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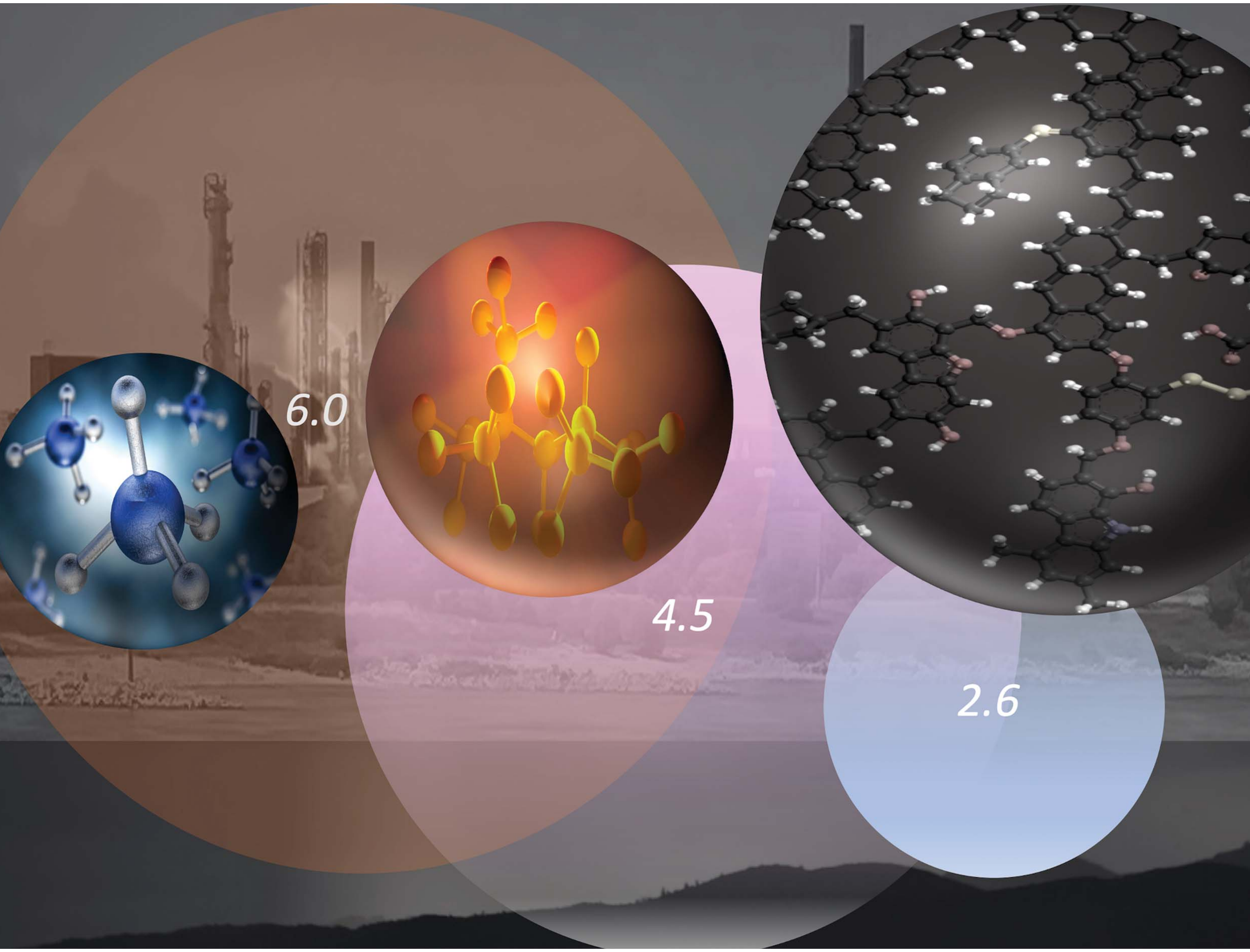

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PAPER
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What happens if we 'burn all the carbon'? carbon reserves, carbon budgets, and policy options for governments†

Kevin M. A. Parker *[a] and Michael R. Mainelli [b]

Our estimates show that 'proven reserves' of fossil fuels in 2022, would generate an estimated 4777 Gt of CO_2 after allowing for non-fuel uses. This quantity already could 'bust CO_2 budgets' for IPCC RCP2.6, RCP4.5, and RCP6.0 and is approaching the range for RCP8.5. Notwithstanding these results, fossil fuel companies are still exploring and bringing new reserves onstream. We discuss the reasons behind this, and propose some policy options for governments as they address this situation.

Environmental significance

In 2006 the authors posed a question to a major oil company, and members of the wider financial community. What happens if we burn all the oil you have now? The answers indicated that the world already had sufficient fossil fuel reserves to raise atmospheric carbon to unacceptable levels of 1000 ppm or more. It looked like there was a lot of 'unburnable carbon' or 'stranded assets' on Oil & Gas company balance sheets. The intention of this paper is improve the 2006 estimates, and carry out new calculations based on reserves in 2022. Is there any evidence that the concept of 'unburnable carbon' has in fact led to reduction in fossil fuel reserves? What might happen to IPCC carbon budgets, and atmospheric CO_2 levels, if these reserves are in fact very 'burnable'? Our estimates show that 'proven reserves' of fossil fuels in 2022, would generate an estimated 4777 Gt of CO_2 after allowing for non-fuel uses. This quantity already could 'bust CO_2 budgets' for IPCC RCP2.6, RCP4.5, and RCP6.0, and is approaching the range for RCP8.5. Notwithstanding these results, fossil fuel companies are still exploring and bringing new reserves onstream. We discuss the reasons behind this, and propose some policy options for governments as they address this situation. The authors for the paper, Dr Kevin Parker, and Professor Michael Mainelli, are respectively Science Advisor and Founder of the leading city of London think-tank Z/Yen Group. Among other achievements, Professor Mainelli is currently serving as Lord Mayor of the City of London, where he is making the Financing of Green developments as a theme of his year in office.

1 Introduction

1.1 Historical background – what happens if we 'burn it all'?

In 2006 the authors posed a question to a major oil company, and members of the 'London Accord'. *What happens if we burn it all?* (*i.e.*, burn all known reserves on balance sheets).

The London Accord[1] was an agreement by over 100 researchers from 25 organisations around the world to "share investment research with policy-makers and the public" on climate change for the sake of the planet. The organisations included the investment research arms of several global banks, research firms, and academics. The London Accord's thinking began at Z/Yen Group, was conducted under the auspices of the City of London Corporation with the support of the then Lord Mayor, Sir David Lewis, and had significant operational support from British Petroleum (BP).

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In December 2007, the London Accord group published a 780 page 'open source' research report on the 'investability' of climate change.[2] Their methodology involved extensive Monte Carlo portfolio modelling as used in financial markets rather than macroeconomics, social cost models, or shadow pricing. The report's conclusion was that carbon prices somewhere above \$30 to \$60 per tonne of CO_2 (in 2007 circa €1 = \$1.4, *i.e.* €21 to €43 per tonne) would provide sufficient opportunities for investment and asset managers to prevent climate change so long as governments restricted emission permits above the \$30 to \$60 range. Given that, traditional financial services could do much of the work to prevent climate change.

For reference, the then price of carbon allowances on the EU emissions trading system (EU ETS) had hit a peak of almost €30 per tonne in April 2006, but due to oversupply by governments, the price dropped 54% from €29.20 to €13.35 in the last week of April 2006. At the time of the London Accord's report launch, carbon prices were nearly zero.

Perhaps the most referred to reference point during the period of the report was the concentration of carbon dioxide in the atmosphere in parts-per-million (ppm). In 2005–6 it was approximately 370, and the likelihood exceeding 400 ppm around 2015 was seen as a significant, negative, milestone. Later, a more common reference point was 'degrees warming' which relies on models. Science advisers on the Intergovernmental Panel on Climate Change estimated an atmospheric CO_2 concentration of no more than 450 parts per million for 2 degrees of warming, or 430 ppm for 1.5 degrees. Still later, 'net zero' dates and 'carbon budgets' have become the more common reference. This change derived from the recognition that global warming is closely tied to cumulative carbon emissions, thus directly linking historic and future reserves exploited over time.

During the London Accord work, researchers queried BP's involvement. Shouldn't the traditional 'seven sisters' of oil just stop? Wouldn't BP be better to close itself down than spend time on the project? At the time BP believed that its reserves might only change atmospheric CO_2 by 1.5 to 2 ppm, and that the same would be true of the small number of other oil majors. Where would the additional 75+ ppm (450–370) come from to heat the planet by 2 degrees?

In 2006 BP's team and Z/Yen researchers independently came up with some new estimates, largely from the reserves of the national oil companies, of the CO_2 levels in ppm from burning the then known fossil fuel reserves (Fig. 1).[3]

At the time, fracking and shale gas was in its infancy. With fracking and shale gas the numbers could rise much higher. It is fair to say that these numbers were considerably higher than expected at the time.

This led to an obvious question, if it would be impossible to 'burn' reserves above 450 ppm or 500 ppm or 550 ppm because society would not allow it, how could the reserves above that level be on corporate balance sheets at current market prices? If one assumed for the sake of example that 450 ppm was the level at which an overheated society would no longer tolerate fossil fuel usage, then 1222 − 450 = 772 that couldn't be burnt. In rough terms at that time, this meant that up to 92% of listed assets had no value.

Current CO2 (ppm)	370
Amount if all oil burnt	619
Plus tar sands	629
Plus coal	946
Plus Gas	1222

Fig. 1 2006 predictions of increase in atmospheric CO_2 levels from 'burning it all' ppm v/v.

These discussions were shared with central bankers as a systemic stability issue, especially once they realised the extent to which many pension funds relied on income from fossil fuel giants like BP and Shell.[4] This led to the formation of the think-tank Carbon Tracker, who produced their first report in 2011,[5] coining the phrases 'unburnable carbon' and 'stranded assets'. The financial community, especially UK pension funds, have widely accepted these concepts.

Meanwhile environmental researchers have realised the threat that large fossil fuel reserves pose to the prospect of limiting climate change. Researchers are attempting to quantify the discrepancies between the carbon budgets for various IPCC scenarios and the CO_2 outputs implicit in fossil fuel reserves, pointing out that the latter are much larger than the former.

The work carried out by Z/Yen in 2006 was an estimate based on the limited knowledge of the time. The intention of this paper is to improve the original estimates, and carry out new calculations based on reserves in 2022. Key Questions to be addressed include:

• Is there any evidence that the concept of 'unburnable carbon' has in fact led to a reduction in fossil fuel reserves?

• What might happen to IPCC carbon budgets, and atmospheric CO_2 levels, if these reserves are in fact very 'burnable'?

• Do the comments around carbon pricing at \$30–60 per tonne still apply?

• What are the implications of the current situation for both financial organisations and policy makers?

We leave to other writers the questions around how policy changes such as 'net zero by 2050' targets might reduce CO_2 emissions. Our focus is instead on the question 'what is the outcome if these policies are not implemented or are unsuccessful?'

1.2 Carbon budgets

Since around 2009–10, the concept of the 'carbon budget' has overtaken a concern for predicted CO_2 concentration levels. The carbon budget is the quantity of carbon dioxide (usually measured as mass in Gigatonne) *'that can be emitted to the*

Table SPM.3 | Cumulative CO_2 emissions for the 2012 to 2100 period compatible with the RCP atmospheric concentrations simulated by the CMIP5 Earth System Models. {6.4, Table 6.12, Figure TS.19}

Scenario	Cumulative CO_2 Emissions 2012 to 2100[a]			
	GtC		$GtCO_2$	
	Mean	Range	Mean	Range
RCP2.6	270	140 to 410	990	510 to 1505
RCP4.5	780	595 to 1005	2860	2180 to 3690
RCP6.0	1060	840 to 1250	3885	3080 to 4585
RCP8.5	1685	1415 to 1910	6180	5185 to 7005

Notes:
[a] 1 Gigatonne of carbon = 1 GtC = 10^{15} grams of carbon. This corresponds to 3.667 $GtCO_2$.

Fig. 2 CO_2 'Budgets' for IPCC Scenarios RCP2.6 to RCP8.5 (IPCC AR5).

atmosphere before global temperature rise can be expected to exceed a given limit'[6]

The IPCC have produced a number of climate scenarios, which relate potential climate change to various carbon budgets. They are described in the comprehensive summary for policy makers as part of the 2018 AR5 report[7] They described a series of 'representative concentration pathways' (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) which specify radiative forcing values between 2.6 and 8.5 W m^{-2} in the year 2100. These pathways lead to warming in the 2081–2100 period of 1.6 C, 2.4 C, 2.8 C, and 4.3 C respectively (all estimates ± 0.7 C) (Fig. 2).

Carbon budgets are not fixed numbers, but correspond to broad estimates of the probabilities of temperature outcomes, which are being constantly studied and revised. However the overall trend is clear, that budgets are reducing as CO_2 emissions continue at increasingly high levels. The Global Carbon Project[8] in 2022 commented that *'The remaining carbon budget for a 50% likelihood to limit global warming to 1.5, 1.7, and 2 °C has, respectively, reduced to 105 GtC (380 GtCO$_2$), 200 GtC (730 GtCO$_2$), and 335 GtC (1230 GtCO$_2$) from the beginning of 2023, equivalent to 9, 18, and 30 years, assuming 2022 emissions levels.'*

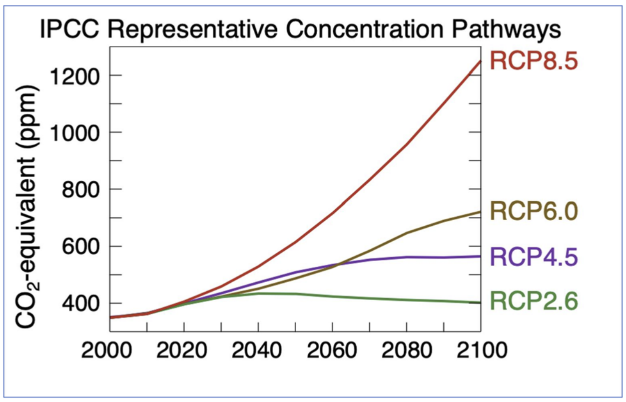


Fig. 3 Atmospheric CO_2 levels for IPCC scenarios RCP2.6 to RCP8.5 (IPCC AR5 data) (Wikimedia Creative Commons License).

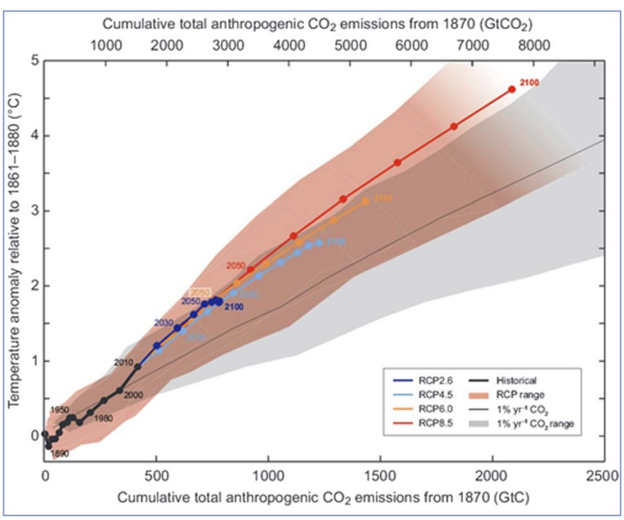


Fig. 4 Cumulative CO_2 emissions: scenarios RCP2.6 to RCP8.5 (IPCC AR5 SPM Fig. 10).

We will use the numbers listed in the budgets above to compare with the potential CO_2 emissions from current, proven fossil fuel reserves.

The IPCC RCP pathways can be visualised in a number of different ways. One approach (Fig. 3) relates the pathways to increasing atmospheric CO_2.

Another approach (Fig. 4) is to relate the pathways to cumulative anthropogenic CO_2 emissions.

1.3 Recent work on fossil fuel reserves

Carbon Tracker reported in 2013 (ref. 9) that potential emissions from the world's 200 largest oil companies could be 1541 GtCO$_2$, already larger than the IPCC budget for a 2.0 °C rise in temperature (986GtCO$_2$ (ref. 10)). In addition to ecological implications, this also suggests that large portions of those companies stated reserves are effectively unusable or 'stranded assets'.[11]

The Fossil Fuels registry has pointed out that current reserves would already exceed the carbon budgets for a 1.5 °C rise in temperature, and that the reserves of certain countries, including the US, could exceed IPCC targets by themselves.[12,13]

In 2015, Greenstone and Stewart calculated the impact of world fossil fuel reserves as potentially producing 5520 GtCO$_2$ emissions, and used this to estimate consequential temperature increases.[14,15]

In 2016, Heede, (a pioneer in this area), and Oreskes analysed the reserves data of the largest seventy eight companies and state entities involved in oil, gas and coal extraction. They found that the reserves of these organisations would produce over 160% of the 2 °C carbon budget pathway from IPCC AR5.[16]

In contrast to the above studies, Wang *et al.* argued in 2016 that total CO_2 emissions and consequent climate change would be limited by supply-side effects, notably that 'recoverable reserves' (oil that could be produced) were usually considerably less than 'total reserves' that appeared in estimates and balance sheets[17] They expect fossil fuel production to reach a supply-limited peak around the mid-21st century. Incorporating this in their models limits the maximum atmospheric concentration of CO_2 to 610 ppm by 2100, with a corresponding temperature rise of 2.6 °C.

There are considerable variations and hence uncertainties in these estimates, as different countries and companies have different definition of proven reserves. The BP review of World Energy states, for example that *'The data series for proved oil reserves in this year's review does not necessarily meet the definitions, guidelines and practices used for determining proved reserves at company level'*.[18] Coal reserves, even in the USA, are subject to wider variations in estimation methodology, as discussed on Global Energy Monitor[19]

The variations increase in 'unconventional' reserves such as shale oil and gas. A thorough review of these uncertainties was carried out by McGlade in 2012.[20] While some producers exaggerate their reserves for political reasons, using proven reserves leads to generally conservative estimates. In addition, changes in technology can move potential reserves to proven reserves, especially in unconventional sources and new regions (such as the offshore Arctic). We discuss this further in our summary below.

1.4 Carbon sinks

Previous studies, including our first analysis in 2005, did not take into account carbon sinks in predicting CO_2 levels resulting from exploiting all fossil fuel reserves. One important question, is the uncertainty of whether current sinks (oceans, soils, forests) would continue to function as at present at increasingly high CO_2 levels. Friedlingstein expressed this cogently in 2015:[21]

'*It was initially believed that the ocean was the main sink of carbon until it became clear that a land sink was needed to close the carbon budget.*[25] *It is now admitted that both the land and the ocean play a comparable role, each removing from the atmosphere about 25% of the anthropogenic CO_2 emissions.*[4,26,27]

However, the obvious question is whether the ocean and the land ecosystems will continue to provide such a service to humanity, removing about half of the CO_2 emitted by human activities. Without these land and ocean sinks, the atmospheric CO_2 increase would be about twice as fast; current atmospheric CO_2 concentration would be already above 500 ppm, inducing a warming of more than 2 K above pre-industrial level (assuming a median estimate of 3 K for the climate sensitivity).

A longer discussion can be found in ESI† to IPCC AR5 (ref. 22) (ref. 4 in Freidlingstein's report above). and in ref. 25–27 cited above. Tans discusses constraints on the CO_2 budget, while two papers by Le Quéré discuss trends in CO_2 sources & sinks and set out global carbon budget data.[23–25]

While the concept of carbon budgets does side step, to some extent, the issues around the uncertainty of carbon sinks, we have incorporated some simple calculations into this paper. Essentially our numbers show *'this is the best case estimate for carbon dioxide concentrations assuming that carbon sinks continue to function as they do at present'*.

2 Methodology

We have attempted where possible to follow the recommendations of the World Resources Institute in distinguishing between proven and probable reserves of fossil fuels.[26] We have used the US Energy Information Administration estimate of 7% of oil and gas fossil reserves[27] are used for non-fuel uses.

Our major source for 2022 data is the BP Annual Statistical Bulletin of World Energy[28] and other sources include the fossil fuel registry,[29] the US National Oceanic and Atmospheric Administration,[30] and the US Energy Information Administration data sets.[31]

Our data for 2005 represents the best retrospective sources we can find for that year, sometime published quite a lot afterwards. This can lead to discrepancies with the numbers of our original calculations done in 2006, where we were producing 'best estimates' with the data available at the time. In particular, our current calculation of 2005 gas reserves is notably lower than our original estimate, largely due to the distinction between proven and probable reserves. At the end of 2023, we checked whether new estimates of reserves had become available during the writing of this paper in 2022–23 and found no new numbers.

All of our data sources, and the relevant calculations, are available in a downloadable Excel Workbook. We have also written an appendix to this paper going through our step by step calculations in a series of tables (*e.g.* 'Table x has the total carbon from quoted reserves, Table y deducts non fuel uses, Table z estimates the impact of 77 years fossil fuel use at current levels' *etc*).

Not all hydrocarbon reserves end up as fuel. The US Energy Information Administration estimates that around 7% of oil is converted into non-fuel uses such as industrial solvents, lubricants and bitumen.[32] For natural gas, the proportion looks to be slightly lower (3.75%) when comparing current total annual consumption of 4 trillion cubic metres with the 150 billion cubic metres used in non-fuel applications. The largest of these are fertilizer manufacture and methanol production.[33]

While coal has potential for being a rich source of valuable chemical intermediates, this is still a developing application, albeit with increasing development in China for olefin and glycol production. Figures from IEA resources on non-energy use of coal suggests these amount to around 4.5%.[34,35]

The relevant equations for converting commonly used fossil fuel quantities to tonnes of carbon dioxide can be summarised as below.

Coal: (reserves 'short tons' $\times$ 0.90718 = reserves in metric tonnes).
(reserves in metric tonnes $\times$ 0.9 = tonnes carbon in anthracite/hard coal).
(reserves in metric tonnes $\times$ 0.6 = tonnes in sub-bituminous 'brown coal')
(tonnes carbon in coal $\times$ 3.67 (44/12) = tonnes CO_2 from coal reserves).
(tonnes CO_2 from coal reserves $\times$ 0.955 = total CO_2 allowing for 4.5% non-fuel use).

The calculations for coal are fairly straightforward, with the major uncertainty being the differing proportions of carbon in the various types of coal.

Oil: (reserves in barrels $\times$ 0.1364 = reserves in metric tonnes).
(reserves in tonnes $\times$ 0.85 = tonnes of carbon in reserves).
(tonnes carbon in reserves $\times$ 3.67 = tonnes CO_2 from oil reserves).
(tonnes CO_2 from oil reserves $\times$ 0.93 = total CO_2 allowing for 7% non-fuel use).

Crude oil has a number of fairly standardised industry conversion factors owing to the wide variety of Imperial and metric units used by the industry for more than a century. A 'barrel' of oil is, these days, an abstract 42 US gallon quantity derived from historic wooden barrels, and the conversion factor of 0.1364 reflects the average density of the most common crude oils. For tar sands, which have a higher density than conventional crude, the conversion factor could be higher (around 0.15 tonnes per barrel).

Gas: (reserves in billion cubic metres $\times$ 0.76 = mass of natural gas in 10^6 tonnes).
(tonnes natural gas $\times$ 2.75 = tonnes CO_2 from gas combustion).
(tonnes CO_2 from gas combustion $\times$ 0.965 = total CO_2 allowing for 3.7% non-fuel use
or

(reserves in billion cubic metres × 34.121 = energy content in trillion British Thermal Units – 'btu')

(Energy content in million btu × 14.43 = kg carbon per million btu).

(kg carbon × 1000 × 3.67 = tonnes carbon dioxide).

The conversion *via* energy content (btu) looks unusual but is actually widely used in the industry. It allows for variations of gas volume at various temperatures and pressures, and the fact that natural gas is not pure methane but has variable amounts of ethane and higher hydrocarbons. The two methods give results that can be reconciled.

Table 2 Proven reserves for major fossil fuels

Parameter	2022	2005
'Hard coal' anthracite and bituminous (billion metric tonnes)	754	478
'Brown coal' sub-bituminous and lignite (billion metric tonnes)	321	430
Oil (billion barrels)	1735	1201
Natural gas (trillion cubic metres)	188	156
Oil sands (billion barrels)	423	84.7
Shale oil (billion barrels)	419	0
Shale gas (trillion cubic metres)	214	15

3 Calculation results

3.1 Fuel reserves and asset life

Using the proven reserves for fossil fuels, and conversion factors mentioned above, allows direct calculation of the CO_2 emitted by combustion of those reserves. We have calculated these individually for each fossil fuel, and details of those calculations can be seen in the appendix to this paper.

Looking at Table 2 we can see that reserves of all types of fossil fuel, except for 'Brown Coal', have increased from 2005 to 2023. This has implications for the potential life of these assets:

• Global coal consumption reached 8 billion (8.0×10^9) tonnes in 2022.[36] Proven coal stocks could supply over 130 years of coal consumption at 2022 levels.

• Global Oil consumption reached 36.37 billion barrels pa in 2022.[37] Proven oil stocks could supply over 47 years of oil consumption at 2022 levels. Oil sands and shale fracking add an extra 23 years, summing to 70 years.

• Current natural gas consumption is around 4 trillion cubic metres pa,[38] so the gas reserves above represent around 46 years supply for conventional reserves and an additional 54 years when shale gas is included.

These numbers suggest that there are already sufficient reserves of fossil fuels to take the world to, or very close to, the year 2100, the endpoint for the various IPCC RCP scenarios.

3.2 Potential emissions from fossil fuel reserves, allowing for non fuel usage

Using the algorithms described in the Methodology (section 2 above), we can estimate the potential CO_2 emissions from current proven reserves. This amounts to 4777 Gt CO_2 (Fig. 5).

Of this 4777 Gt CO_2 total, over half (3048 Gt CO_2) comes from various forms of coal, 1029 Gt comes from traditional and novel oil reserves, and 700 Gt CO_2 from gas. It is notable how the advent of new techniques for oil and gas exploitation (tar sands and fracking) have more than doubled the potential impact of these fuels since 2005.

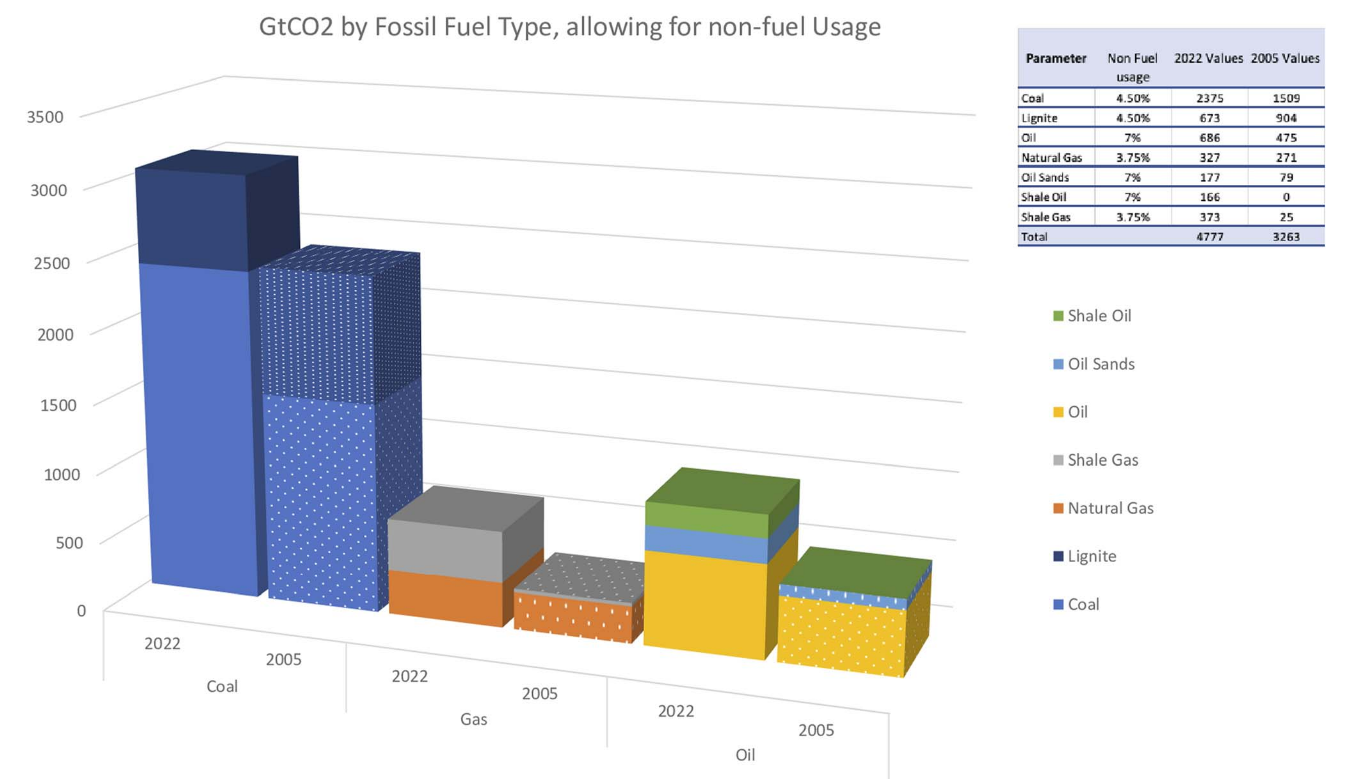
Our estimates are slightly lower than some previous ones, partly due to the use of more recent data, and partly because of taking into account the lower carbon content of 'Brown Coals' (sub-bituminous and lignite).

Fig. 6 compares the potential CO_2 emissions from Fig. 5 with the IPCC RCP scenarios. The background colours reflect the

Table 1 Data sources and values

Parameter	Values	Data sources
Global proved coal reserves/tonnes	1.07411×10^{12}	BP
Global proved oil reserves/barrels	1.7348×10^{12}	BP
Oil sands reserves/barrels	4.232×10^{11}	BP
Proven natural gas reserves/10^9 m^3	1.881×10^5	EIA
Shale tight oil reserves/10^9 barrels	418.9	EIA
Shale gas reserves/ft^3	7576.6	EIA
CO_2/C ratio	3.67	
Proportion of carbon in coal	0.9	EIA
Proportion of carbon in sub-bituminous coal & lignite	0.6	EIA
Mass of Earth's atmosphere/metric tonnes	5.148×10^{15}	Trenbeth & Smith[a]
Density of crude oil (tonne/barrel)	0.1364	BP
Proportion of carbon in oil (w/w)	0.85	Britannica
Proportion of carbon in natural gas (kg/10^6 btu)	14.43	US EPA
2022 proportion of CO_2 in atmosphere/ppm	417	NOAA
Oil reserves used non-combustion purposes (USA)	7%	EIA
Conversion of wt/wt to vol/vol	0.667	Lenntech[b]

[a] Trenbeth K, and Smith L, 2005 The Mass of the Atmosphere: A Constraint on Global Analyses *J.Climate*, **6**, 864-875. [b] PPM converter for Gases https://www.lenntech.com/calculators/ppm/converter-parts-per-million.htm (accessed May 2023).



Parameter	Non Fuel usage	2022 Values	2005 Values
Coal	4.50%	2375	1509
Lignite	4.50%	673	904
Oil	7%	686	475
Natural Gas	3.75%	327	271
Oil Sands	7%	177	79
Shale Oil	7%	166	0
Shale Gas	3.75%	373	25
Total		4777	3263

Fig. 5 Potential CO_2 emissions deducting non-fuel uses (Gt CO_2).

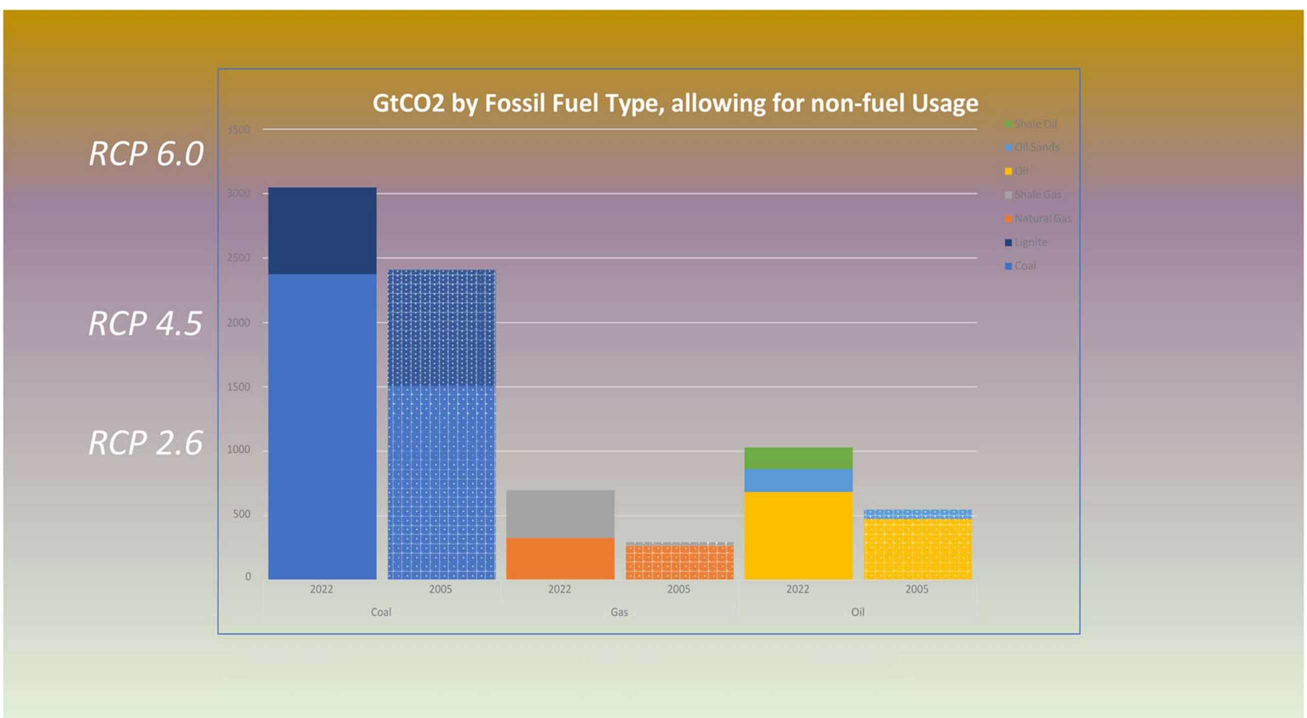


Fig. 6 Potential CO_2 emissions compared to IPCC RCP scenarios.

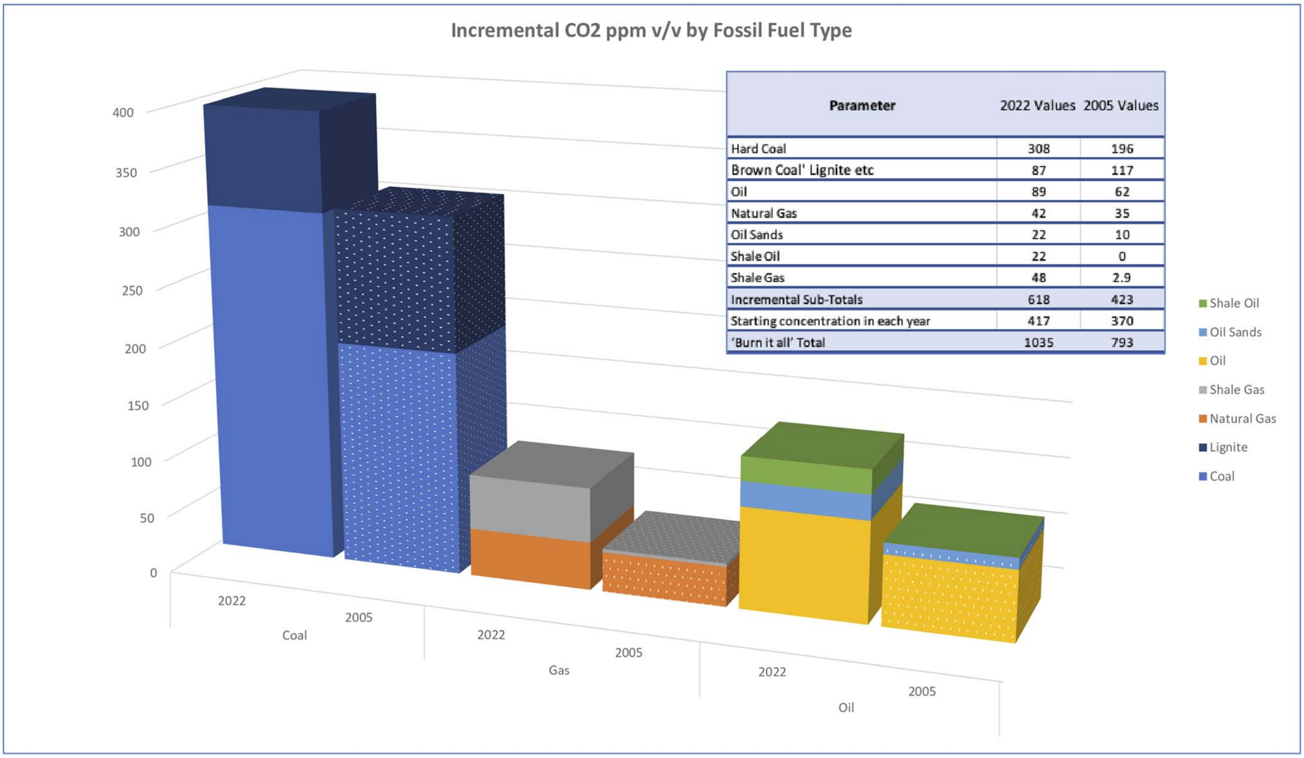


Fig. 7 Potential increase in CO_2 concentration in atmosphere, deducting non-fuel uses (ppm v/v).

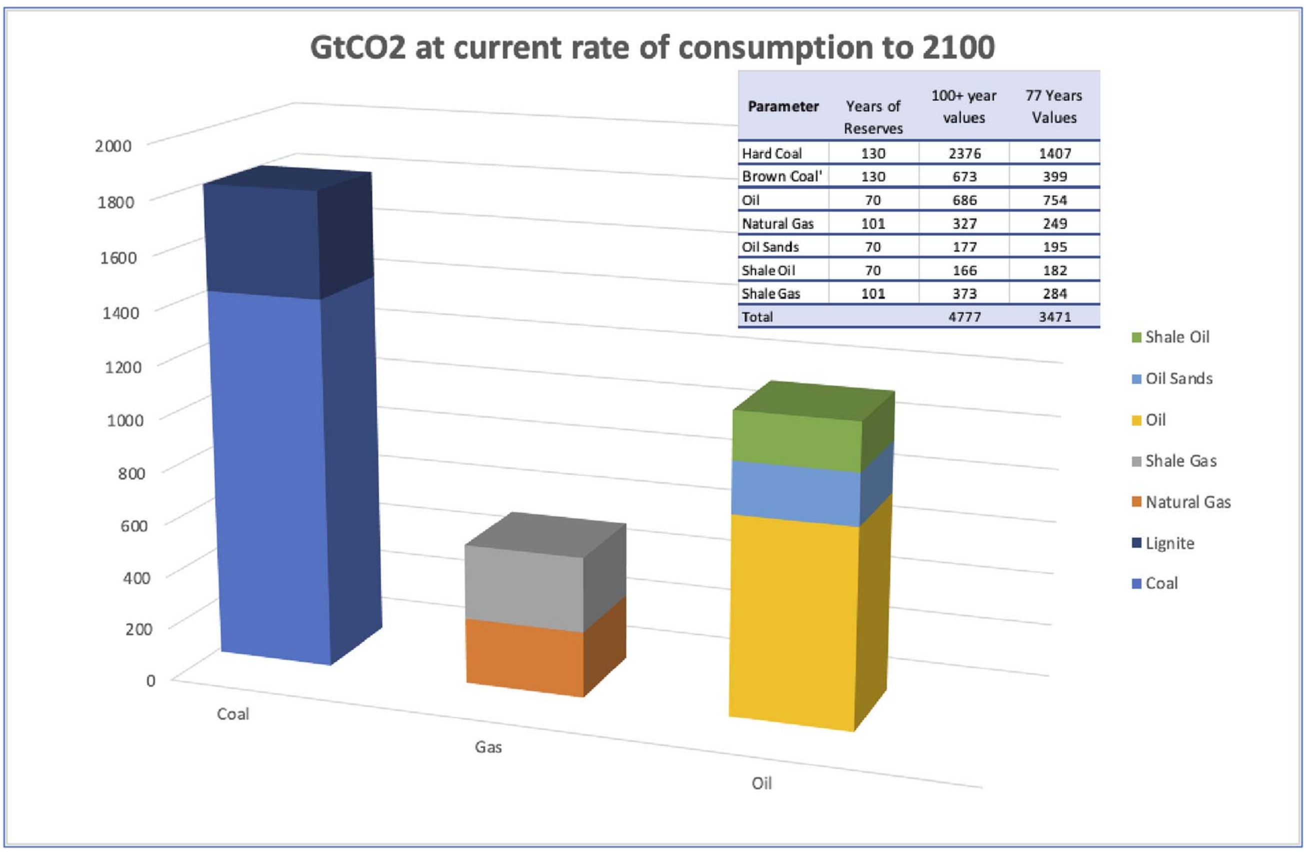


Fig. 8 Potential CO_2 emissions to 2100 (Gt CO_2).

wide range of uncertainty in the IPCC scenarios mentioned in Fig. 1 above. RCP 2.6 (light green) was estimated as 510 to 1505 $GtCO_2$, RCP 4.5 (mauve) was estimated as 2180 to 3690 Gt CO_2, and RCP 6.0 (brown) was 3080 to 4585 Gt CO_2.

Potential CO_2 from oil reserves alone (1029 Gt) takes the world past the IPCC RCP 2.6 threshold, while adding gas (+700 Gt) takes it close to the start of RCP 4.5. Coal reserves alone (3048 Gt CO_2) take the world close to the threshold of RCP 6.0.

3.3 Increase in atmospheric CO_2, allowing for non-fuel usage

Using the algorithms described in the methodology section above, we can estimate the possible incremental change in atmospheric CO_2 emissions from current proven reserves. For our 2022 figures, this amounts to 618 ppm v/v. Added to 2022 CO_2 levels of 417 ppm this would result in an atmosphere with over 1000 ppm CO_2.

Although our re-estimate of 2005 figures is lower than our original 2006 calculation, burning all the reserves present in 2005 would still result in atmospheric CO_2 approaching 800 ppm (Fig. 7).

This figure represents the results of the (hopefully) hypothetical experiment – *what happens to CO2 levels if all current reserves were combusted in an instantaneous process?* While these numbers look alarming, there are a number of factors that could reduce them somewhat.

3.4 Calculations for 2100 – burning 77 years of reserves

The IPCC RCP scenarios predict pathways to various radiative forcing values in the year 2100, 77 years in the future from this paper. In the graphics and tables above, it can be seen that proven reserves are already sufficient to satisfy demands of fossil fuels well beyond 2100 at current levels of consumption. For example proven coal stocks could last for 130 years at current levels of consumption. A reasonable question to ask is, therefore, *'What happens if we burn 77 years of fossil fuel reserves?* This methodology reduces coal CO_2 by 77/130 (where 130 is the total years of reserves at current consumption), and gas CO_2 by 77/100 (where 100 is the years of reserves at current consumption). Oil CO_2 is slightly increased, as current reserves are 70 years (Fig. 8).

This analysis notably reduces the contribution of coal to the carbon budget, as a sizeable portion of coal reserves might only be consumed after 2100. Nonetheless, the potential emissions from 77 years consuming current reserves are still sufficient to exceed the IPCC RCP2.6 and RCP4.5 budgets, and to land within the range for RCP6.0 (Fig. 9).

3.5 Potential CO_2 levels and the impact of carbon sinks

Steady 'business as usual' levels of fossil fuel consumption would be to some extent mitigated by various carbon sinks, in soil, plants (especially trees) and in the ocean. We can estimate how much CO_2 is currently being absorbed by these sinks using data from recent years. In 2005, CO_2 levels were 370 ppm and carbon emissions were 29.6 billion tonnes. Carbon emission from 2005 to 2021 totalled 583 billion tonnes,[39] in theory sufficient to increase atmospheric levels by 72.5 ppm. The actual increase from 2005 to 2022 was 38 ppm, so that approximately 47% was absorbed by carbon sinks. A more detailed tabulation and calculation is shown in Table 15 of the appendix to this paper.

Fig. 10 shows the possible changes to CO_2 levels following fossil fuel consumption continuing at current rates until 2100 with carbon sinks maintaining their efficiency. Essentially these numbers show that 'business as usual' carbon dioxide emissions are likely to produce atmospheric CO_2 levels in 2100 exceeding, at best, 620 ppm. If carbon sinks become less effective, we could see that rise to around 860 ppm.

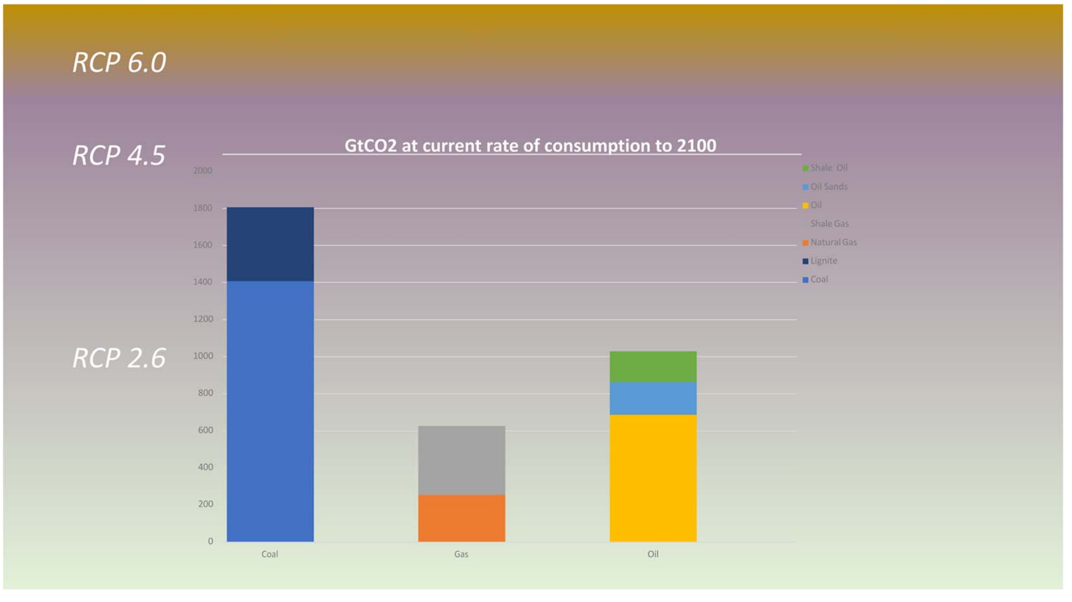
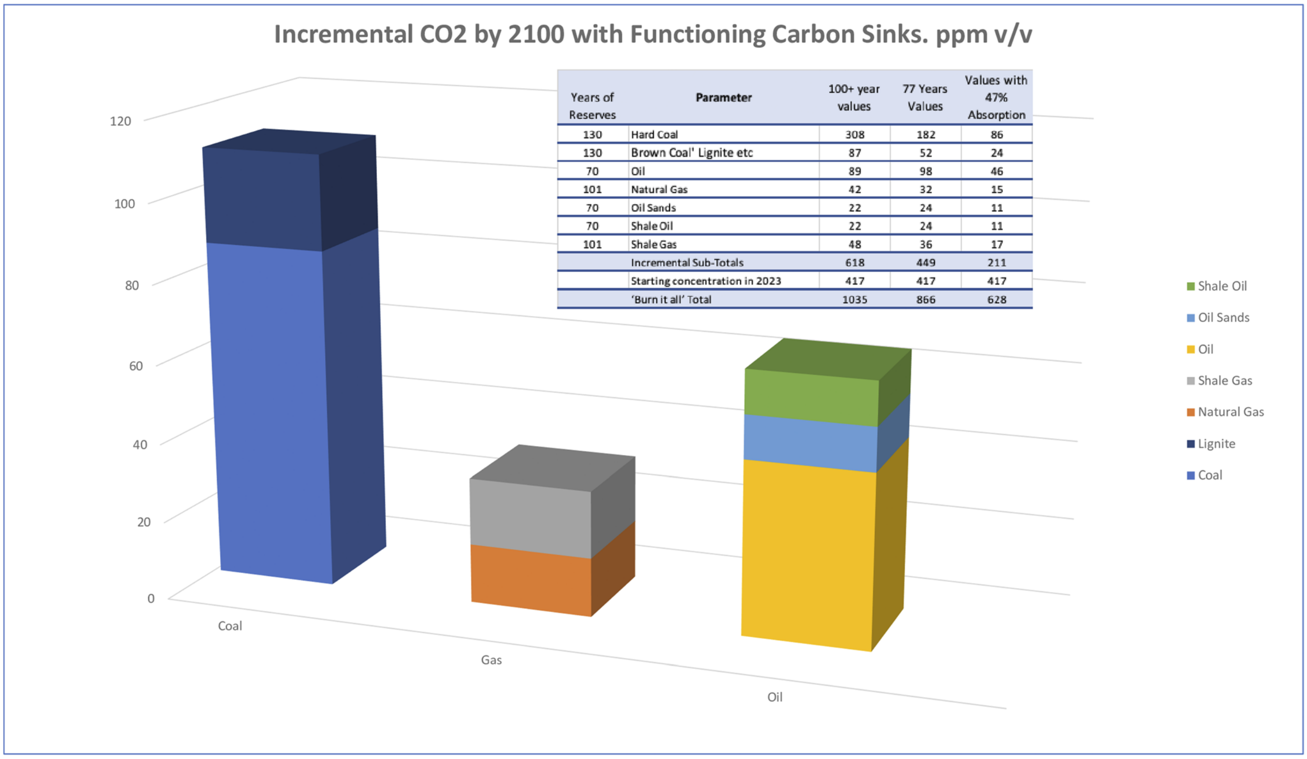


Fig. 9 Potential CO_2 emissions to 2100 compared to IPCC RCP scenarios.



Years of Reserves	Parameter	100+ year values	77 Years Values	Values with 47% Absorption
130	Hard Coal	308	182	86
130	Brown Coal' Lignite etc	87	52	24
70	Oil	89	98	46
101	Natural Gas	42	32	15
70	Oil Sands	22	24	11
70	Shale Oil	22	24	11
101	Shale Gas	48	36	17
	Incremental Sub-Totals	618	449	211
	Starting concentration in 2023	417	417	417
	'Burn it all' Total	1035	866	628

Fig. 10 Potential CO_2 concentrations by 2100 with functioning carbon sinks.

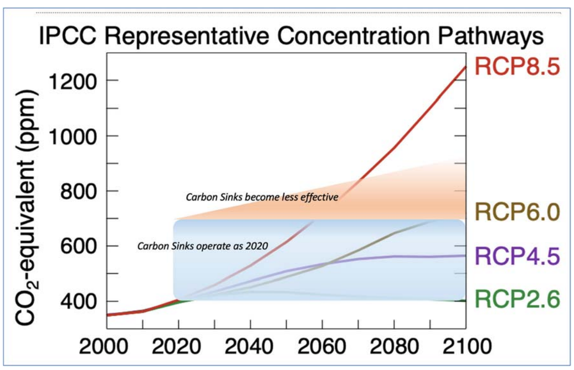


Fig. 11 How current reserves impact potential CO_2 levels in IPCC scenarios RCP2.6 to RCP8.5 (IPCC AR5 data).

The graphic below relates the numbers from Fig. 10 to the IPCC scenarios previously shown in Fig. 3 above (Fig. 11).

Even if carbon sinks continue to function as at present, there is sufficient CO_2 from proven reserves to maintain current rates of fossil fuel consumption, taking the world past RCP 4.5 and towards RCP 6.0.

4 Summary and discussion of results

What are the main points gathered from the data analysis above, and what implications does this have for current carbon budgets and the future of the fossil fuel industry? Our thoughts are as follows.

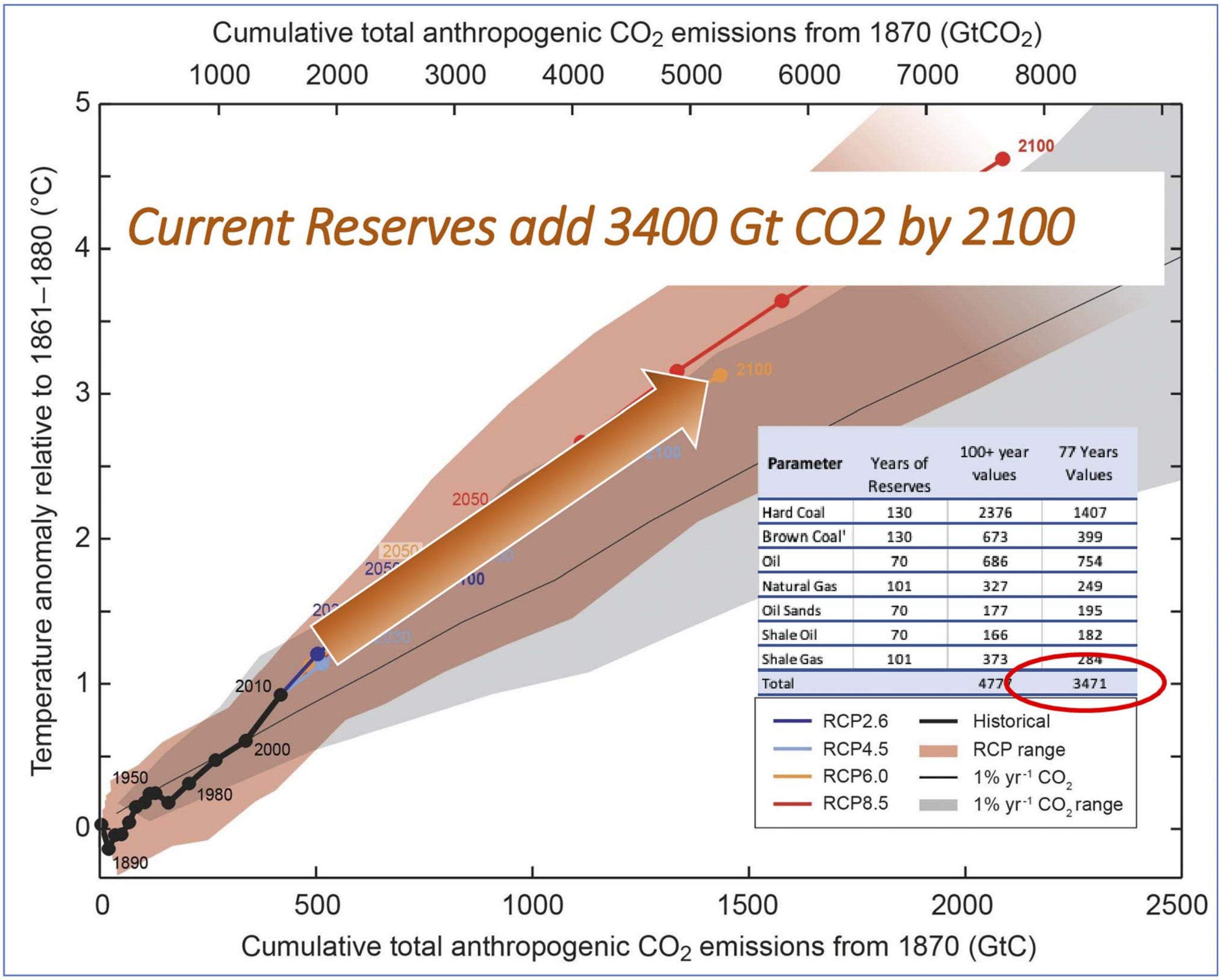
4.1 Current reserves generate sufficient CO_2 to 'bust' IPCC budgets

Current 'proven reserves' at the start of 2022, would generate an estimated 4777 Gt CO_2 after allowing for non-fuel uses. This quantity exceeds the mean CO_2 budgets for IPCC RCP2.6 (990 Gt), RCP4.5 (2860 Gt), and RCP6.0 (3885 Gt) and is close to the lower range for RCP8.5 (5185 Gt).

Fig. 12 relates the potential CO_2 emissions of current reserves to the IPCC RCP pathways mentioned in Fig. 4 above. The RCP pathways generate estimates of cumulative CO_2 by adding the numbers quoted in the paragraph above to the historic emissions from 1870–2010 (for IPCC AR5) and/or 2019 (for IPCC AR6). The latter source quotes cumulative historic emissions as 2400 Gt CO_2. Adding the 3400+ Gt from exploiting current reserves at their current rate, takes the total to 5800 Gt CO_2 by 2100. As Fig. 12 shows, this is very much in the range of RCP 6.0 – a temperature anomaly over 2.5 C. These numbers provide support for the position of the International Energy Agency that '*no new long-lead time oil and gas projects are needed. Neither are new coal mines, mine extensions, or unabated coal plants*'.

4.2 No evidence of peak oil

Our estimates of the carbon potential of current (early 2022) reserves are over 50% higher than our revised estimates from 2005 proven reserves. Recent attention[40] to new 'carbon bomb' fossil fuel discoveries suggest this increasing trend is set to continue into the short-medium term. These developments could add over 600 Gt to our estimates above. Fig. 13



Parameter	Years of Reserves	100+ year values	77 Years Values
Hard Coal	130	2376	1407
Brown Coal'	130	673	399
Oil	70	686	754
Natural Gas	101	327	249
Oil Sands	70	177	195
Shale Oil	70	166	182
Shale Gas	101	373	284
Total		477	3471

Fig. 12 Cumulative CO_2 emissions: scenarios RCP2.6 to RCP8.5 (IPCC AR5 SPM Fig. 10).

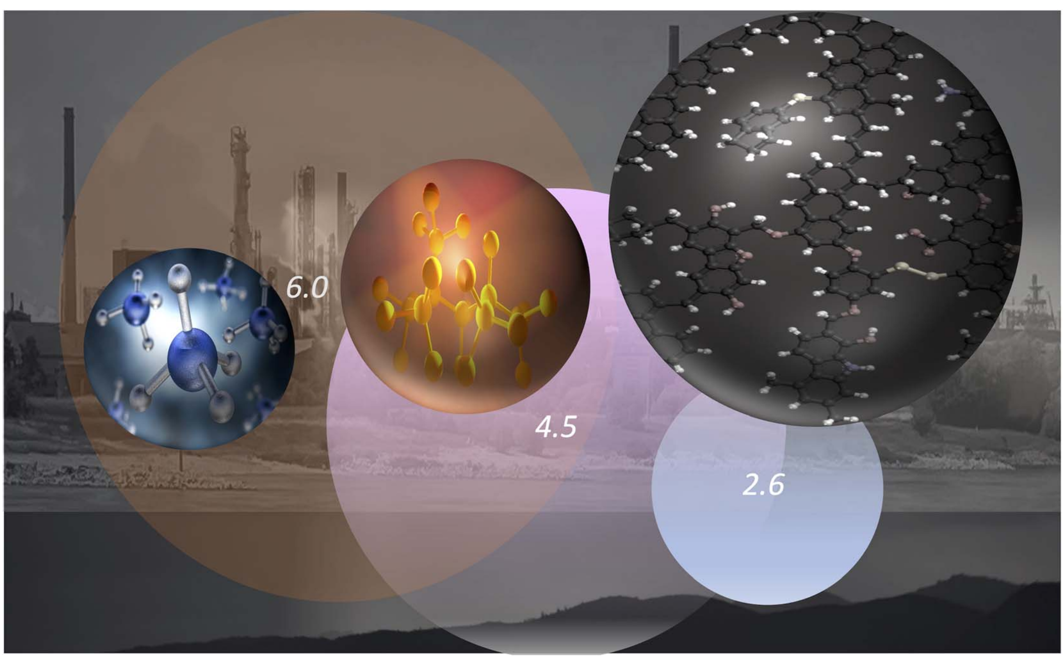


Fig. 13 A semi-quantitative representation of the carbon potential of coal, oil and gas reserves.

shows a semi-quantitative representation of this situation. The blue, orange and black circles in the foreground indicate the relative sizes of CO_2 from gas, oil and coal, and are superimposed on translucent circles representing IPCC RCP budgets. The oil circle alone is close to exceeding that of RCP2.6, especially if these new developments are taken into account.

4.3 Fracking and tar sands are driving reserves increases

The largest change in proven fossil fuels reserves has been from the advent of new sources such as oil from tar sands and both oil and gas from fracking oil shale. Gas reserves from shale fracking now exceed that in 'conventional' gas fields. Worryingly, 'potentially exploitable' shale gas resources in Russia, Chain, Argentina and Algeria are around 3 times higher than the 'proven reserves' (mainly US) in our calculations above.[41]

4.4 Our numbers are very probably underestimates

The numbers presented above should be regarded as 'lower limits' which would almost certainly be exceeded in real life.

Firstly, oil companies tend to have conservative accounting policies – usually recording only those reserves which have a very high certainty (>90%) of being successfully exploited.[42]

Secondly, advances in technology will often extend the actual amount extracted from Oil and Gas fields. This is particularly notable for large fields producing over an extended period of time, where companies are incentivised to exploit infrastructure in place.

A well-documented example is BP's large Forties field in the North Sea. In 1970 when the discovery of the field was announced, it was estimated that the recoverable amount of oil was 1.8 billion barrels,[43] and production was expected to stop in the 1990's. In 2003 the field was sold to a smaller company, (Apache Oil) after BP estimated just 144 million barrels remained. By 2010, the field had produced 2.64 billion barrels.[44] The field is still producing oil in 2023,[45] with estimated production by Apache approaching 300 million barrels.[46]

We also note the number of new discoveries made during the preparation of this paper – not yet classified as proven reserves, but significant in size. The 'Carbon Bomb' report mentioned above (from the Guardian Newspaper) identified 195 oil and gas projects that could each add a billion tonnes of CO_2 to the atmosphere.[42] These projects are not included in our calculations, as they do not yet appear in authoritative sources like the BP Guide to World Energy (who have not included reserves estimates in the last two surveys).

5 Conclusions and the way forward

5.1 Is coal the big problem?

Even with the advent of shale gas and oil from fracking, coal still represents well over 60% of the potential CO_2 emissions from fossil fuel reserves. Although coal usage is falling in some countries, 38% of global electricity, and over 40% of global CO_2 emissions, comes from coal and new thermal coal-burning power stations are still being commissioned, notably in China,[47] India and many less developed countries. Reasons for this include coal becoming cheaper as some countries abandon it, the ease of overland transport (in places without pipeline infrastructure), and the ease of implementing well tried thermal technology.[48,49] For example, several countries in the EU have reopened or extended coal power plants following natural gas prices rising after the invasion of Ukraine.[50]

We might expect that proven coal reserves will continue to rise, given the wide distribution of coal around the world (with notable untapped reserves in Russian Siberia). However it is also likely that some coal will be 'left in the ground' as the operating cost advantages of other technologies increase. Some thermal power stations designed for coal can be converted to run on natural gas or biomass,[51] increasing their efficiency as well as reducing their carbon footprint. It is also feasible, though economically challenging, to mothball coal mines.[52] Individual countries can make telling contributions, such as the recent decision of India to pause coal generating capacity for five years[53]

However, the widespread availability of coal deposits around the world means there is always a temptation for users to switch back to coal when expedient or cheap. The international community could discourage that 'switching-back' by measures such as:

• Technology sharing of renewable electrical generation methods such as solar PV.

• Converting coal to gas powered generation. In the appendix (Table 16) we show calculations for a 1000 MW coal powered plant that would emit 5 million tonnes CO_2 at 60% capacity factor. A gas powered 1000 MW plant would emit less than 2 million tonnes CO_2 at the same capacity factor (not only does gas have a lower carbon content, combined cycle gas generators have a better energy efficiency than coal plants[54]). Additionally, gas generation can be used with non-fossil fuel biogas sources.

• Subsidizing the decommissioning and removal of coal power stations to remove the temptation to switch back.[55]

• Building renewable electrical generating plants on old coal plant premises, to take advantage of existing electrical infrastructure, generators, and grid connections. A long-term example of this is the UK's new STEP fusion reactor at an old coal power site in Nottinghamshire – ultimately using traditional steam turbines and generators to connect to the grid. See the graphic on Bay-Fusion's blog page.[56]

Encouragingly, a 2022 analysis of Chinese coal station construction posits that much of the new building is carried out by provincial authorities seeking short term economic stimulus. The capacity factor of these power plants is below 50%, many are loss-making and liable to closure in the not too distant future.[57] Coal may indeed be the big problem, but hopefully not an insuperable one.

5.2 Carbon pricing and 'shutting down coal'

The section above leads to the consideration of the role of carbon pricing to control emissions. In the introduction above, we commented that in 2005 it seemed that carbon prices around \$30–60 per tonne of CO_2 would allow sufficient investment to avoid severe climate change. One positive development since then has been the expansion of carbon trading schemes.

The IMF report that now around 30% of emissions are covered by carbon taxes or emissions trading schemes.[58]

It is perhaps not surprising that much current thinking calls for governments to impose/enforce rather higher prices. The IMF report mentioned above calls for carbon to be priced around $75 per tonne CO_2. A Reuters poll of climate economists in 2012 suggested that prices of $100 per tonne CO_2 were required for countries to meet their 'net-zero by 2050' targets.[59]

Our analysis prompts the obvious question – if coal is potentially responsible for over half of carbon emitted up to 2100, how can we get rid of it? The 1000 MW power station mentioned in the discussion on coal above might more than halve its emissions by converting to gas. Table 16 in the appendix shows how the economics of the plant might change. Using medium term prices (pre Covid and Ukraine) such a plant would save 16% on its annual fuel cost without a carbon tax – perhaps not enough to defray the costs of switching? At $20 per tonne this rises to 35% saving, at $50 per tonne 44%, and at $75 per tonne 49%.

This simple analysis shows that prices in the $50–$75 per tonne band might induce switching out of coal and consequent reduction in emissions. A more sophisticated analysis has been carried out by Stanford University in a 2022 report on 'carbon arbitrage', the process of investing to 'go short on coal'.[60] They put the 'social cost of carbon' and the corresponding benefit of removing it at $75 per tonne.

5.3 Why are fossil fuel companies still exploring for new reserves – don't they believe the science of climate change?

From the authors' experience, and industry contacts, these are some of the reasons that the fossil fuel industry (particularly oil companies) are continuing to explore for new reserves.

(a) Demand for energy: Fossil fuels, such as oil, gas, and coal, still account for a significant portion of global energy consumption. As the global population continues to grow, and developing economies increase their energy needs, there remains a demand for these energy sources. Even with the emergence of renewable energy sources, fossil fuels still offer a lucrative market with established infrastructure and customer base.

(b) Scepticism around 'stranded assets' and Environmental, Social, & Governance (ESG) factors in general. While some investors have accepted the concept of 'stranded assets and 'unburnable carbon', this has not translated into significant share price impact according to a 2015 analysis by Griffin *et al.*[61] Bebbington[62] (2020) amplified this in a series of interviews with Oil industry stakeholders and observers – stranded assets were 'accepted as a concept' but one that had little importance until 'information was demanded by stock markets and/or governments'.

(c) Profitability and price spikes: Fossil fuel exploration and production can be highly profitable for companies. Companies aim to maximize their profits by meeting the existing demand. In particular, companies with lower cost crude can take profitable advantage of price volatility even in an overall declining market. In contrast to coal, reducing oil production capacity by shutting down entire fields is 'lumpy' and there is little option to mothball oil wells.[63] This is likely to lead to price spikes in an otherwise declining oil price[64,65] A recent article in Reuters noted that companies claim to 'invest to maintain price stability'[66] – although one might be sceptical of this claim given the large profits made by companies during the recent oil and gas price rises caused by the war in Ukraine. An economically rational approach might be to develop a new field and run it at less than full production capacity until prices spike. This approach effectively generates a 'real option' value to expanding or maintaining oil reserves, which has been recognised by industry economists since the 1990's.[67] One could imagine these valuations being used in compensation cases if/when legislation forces oil fields to be abandoned (see next point).

(d) The value of 'booked reserves': Companies instinctively explore and develop new reserves as their current reserves deplete. Given that firms are often valued by reserve capacity, adding to it cheaply (by acquiring rights to undeveloped reserves) looks good for shareholders. One might summarise the attitude as '*if it can be brought onstream quickly and cheaply, then explore and drill*'. Furthermore, once a reserve has been quantified and valued, it can be the subject of compensation claims in Investor-State Dispute Settlement (ISDS) cases.[68] ISDS clauses embedded in the international energy charter treaty have allowed Oil and Gas companies to pursue over 200 court cases against countries seeking to implement fossil fuel reduction policies.

(e) Uncertain transition and new technologies: While there is a global push towards transitioning to renewable energy, the transition process takes time. Fossil fuel companies may continue exploration as they anticipate a gradual shift in energy sources, allowing them to adapt their business models and investments accordingly.[69] Many Oil and Gas companies are pursuing technological solutions that promise the exploitation of fossil fuels in a low/lower carbon way. Examples include the production of blue/green hydrogen,[70] carbon capture,[71] and ammonia production.[72]

Left alone, fossil fuel industries are likely to carry on a large amount of business as usual, interspersed with a rather gradual response to changes they see taking decades to come to fruition. Investment in oil and gas fields continues unabated.[73] While they recognise that governments may reach international agreements and enact policies to restrict fossil fuel use, their actions show that 'they don't believe it will happen any time soon'. The long-standing industry discount rate (10%)[74] to assess new energy investments is still being applied in 2023[75] despite the substantial rise in interest rates over the last few years. Given that discount rates are a combination of 'risk-free' bond interest rates and an industry-related 'risk premium', this can only imply that they do not see increased risks from climate change policies. What are the policy options for governments in this situation?

5.4 What policies could governments implement to convince investors and fossil fuel companies that they are serious about climate change?

Governments can implement several policies to convince investors and fossil fuel companies that they are serious about their net zero carbon targets:

(1) Clear and ambitious regulations: Governments should establish clear and ambitious regulations that set out the requirements and timeline for achieving net zero carbon targets.

These regulations should provide a stable and predictable policy framework, giving investors and companies the confidence to transition towards cleaner energy sources. The breadth of the challenge is illustrated by the lengthy, comprehensive, report[76] by the Energy Transitions Commission (ETC), which discusses the need to cut coal use by >80%, gas use by >55% and oil use by >75% by 2050. ETC does not expect carbon capture or removal to play a significant role in reduction, and instead call for reduced investment in fossil fuel supply. In some notable cases,[77] countries have actually announced that no further fossil fuel exploration will be allowed in their territories.

(2) Carbon pricing: More governments could introduce or strengthen carbon pricing mechanisms like the EU ETS. These mechanisms put a price on carbon emissions, incentivizing companies to reduce their carbon footprint and invest in cleaner technologies. Carbon pricing provides economic signals that align with net zero goals and encourages investors to support low-carbon projects.

(3) Renewable energy incentives: Governments can provide incentives and subsidies for renewable energy projects, making them more attractive for investors. These incentives can include tax credits, feed-in tariffs, grants, or low-interest loans. By promoting the growth of renewable energy, governments signal their commitment to decarbonization and create investment opportunities in the sector.

(4) Support for research and development: Governments can invest in research and development (R&D) initiatives focused on clean energy technologies. By funding R&D projects and offering grants or tax credits for innovation, governments can stimulate the development of new solutions and attract private investment in clean technologies.

(5) Green infrastructure investment: Governments can prioritize investments in green infrastructure projects, such as renewable energy installations, public transportation systems, and energy-efficient buildings. By demonstrating a commitment to sustainable infrastructure, governments can create a conducive environment for investors and companies to align their activities with net zero goals.

(6) ESG disclosure and reporting: Governments can mandate enhanced environmental, social, and governance (ESG) disclosure and reporting requirements for companies. This ensures that investors have access to transparent and standardized information about companies' climate-related risks and opportunities. Improved disclosure can facilitate informed decision-making and encourage investors to support companies that align with net zero targets. Investors generally welcome clear rules around ESG and become frustrated by regulatory instability[78,79]

(7) Collaborative engagement: Governments can engage in collaborative dialogues with investors, financial institutions, and fossil fuel companies to discuss the transition to a low-carbon economy. By involving stakeholders in the policy-making process, governments can address concerns, build consensus, and foster cooperation towards achieving net zero goals.

(8) 'Just transition' plans: A just transition approach helps mitigate resistance to the transition and ensures a fair and equitable distribution of the benefits of a low-carbon economy. A focused example of such a plan has been promulgated in the North Sea by employee groups working alongside environmentalists.[80] A much broader outline from McKinsey[81] looks at aggregate shifts needed for net-zero economies, on energy, land-use, industries and individuals. It comments that cumulative spending of about $275 trillion on physical assets would be required to achieve this. Governments should develop comprehensive just transition plans that support workers and communities affected by the shift away from fossil fuels. These plans should include measures for retraining and reskilling workers, creating alternative job opportunities, and providing support to impacted regions.

(9) Government 'skin in the game': Governments ask investors to make twenty-five year investment decisions on renewable energy or hydrogen transportation, yet reserve the right to change their minds on policies overnight. A 2011 article about the UK Governments then new 'Green Investment Bank' made the following comment *'Before it risks significant investment in policy-supported new markets, the private sector understandably wants the government to underwrite policy and regulatory risk which is within its control (but not within the private sectors control). In other words, it wants the government to commit to its own policy by putting some skin in the game'.*[82]

One proposal that has recently borne fruit is 'policy performance bonds' or 'sovereign sustainability-linked bonds' (SSLB's). These are financial instruments that hold governments accountable for achieving their policy objectives. The idea is that governments would issue bonds tied to specific 'Sustainability Performance Targets' (SPTs), such as carbon emissions reduction targets, or renewable energy deployment. These bonds would pay a higher yield if the government successfully meets its targets, but would incur a penalty if it fails to do so. The bonds would be tradable in financial markets, allowing investors to speculate on the government's performance. The purpose of policy performance bonds is to create financial incentives for governments to prioritize and actively pursue their policy objectives.[83] SPTs could be set to address some of the factors encouraging continued invest in fossil fuel extraction mentioned in section 5.3 above. First promulgated (by the authors) in 2009, it took until 2022 for the first SSLB's to be issued by the Governments of Chile and Uruguay[84] leading to interest from a wider range of countries and institutions. Chile's Government has committed to targets that include decarbonising 60% of its electricity production by 2032, while Uruguay has set a challenging gross greenhouse gas reduction target for 2025. The issues combined longer maturity dates and lower interest rates than traditional bonds, yet were immediately oversubscribed by a wide range of investors, and achieved high credit ratings.[85]

5.5 Final comments – answers to questions from introduction

In the introduction to this paper, the authors posed four questions to address.

• Q. Is there any evidence that the concept of 'unburnable carbon' has in fact lead to reduction in fossil fuel reserves?

• A. *Apart from 'Brown Coal', there is no evidence from our results of any reserve reduction. Potential carbon emissions from fossil fuels show a 46% rise in since 2005.*

• Q. What might happen to IPCC carbon budgets, and atmospheric CO_2 levels, if these reserves are in fact very 'burnable'?

• A. *Current reserves consumed at current rates are sufficient to add 3400 Gt CO_2 by 2100, taking the world a long way towards IPCC path RCP 6.0. Atmospheric CO_2* would *exceed 620 ppm v/v by 2100.*

• Q. Do the comments around carbon pricing at $30–60 per tonne still apply?

• A. *Current expert opinion is that carbon prices around and over $75 per tonne are required to achieve net zero by 2050. We estimate coal to gas switching in thermal power stations would be prompted as carbon prices approach $50 per tonne.*

• Q. What are the implications of the current situation for both financial organisations and policy makers?

• A. *Policy makers, helped by private and public sector investors, need to develop laws, regulations, and incentives, that steer fossil fuel companies away from 'business as usual' approaches to exploration and development. It seems unlikely that fossil fuel companies will change direction without these incentives.*

We hope this paper will promote further thoughts, both around the reserves data discussed above, and the policy options and constraints for governments addressing these issues.

Appendix

Our estimates show that 'proven reserves' of fossil fuels in 2022, would generate an estimated 4777 Gt of CO_2 after allowing for non-fuel uses. This appendix gives a tabulated breakdown of our calculations for each of the major fossil fuel types.

Calculations

Potential emissions from major fossil fuels. Using the proven reserves for fossil fuels, and conversion factors mentioned in Table 1 of the main document, we can directly calculate the CO_2 emitted by combustion of those reserves (Tables 3 and 4).

The 'Proven Global Reserves' of coal have increased by nearly 40% since 2005, despite coal being consumed at increasing amounts throughout the period. Global coal consumption reached 8 billion (8.0×10^9) tonnes in 2022.[36] Proven coal stocks of 'hard' and 'brown' together coal could supply over 130 years of coal consumption at 2022 levels.

The CO_2 produced in burning all current coal reserves, is estimated as 3192 Gigatonnes, enough to take the world past the RCP2.6 target towards RCP4.5 (Table 5).

Table 3 CO_2 emissions from proven 'hard coal' (bituminous and anthracite) reserves

Parameter	2022 values	2005 values
Mass (coal)/metric tonnes	7.536×10^{11} (ref. 18)	4.788×10^{11}
Mass (carbon)/metric tonnes	6.782×10^{11}	4.070×10^{11}
Mass (CO_2)/metric tonnes	2.487×10^{12}	1.492×10^{12}
Fraction of CO_2/total atmosphere	4.831×10^{-4}	3.069×10^{-4}
Increase of CO_2/ppm by wt	483	307
Increase of CO_2/ppm v/v	322	205

Table 4 CO_2 emissions from proven 'brown coal' (sub-bituminous and lignite) reserves

Parameter	2022 values	2005 values
Mass (coal)/metric tonnes	3.205×10^{11}	4.303×10^{11}
Mass (carbon)/metric tonnes	1.923×10^{11}	2.582×10^{11}
Mass (CO_2)/metric tonnes	7.050×10^{11}	9.467×10^{11}
Fraction of CO_2/total atmosphere	1.370×10^{-4}	1.84×10^{-4}
Increase of CO_2/ppm by wt	137	184
Increase of CO_2/ppm v/v	91	123

Table 5 CO_2 emissions from proven oil reserves

Parameter	2022 values	2005 values
Volume (oil)/barrels	1.735×10^{12}	1.201×10^{12}
Mass (oil)/metric tonnes	2.366×10^{11}	1.638×10^{11}
Mass (carbon)/metric tonnes	2.011×10^{11}	1.392×10^{11}
Mass (CO_2)/metric tonnes	7.375×10^{11}	5.104×10^{11}
Fraction of CO_2/total atmosphere	1.433×10^{-4}	9.915×10^{-5}
Increase of CO_2/ppm by wt	143	99
Increase of CO_2/ppm v/v	96	66

Table 6 CO_2 emissions from proven natural gas reserves

Parameter	2022 values	2005 values
Volume (gas/10^9 m^3)	1.881×10^5	1.557×10^5
Energy (gas)/10^{12} btu	6.418×10^6	5.313×10^6
Mass (carbon)/kg	9.261×10^{13}	7.666×10^{13}
Mass (CO_2)/metric tonnes	3.396×10^{10}	2.811×10^{10}
Fraction of CO_2/total atmosphere	6.596×10^{-5}	5.460×10^{-5}
Increase of CO_2/ppm by wt	66	55
Increase of CO_2/ppm v/v	44	36

There is no sign of 'peak oil' in this data, as reserves have increased by over 40%, despite the increasing consumption of oil. These reserves, representing about 47 years supply at current rates of consumption, are again sufficient to take the world past the RCP2.6 budget (Table 6).

Proven natural gas from 'conventional' (e.g. non fracking) reserves have increased by around 21%, again despite the switch to gas fired electricity generation in multiple countries. Current natural gas consumption is around 4 trillion cubic metres pa,[1] so the gas reserves above represent around 46 years supply (Table 7).

Table 7 CO_2 emissions from extractable oil sands reserves

Parameter	2022 values	2005 values
Barrels	4.232×10^{11}	1.80×10^{11}
Mass (oil)/metric tonnes	5.77×10^{10}	2.57×10^{10}
Proportion carbon	0.9	0.9
Mass (carbon)/metric tonnes	5.20×10^{10}	2.31×10^{10}
Mass (CO_2)/metric tonnes	1.905×10^{11}	8.486×10^{10}
Fraction of CO_2/total atmosphere	3.49472×10^{-5}	1.56×10^{-5}
Increase of CO_2/ppm by wt	35	15.57
Increase of CO_2/ppm v/v	23	11

Table 8 CO_2 emissions from extractable shale oil reserves

Parameter	2022 values	2005 values
V (oil)/barrels	4.189×10^{11}	0
m (oil)/metric tonnes	5.7×10^{10}	0
Mass (carbon)/metric tonnes	4.86×10^{10}	0
Mass (CO_2)/metric tonnes	1.781×10^{11}	0
Fraction of CO_2/total atmosphere	3.4592×10^{-5}	0
Increase of CO_2/ppm by wt	35	0
Increase of CO_2/ppm v/v	23	0

The increasing demand for hydrocarbon fuels has led to new resources being discovered and exploited. Proven reserves from oil sands (sometimes termed tar sands) such as those found in Athabasca, have increased by over 220% since 2005. This represents an incremental 11.6 years supply of oil at current rates of demand (Table 8).

As well as oil sands, significant amounts of oil are now being extracted from shale *via* fracking. In 2005 this was still a new technology and no proven reserves were recorded in our analysis. 2022 reserves are similar to those for oil sands, providing an incremental 11.5 years at current demands (Table 9).

'Unconventional' (e.g. from fracking) shale gas reserves have increased by nearly 15 times since 2005. Proven reserves are now higher than those in conventional natural gas fields, and provide an estimated 53 years at current consumption levels.

Summary data – potential emissions from major fossil fuels. Our estimates put the total carbon dioxide potential of 2022 reserves at 5025 Gt, compared to 3429 Gt in 2005 (Table 10).

Except for 'brown coal, fossil fuel reserves have increased since 2005, with coal overall still much the largest contributor to potential carbon dioxide increase. Coal has decreased as a portion of the total emissions potential, mainly due to the notable increase from shale gas (Table 11).

Table 9 CO_2 emissions from extractable shale gas reserves

Parameter	2022 values	2005 values
Volume (gas/m^3)	2.14543×10^{14}	1.46114×10^{13}
Energy (gas)/10^{12} btu	7320435.186	498554.0422
Mass (carbon)/metric tonnes	1.05634×10^{11}	7.19×10^{9}
Mass (CO_2)/metric tonnes	3.873×10^{11}	2.638×10^{10}
Fraction of CO_2/total atmosphere	7.52378×10^{-5}	5.124×10^{-6}
Increase of CO_2/ppm by wt	75	5
Increase of CO_2/ppm v/v	50	3

Table 10 Potential CO_2 emissions from all reserves (Gt CO_2)

Parameter	2022 values	2005 values
'Hard' coal	2487	1580
'Brown' coal	705	947
Oil	737	510
Natural gas	340	281
Oil sands	190	85
Shale oil	178	0
Shale gas	387	26
Total	**5025**	**3429**

Table 11 Potential increase in CO_2 concentration in atmosphere (ppm v/v)

Parameter	2022 values	2005 values
'Hard' coal	322	205
'Brown' coal	91	123
Oil	96	66
Natural gas	44	36
Oil sands	23	11
Shale oil	23	0
Shale gas	50	3
Sub-totals	650	444
Starting concentration in each year	417	370
'Burn it all' total	1067	814

Non fuel uses of hydrocarbon reserves

Not all hydrocarbon reserves end up as fuel. The US Energy Information Administration estimates that around 7% of oil is converted into non-fuel uses such as industrial solvents, lubricants and bitumen.[32] For natural gas, the proportion looks to be slightly lower (3.75%). Non-fuel applications of gas (mainly fertilizer manufacture and methanol production) are around 150 billion cubic metres. While coal has potential for being a rich source of valuable chemical intermediates, this is still underexploited, except in China for olefin and glycol production. Figures from IEA resources on non-energy uses of coal suggests these amount to around 4.5%.[34,35] The tables on this page reflect this data by deducting the non-fuel usage (Tables 12 and 13).

Table 12 Potential CO_2 emissions deducting non-fuel uses (Gt CO_2)

Parameter	Non fuel usage	2022 values	2005 values
'Hard' coal	4.5%	2375	1509
'Brown' coal	4.5%	673	904
Oil	7%	686	475
Natural gas	3.75%	327	271
Oil sands	7%	177	79
Shale oil	7%	166	0
Shale gas	3.75%	373	25
Total		**4777**	**3263**

Table 13 Potential increase in atmospheric CO_2 deducting non-fuel uses (ppm v/v)

Parameter	Non fuel usage	2022 values	2005 values
'Hard' coal	4.5%	308	196
'Brown' coal	4.5%	87	117
Oil	7%	89	62
Natural gas	3.75%	42	35
Oil sands	7%	22	10
Shale oil	7%	21	0
Shale gas	3.75%	48	3
Sub-totals		*618*	*422*
Total adding starting concentrations from Table 11		**1035**	**792**

Table 14 Potential CO_2 emissions and concentration (deducting non-fuel uses) to 2100 (Gt CO_2) and ppm (v/v)

Parameter	'Burn it all' emissions	Years of reserves at current consumption	'Burn 77 years' emissions at current consumption)
Coal	**3048**	**130**	**1805**
Oil			
Conventional oil	686	47	
Oil sands	177	12	
Oil shale	166	11	
All oil sub-total	**1029**	**70**	**1132**
Gas			
Conventional gas	327	47	
Shale gas	373	54	
All gas sub-total	**700**	**101**	**504**
Total	**4777**		**3441**
Potential CO_2 increase in atmosphere ppm (v/v)	619		446
Starting concentration 2023	417		417
Total atmospheric concentration	**1036 ppm**		**863 ppm**

Table 15 Potential CO_2 concentrations by 2100 with functioning carbon sinks

Year	CO_2 emissions (tonnes)
2005	2.96×10^{10}
2006	3.06×10^{10}
2007	3.15×10^{10}
2008	3.21×10^{10}
2009	3.16×10^{10}
2010	3.34×10^{10}
2011	3.45×10^{10}
2012	3.50×10^{10}
2013	3.53×10^{10}
2014	3.56×10^{10}
2015	3.56×10^{10}
2016	3.55×10^{10}
2017	3.61×10^{10}
2018	3.68×10^{10}
2019	3.71×10^{10}
2020	3.53×10^{10}
2021	3.71×10^{10}
Total	$\mathbf{5.83 \times 10^{11}}$
Potential CO_2 increase in atmosphere 2005–21 (ppm v/v)	72.5
Actual increase in atmosphere (ppm v/v)	38
Proportion CO_2 absorbed by carbon sinks	47.3%
Potential increase in CO_2 2023–2100 (from Table 14, ppm v/v)	456
Potential increase if sinks function as now (ppm v/v)	240
Current CO_2 concentration in atmosphere (ppm v/v)	417
Potential total concentration 2100 (ppm v/v)	**657**

Table 16 Potential CO_2 emission reduction converting coal to gas generation

Parameter	Values	Coal	Gas
Power station	**1000 MW**		
Annual energy output at 60% capacity factor	5256 GWh		
Energy from 1 tonne (MWh)		8.33	13.63
Mass of fuel needed at 100% efficiency (tonnes)		630,720	385,534
Typical efficiency		37%	55%
Realistic mass fuel required (tonnes)		1 704 649	700 971
Proportion of carbon		80%	75%
Carbon emitted (tonnes)		1 363 719	525 728
CO_2 emitted (tonnes)		**5 000 303**	**1 927 670**
Average fuel cost 2017–2020		\$84 per tonne	\$170 per tonne
Realistic fuel cost		\$143 m	\$121 m
Carbon price additional cost	\$20 per tonne CO_2	\$100 m	\$38 m
	\$50 per tonne CO_2	\$250 m	\$96 m
	\$75 per tonne CO_2	\$375 m	\$144 m
Total fuel cost at \$75 per tonne		**\$518 m**	**\$265 m**

Calculations for 2100 – burning 77 years of reserves. The IPCC RCP scenarios predict pathways to various radiative forcing values in the year 2100, 77 years in the future from this paper. In Tables 4–9 above, it can be seen that proven reserves are already sufficient to satisfy demands of fossil fuels well beyond 2100 at current levels of consumption. For example, proven coal stocks could last for 130 years at current levels of consumption. A reasonable question to ask is, therefore, *'What happens if we burn 77 years of fossil fuel reserves?* Results answering this question are shown in Table 14 below.

This analysis notably reduces the contribution of coal to the carbon budget, as a sizeable portion of coal reserves might only be consumed after 2100. Nonetheless, the potential emissions from current reserves are still sufficient to exceed the IPCC RCP 2.6 and RCP4.5 budgets, and to land within the range for RCP6.0. The last three lines of the table calculate the potential rise in CO_2 concentration if 77 years of fossil fuel reserves were consumed in one fast 'burn it all' process. They are not a prediction of what concentrations might be like in 2100 if the reserves were consumed steadily over the period to 2100. What, if anything, can we say about that scenario? Table 15 addresses this question, using the assumption that carbon sinks continue to function as they do now.

Finally, Table 16 summarises some calculations illustrating the reduction in carbon dioxide emission and fuel costs by switching from a hypothetical coal power station to a natural gas plant producing the same energy.

Author contributions

Author KP: formal analysis, investigation, methodology, visualisation, writing – original draft, writing – review and editing.

Author MM. conceptualization, supervision, writing (section 1.1, 5.3, 5.4) writing – review and editing.

Conflicts of interest

Both authors have previously worked in parts of the Oil and Gas Industry in a variety of roles as both employees and consultants. None of these roles has been more recent than 2006. No external sources of funding were required for this paper. Z/Yen is promulgating one of the policy options (SSLB's) discussed in the report and may conceivably benefit from advisory work should these become widely adopted.

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