely on existing reserves, the CTI analysis assumes that oil companies will continue to explore and develop new reserves through 2050, and includes this extrapolation in their analysis.

We believe this is a crucial difference, insofar as it focuses attention on the problem of the on-going exploration for new resources, particular of oil and gas, by investor-owned companies. While our results demonstrate the importance of state-owned entities in preventing DAI, they also point to an important aspect of the role of private-sector corporations not addressed in previous studies. In contrast with previous analyses, our results suggests that *the use of the existing proved reserves held by the largest investor-owned corporations does not lead to climate warming above the 2 degree limit.* However, exploration for and development of new reserves – beyond those that are presently proved – will exceed the carbon budget and push the global climate well past the 2-degree limit.

That is to say, so far as the contribution from private sector activity goes, the core threat to the goal of holding anthropogenic temperature increase below the 2 °C target is not the exploitation of existing proved reserves, but in the continued exploration for and development of new ones. This has important implications for how investors think about the role of the private sector in the problem of anthropogenic climate change, and the problem of stranded assets.

Our analysis suggests that what is needed to prevent DAI is different when one considers the state-owned entities v. the investor-owned entities. For the former, there is a profound climate risk involved simply in the prospect of their developing their proved reserves. Negotiations should therefore pay serious attention to the question of how the nations that own these entities may be persuaded not to develop the reserves that they have already proven out. However, when considering the question of private sector entities and the risk of reserves becoming stranded, our study shows that existing reserves need not become stranded. The risk to private sector investors arises not so much

Table 9
Top Ten Countries ranked in terms of historic emissions, current emissions, and reserves.

Rank	Historic emissions	Current emissions	Reserves
1.	United States	China	United States
2.	China	United States	Russia
3.	Russia	India	China
4.	India	Russia	Australia
5.	Brazil	Japan	India
6.	Germany	Germany	Iran
7.	United Kingdom	Iran	Saudi Arabia
8.	Japan	South Korea	Venezuela
9.	Canada	Canada	Kazakhstan
10.	Indonesia	United Kingdom	Canada

Historic emissions include land use changes (Matthews et al., 2014); current emissions (Boden et al., 2013); reserves calculated from BP (2014b) by the authors.

Table 10
Selected investor-owned & state-owned companies: potential emissions from reserves, 2013.

Entity	Oil & NGL $MtCO_2$	Natural Gas $MtCO_2$	Coal $MtCO_2$	Vented & Flared $MtCO_2$	Methane $MtCO_2e$	Total $MtCO_2e$
National Iranian Oil Company	58,426	63,741		3085	15,583	140,835
Saudi Aramco	98,744	15,539		2423	7212	123,919
Gazprom	3013	35,836		1144	7556	47,549
Peabody Energy			18,074		1,531	19,606
BHP Billiton	325	541	14,097	23	1,320	16,306
Consol Energy		213	9422	6	843	10,485
ExxonMobil	4917	3840		213	995	9966
BP	3740	2457		148	661	7006
Royal Dutch Shell	2459	2269		117	570	5416
Chevron	2357	1557		94	418	4426
ConocoPhillips	2051	1089		74	309	3523
Statoil	861	984		47	239	2131

Potential emissions calculations by Heede. See Supplementary materials for additional companies.

from proved reserves of investor-owned companies but from these companies' on-going exploration and development of new fossil fuel resources.

It has been estimated that investor-owned companies invest over $700 billion per year in exploration and production in order to assure continued flow of carbon fuels well beyond the exhaustion of current reserves (Barclays, 2013). These companies, particularly the multinational oil and gas companies, have been the focus of divestment campaigns and of analyses of stranded assets (CTI, 2013, 2014b,c; Canadian Centre for Policy Alternatives, 2013; Generation Foundation, 2013; Gore and Blood, 2013; The Economist, 2014; University of Oxford Stranded Assets Program, 2014; Cleveland and Reibstein, 2015). Their accountability to investors, pension funds, and university endowment managers makes them highly visible targets for such concerns, which appear well-founded insofar as corporate reports make clear their intent to invest trillions of dollars of additional capital in exploration and production in the next several years and even decades (ExxonMobil, 2014b; Royal Dutch Shell, 2014; Frumhoff et al., 2015; CTI and ETA, 2014). Our analysis suggests that investor concern should be focused on dissuading these corporations from further investment in fossil fuel exploration and development.

8. Conclusion

Much of the concern expressed to date over stranded assets is focused on the investor-owned oil and gas companies, presumably because of the leverage that investors, regulators, and lenders have over the economic and regulatory environment in which these companies operate. These companies represent a substantial risk to the 2 °C target not so much because of their proved reserves (most of which will likely be exhausted by 2030 or earlier), but because of their ability and expressed intent to continue to explore for new sources of fossil fuels, and to convert existing probable and possible reserves into additional proved reserves (ExxonMobil, 2014a,b; Royal Dutch Shell, 2014; BP, 2014a). Given this, we suggest that investor and consumer pressure should focus on the question of phasing out exploration for new resources, especially in high-cost environments and of carbon-intensive resources (McGlade and Ekins, 2015).

However, investor-owned companies hold only 7.1% of oil reserves and 6.6% of natural gas reserves; the majority of current production and the vast majority of reserves are held by companies that are not publicly traded (Table 10). While the financial risk faced by investor-owned oil and gas majors may be ameliorated by prudent shedding of high-cost reserves, or by a comprehensive change in investment priorities (including in non-carbon energy sources), the objective of limiting future production of fossil fuels in order to achieve the 2 °C temperature target will not succeed if production of reserves held by state-owned oil, natural gas, and coal companies is not also brought under control. For preventing DAI overall, effective action must include the state-owned companies and their governments.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2015.10.005.

References

Allen, Myles R., Frame, David J., Huntingford, Chris, Jones, Chris D., Lowe, Jason A., Meinshausen, Malte, Meinshausen, Nicolai, 2009. Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 458, 1163–1166.
Anand, S.K., 2010. How long will India's coal last? The Financial Express, Anand, Sr Fellow of TERI, New Delhi, www.teriin.org/index.php?option=com_featurearticle&task=details&sid=657.
Anon., 2004. Royal Dutch/Shell lowers proved reserves estimate 20%, Oil & Gas Journal, (2004). 19 January.
BP, 2014a. Energy Outlook 2035, London.
BP, 2014b, 2013. Statistical Review of World Energy. London, www.bp.com/statisticalreview.
Barclays, 2013. Global E&P Spending Outlook. Barclays Equity Research, New York & London.
Boden, T.A., Marland, G., Andres, R.J., 2013. Global, Regional, and National Fossil-Fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Dept. of Energy, Oak Ridge, TN.
CERES, 2012. Sustainable Extraction? An Analysis of SEC Disclosure by Major Oil & Gas Companies on Climate Risk and Deepwater Drilling Risk. Jim Coburn & Ryan Salmon (CERES) and Dave Grossman (David Gardiner & Associates).
Carbon Tracker Initiative & Energy Transition Advisors, 2014. Responding to Shell—An Analytical Perspective, Exec. Sum., London, 7 pp. www.carbontracker.org/wp-content/uploads/2014/07/CTI_Shell_Response_Exec_Summ_030714_2.pdf.
Carbon Tracker Initiative, 2011. Unburnable Carbon—Are the world's financial markets carrying a carbon bubble? London. Appendix 1: reserves data was based on the most recent reported information on proven reserves at the end of 2010.
Carbon Tracker Initiative, 2013. Unburnable Carbon 2013: Wasted capital and stranded assets, CTI & Grantham Research Institute on Climate Change and the Environment. CTI, London. accaglobal.co.uk.
Carbon Tracker Initiative, 2014a. Oil Demand: Comparing Projections and Examining Risks. CTI, London.
Carbon Tracker Initiative, 2014b. Carbon Supply Cost Curves—Evaluating Financial Risk to Oil Capital Expenditures. CTI, London.

Carbon Tracker Initiative, 2014c. Responding to Exxon: A Strategic Perspective. CTI, London.
Canadian Centre for Policy Alternatives, 2013. Canada's Carbon Liabilities: The Implications of Stranded Fossil Fuel Assets for Financial Markets and Pension Funds, by Marc Lee & Brock Ellis, March 2013. 58 pp.
Center for Naval Analysis, 2014. National Security and the Accelerating Risks of Climate Change, Center for Naval Analyses, CNA Military Advisory Board, Alexandria VA, www.cna.org/sites/default/files/MAB_2014.pdf.
Cleveland, Cutler J., Reibstein, Richard, 2015. The Path to Fossil Fuel Divestment for Universities: Climate Responsible Investment. Boston University.
Deffeyes, Kenneth S., 2001. Hubbert's Peak: The Impending World Oil Shortage. Princeton University Press.
Energy Information Administration, 2013. Annual Energy Review, Table 5.17 Strategic Petroleum Reserve, 1971–2011.
ExxonMobil, 2014a The Outlook for Energy: A View to 2040. exxonmobil.com/energyoutlook.
ExxonMobil, 2014b. Energy and Carbon—Managing the Risks, corporate.exxonmobil.com/en/environment/climate-change/managing-climate-change-risks/carbon-asset-risk.
Frumhoff, Peter C., Heede, Richard, Oreskes, Naomi, 2015. The climate responsibilities of industrial carbon producers. Clim. Change 132 (2), 157–171. doi:http://dx.doi.org/10.1007/s10584-015-1472-5.
Generation Foundation, 2013. Stranded Carbon Assets: Why and How Carbon Risks Should Be Incorporated in Investment Analysis, 30 October, London, genfound.org/media/pdf-generation-foundation-stranded-carbon-assets-v1.pdf.
Gordon, Deborah, Brandt, Adam, Bergerson, Joule, Koomey, Jonathan, 2015. Know Your Oil: Creating a Global Oil-climate Index. Carnegie Endowment for International Peace 56 pp.
Gore, Al, & David Blood, (2013). The Coming Carbon Asset Bubble: Fossil-fuel investments are destined to lose their economic value. Investors need to adjust now, New York Times—OpEd, 29 October 2013.
Greenpeace India, 2013. Coal India: Running on empty? CIL misleading investors, extractable reserves could be exhausted in 17 years, September, by Ashish Fernandes (Greenpeace) & Tom Sanzillo. Inst. for Energy Economics and Financial Analysis. www.greenpeace.org/india/Global/india/report/2013/Coal-India-Running-on-Empty.pdf.
Heede, Richard, 2013. Carbon Majors: Accounting for carbon and methane emissions 1854-2010 Methods & Results Report, commissioned by Climate Justice Programme & Greenpeace International, Climate Mitigation Services, Snowmass, CO.
Heede, Richard, 2014. Tracing anthropogenic CO_2 and methane emissions to fossil fuel and cement producers 1854–2010. Clim. Change 122 (1), 229–241. doi:http://dx.doi.org/10.1007/s10584-013-0986-y.
Holy Father Francis, 2015. Encyclical Letter Laudato Si: On Care for our Common Home, The Vatican. w2.vatican.va/content/dam/francesco/pdf/encyclicals/documents/papa-francesco_20150524_enciclica-laudato-si_en.pdf.
International Energy Agency, 2012. World Energy Outlook. International Energy Agency, Paris.
Intergovernmental Panel on Climate Change, 2013. Climate Change 2013: The Physical Science Basis, Summary for Policy Makers, WG1Contribution to IPCC AR5. Intergovernmental Panel on Climate Change.
Intergovernmental Panel on Climate Change, 2014a. Climate Change 2014: Synthesis Report, Summary for Policymakers. Intergovernmental Panel on Climate Change, Geneva.
IPCC Task Force on National Greenhouse Gas Inventories (undated) Frequently Asked Questions, Q1-2-11. ipcc-nggip.iges.or.jp/faq/FAQ.pdf. See also Table 2.14 errata to AR4, ipcc.ch/publications_and_data/ar4/wg1/en/erratataserrata-errata.html.
Laherrère, Jean, 1999. Reserve growth: technological progress, or bad reporting and bad arithmetic? Geopolit. Energy 22 (4), 7–16.
Laherrère, Jean, 2011. OPEC quotas and crude oil production, The Oil Drum. www.theoildrum.com/pdf/theoildrum_7363.pdf.
Leaton, James (2014) Personal communication, 7 February 2014.
Leggett, Jeremy, 2013. The Energy of Nations: Risk Blindness and the Road to Renaissance. Routledge.
Matthews, H. Damon, Solomon, Susan, 2013. Irreversible does not mean unavoidable. Science 340, 438–439.
Matthews, H. Damon, Gillett, Nathan P., Stott, Peter A., Zickfeld, Kirsten, 2009. The proportionality of global warming to cumulative carbon emissions. Nature 459, 829–832.
Matthews, H. Damon, Graham, Tanya L., Keverian, Serge, Lamontagne, Cassandra, Seto, Donny, Smith, Trevor J., 2014. Environ. Res. Lett. 9 (1) doi:http://dx.doi.org/10.1088/1748-9326/9/1/014010.
McGlade, Christophe, Ekins, Paul, 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. Nature 517, 187–190. doi:http://dx.doi.org/10.1038/nature14016.
Mearns, Euan, 2010. Middle East OPEC reserves revisited, 3 December, The Oil Drum, www.theoildrum.com/node/7149.
Meinshausen, Malte, Meinshausen, Nicolai, Hare, William, Raper, Sarah C.B., Frieler, Katja, Knutti, Reto, Frame, David J., Allen, Myles R., 2009. Greenhouse-gas emission targets for limiting global warming to 2 °C. Nature 458, 1158–1162.
Mushalik, Matt, 2004. Next intelligence failure 300 billion barrels OPEC oil missing, December, www.pc.gov.au/inquiries/completed/energy-efficiency/submissions/matt_mushalik_2/sub075attachment2.pdf.
Royal Dutch Shell, 2014. Untitled: Shell statement on carbon bubble and stranded assets, 16 May. The Hague. http://s02.static-shell.com/content/dam/shell-new/local/corporate/corporate/downloads/pdf/investor/presentations/2014/sri-web-response-climate-change-may14.pdf.
Securities and Exchange Commission, 2009. Modernization of Oil and Gas Reporting; Final Rule, 17CFR Parts 210, 211, Federal Register, vol. 74(9): 2158-2197, 14Jan09, www.sec.gov/rules/final/2009/33-8995fr.pdf.
Society of Petroleum Engineers, 2011. Guidelines for Application of the Petroleum Resources Management System. Society of Petroleum Engineers.
Sandrea, Rafael, 2003. OPEC's challenge: Rethinking its quota system, Oil & Gas Journal, 28 July 2003.
Simmons, Matthew R., 2005. Twilight in the Desert: The Coming Saudi Oil Shock and the World Economy. John Wiley.
The Economist, 2014. The elephant in the atmosphere: Managers at the biggest oil firms clash with investors over climate change, 19 July 2014.
Tippee, Bob, 2010. OPEC's reserves reflect politics—and a lot of oil, Oil & Gas Journal, 1Nov10.
Treanor, Jill, 2009. Royal Dutch Shell to compensate shareholders for reserves scandal, The Guardian, 31 May.
United Nations, 1992. United Nations Framework Convention on Climate Change. United Nations, New York.
University of Oxford, Stranded Assets Program, 2014. Stranded assets and the fossil fuel divestment campaign: what does divestment mean for the valuation of fossil fuel assets? By Atif Ansar, Ben Caldecott, and James Tilbury. www.smithschool.ox.ac.uk/research/stranded-assets/SAP-divestment-report-final.pdf.
Victor, David G., 2011. Global Warming Gridlock: Creating More Effective Strategies for Protecting the Planet. Cambridge University Press.
World Bank, 2011. National Oil Companies and Value Creation, Volume I by Silvana Tordo with Brandon Tracy and Noora Arfaa. World Bank Working Paper Series #218, Washington.
World Bank, 2012. Turn Down the Heat: Why a 4°C Warmer World Must be Avoided, by the Potsdam Institute for Climate Impact Research, and Climate Analytics, climatechange.worldbank.org.
World Energy Council, 2013. World Energy Resources 2013 Survey. World Energy Council, London.
Xu C., Laura, Bell, 2013. Worldwide reserves, oil production post modest rise, Oil & Gas Journal, 2 December.
Xu C., L. Kottungal, 2014. OGJ100 group posts lower 2013 earnings, & OGJ100 production, reserves, and financial data, Oil & Gas Journal, 1 September 2014.