SUBJECT: Calculating the Temperature Potential of Fossil Fuels

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OVERVIEW: In a series of calculations, we convert estimates for reserves and resources by fossil fuel type into associated temperature changes (**Table 1**). This exercise requires estimates of total reserves/resources by type, carbon conversion factors, estimates of historical emissions and a model to convert CO_2 emissions into temperature changes. See **Figure 1** for the final graphic.

DETAILED DESCRIPTION OF CALCULATIONS:

1. We use the median reserve and resource estimates from Extended Data Table 5 of McGlade and Ekins (2015). Reserves/resources are expressed in units of trillion cubic meters for gas, giga-barrels for oil and gigatonnes for coal. McGlade and Ekins use the following definitions:
   - " 'Reserves' are a subset of resources that are defined to be recoverable under current economic conditions and have a specific probability of being produced."
   - " 'Resources' are taken to be the remaining ultimately recoverable resources (RURR)—the quantity of oil, gas or coal remaining that is recoverable over all time with both current and future technology, irrespective of current economic conditions."

2. Breakouts by hard coal and lignite are unavailable from McGlade and Ekins (2015). We use the average ratio of lignite to hard coal as reported in Table 1 in BGR (2014), page 2 in IEA (2013) and Table 7.18/7.19 in GEA (2012). These are the source agencies from Extended Data Table 5 of McGlade and Ekins (2015). See **Table 2** for the exact calculations.

3. We find the carbon potential of the fossil fuels by converting the reserves to emissions in gigatonnes of carbon dioxide. We use the following conversion factors from Matthews (2014) and BP:
   a. 7.33 barrels of oil per tonne of oil and 3.07 tonnes of CO_2 per tonne of oil
   b. 0.9 tonnes of oil equivalent per 1000 cubic meters of gas and 2.35 tonnes of CO_2 per tonne of oil equivalent
   c. 1 tonne of oil equivalent per 1.5 and 3 tonnes of hard coal and lignite respectively and 3.96 tonnes of CO_2 per tonne of oil equivalent.

4. Historical emissions ("Already emitted, 1870-2013") are defined as cumulative CO_2 emissions from fossil fuels, cement and land use change, and are measured in $GtCO_2$ (GCP, 2014). Historical emissions are added to the potential emissions from fossil fuel reserves/resources.

5. Finally, we convert the carbon potential of each category to an associated temperature change. Here, temperature increase is interpreted as the "carbon-climate response". Using the model from Matthews et al. (2009), global mean temperature increases linearly with cumulative carbon emissions. Following the National Academy of Sciences (2011), we take 1.75°C per 1,000 GtC emitted as the central best estimate for this parameter. To convert from GtC to $GtCO_2$, we use the following conversion factor: GtC = (3/11) $GtCO_2$ (EPA, 2004). To convert from Δ°F to Δ°C, we use the following conversion factor: 9/5°F to 1°C.

FAQ:

1. **How does this exercise handle the saturation of CO_2 radiative forcing?**

   This exercise assumes a linear relationship between cumulative carbon emissions and temperature, following Matthews et al. (2009). Their carbon-climate response (CCR) model generalizes the standard climate-sensitivity model by incorporating the feedback effect of natural carbon sinks. This relationship is well-supported by the evidence until 3.6°F (IPCC, 2013). NAS (2011) uses this model until 9°F.

   Surprisingly, the CCR is independent of CO_2 concentrations. This is because there is an "approximate cancellation of the saturation of carbon sinks and the saturation of CO_2 radiative forcing with increasing atmospheric CO_2" (Matthews et al., (2009).

   Table 3 presents a comparison of the DICE model (Nordhaus, 2013) and CCR models over our range of CO_2 emissions. The DICE model exceeds the CCR model until approximately 10°F, after which the CCR model increasingly exceeds the DICE model. We believe this difference is because the DICE model assumes that the saturation of CO_2 radiative forcing dominates the saturation of carbon sinks, while the CCR model assumes that these two effects net to zero.

2. **How does the decay of CO_2 concentrations over time affect these temperature increases?**

   Depending on the rate of fossil fuel consumption, it is possible that the decay of CO_2 concentrations over time will mitigate the temperature impact of fossil fuel emissions.

   However, recent modeling of the atmosphere/ocean carbon cycle suggests that "a single pulse of carbon released into the atmosphere increases globally averaged surface temperature by an amount that remains approximately constant for several centuries, even in the absence of additional emissions" (Matthews and Caldeira, 2008).

   Similarly, Matthews et al., (2009) find that the CCR is approximately independent of time. For a given CO_2 concentration, this is because there is a "cancellation of a decreasing airborne fraction of cumulative emissions, and an increasing temperature change per unit atmospheric CO_2 over time…[due to] the uptake of heat and carbon by the ocean being driven by the same deep-ocean mixing processes on long timescales".

   Under the IPCC A1F1 Emission Scenario (IPCC, 2014) with the assumption of constant consumption after 2100, fossil fuel reserves and resources will be consumed by 2186. This short timescale suggests that we can, to a first approximation, ignore the decay of CO_2 concentrations over time.

3. **Do these calculations include carbon trapped in the permafrost?**

   No. There is 1,700 gigatonnes of organic carbon trapped in the permafrost (Schuur et al. 2015). As the earth warms, this carbon source could be released and accelerate climate change. Under the CCR model, the warming potential of this carbon source is 5.4°F. However, there is very large uncertainty about the timing and size of these potential emissions. The best available evidence suggests that "permafrost carbon emissions are likely to occur over decades and centuries as the permafrost region warms, making climate change happen even faster than we project on the basis of emissions from human activities alone" (Schuur et al. 2015).

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Figure 1:

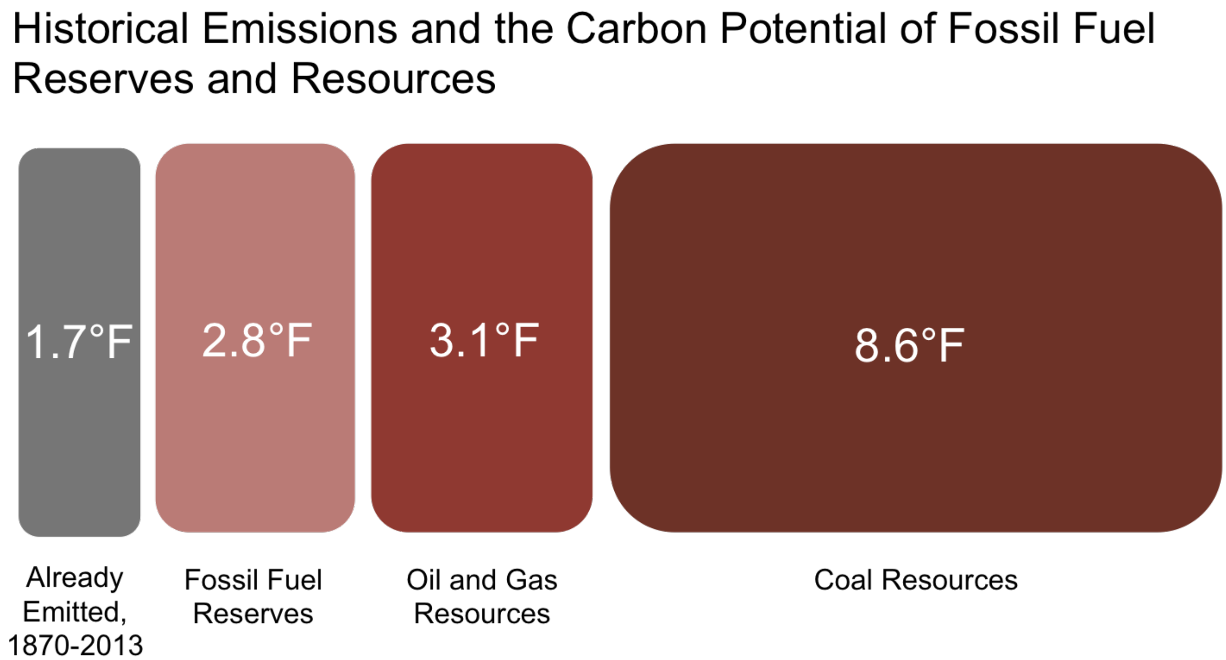
Historical Emissions and the Carbon Potential of Fossil Fuel Reserves and Resources
1.7°F
2.8°F
3.1°F
8.6°F
Already Emitted, 1870-2013
Fossil Fuel Reserves
Oil and Gas Resources
Coal Resources

Table 1:

Calculations for the Temperature Potential of Fossil Fuels

Carbon Source	Reserves	Resources	Carbon Potential, Reserves ($GtCO_2$)	Carbon Potential, Resources ($GtCO_2$)	Temperature Increase, Reserves (°F)	Temperature Increase, Resources (°F)
Total Oil	1300	5070	544	2123	0.468	1.824
Total Gas	190	675	402	1428	0.345	1.226
Total Coal	1000	4085	2322	9967	1.994	8.563
Hard Coal	759	3466	2003	9150	1.721	7.861
Lignite	241	619	318	817	0.274	0.702
Already Emitted, 1870-2013	-	-	1962		1.685	

Notes: Reserves and resources are from Extended Data Table 5 of McGlade and Ekins (2015). The reserves/resources are expressed in units of trillion cubic meters for gas, giga-barrels for oil and gigatonnes for coal. Carbon potential is measured in gigatonnes of carbon and uses the following conversion factors from Matthews (2014)and BP: 1) 7.33 barrels per tonne of oil and 3.07 tonnes of CO_2 per tonne of oil 2) 0.9 tonnes of oil equivalent per 1000 cubic meters of gas and 2.35 tonnes of CO_2 per tonne of oil equivalent 3) 1 tonne of oil equivalent per 1.5 and 3 tonnes of hard coal and lignite respectively and 3.96 tonnes of CO_2 per tonne of oil equivalent. Temperature increase is interpreted as the "carbon-climate response". By this measure, global mean temperature increases linearly with cumulative carbon emissions. Following the National Academy of Sciences (2011) we take 1.75°C per 1,000 GtC emitted as the central best estimate. To convert from $GtCO_2$ to GtC, we use the following conversion factor: 3/11 GtC to $GtCO_2$ (EPA, 2004). To convert from Δ°F to Δ°C, we use the following conversion factor: 9/5 °F to 1 °C. "Already emitted" refers to cumulative CO2 emissions from fossil fuels, cement and land use change and is measured in $GtCO_2$ (GCP, 2014).

Table 2:

Imputed Lignite-Hard Coal Ratio:

	Hard Coal	Lignite	Lignite-Hard Coal Ratio
Reserves			
BGR	585	110	0.188
IEA	730	280	0.384
GEA	18246	2775	0.152
Average			0.241
Resources			
BGR	14946	1765	0.118
IEA	18000	4000	0.222
GEA	391052	44671	0.114
Average			0.152

Notes: Data comes from Table 1, BGR (2014), IEA (2013) and Table 7.18/7.19 GEA (2012). Breakouts by hard coal and lignite status are unavailable from McGlade and Ekins (2015)., so the average ratio from the source documents in Extended Data Table 5 is used.

Table 3:

Cumulative Carbon-Related Temperature Change, By Climate Model

Carbon Sources	**(1)** ($\Delta GtCO_2$)	**(2)** (ΔPPM)	**(3)** (Δ°F)	**(4)** (Δ°F)
Already Emitted, 1870-2013	1,962	251	1.7	1.5
Fossil Fuel Reserves	5,230	670	4.5	4.8
Oil and Gas Resources	8,781	1124	7.5	7.6
Coal Resources	18,748	2401	16.1	12.2
Carbon-climate response model			X	
DICE model				X

Notes: Column 1 reports cumulative CO_2 emissions in gigatonnes, Column 2 reports cumulative atmospheric CO_2 concentrations in PPM, Column 3 reports associated temperature changes using the carbon-climate response model, and Column 4 reports associated temperature changes using the DICE model. The carbon-climate response model comes from Matthews et al. (2009), Following the National Academy of Sciences (2011), we take 1.75°C per 1,000 GtC emitted as the central best estimate for the slope parameter. The DICE model comes from Nordhaus (2013). We use the baseline emissions scenario with the assumption of constant annual carbon emissions after 2130. To convert from GtC to ppm, we use the following conversion factor: 1 ppm by volume of atmosphere CO_2 = 2.13 GtC (CDIAC, 2012).