

**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<sub>2</sub> emissions into temperature changes. See **Figure 1** for the final graphic.

#### **DESCRIPTION OF CALCULATIONS:**

1. We use the reserve and resource estimates for oil, gas, and coal from Extended Data Table 1 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. Resource estimates for oil shale come from [USGS \(2006\)](#). Low and high resource estimates for methane hydrates come from [USGS \(2012\)](#).
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<sub>2</sub> per tonne of oil/oil shale.
  - b. 0.9 tonnes of oil equivalent per 1000 cubic meters of natural gas and 2.35 tonnes of CO<sub>2</sub> 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<sub>2</sub> per tonne of oil equivalent.

See **Table 2** for a comparison of the carbon potential estimates obtained from these conversion factors against the carbon potential estimates reported in Table 1, Panel D of [McGlade and Ekins \(2015\)](#).

4. Historical emissions ("Already emitted, 1870-2010") are defined as cumulative CO<sub>2</sub> emissions from fossil fuels, cement and land use change, and are measured in GtCO<sub>2</sub> ([GCP, 2015](#)). 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<sub>2</sub>, we use the following conversion factor: GtC = (3/11) × GtCO<sub>2</sub> ([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<sub>2</sub> 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<sub>2</sub> concentrations. This is because there is an “approximate cancellation of the saturation of carbon sinks and the saturation of CO<sub>2</sub> radiative forcing with increasing atmospheric CO<sub>2</sub>” ([Matthews et al., \(2009\)](#)).

**Table 3** presents a comparison of the DICE model ([Nordhaus, 2013](#)) and CCR models over our range of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> concentrations over time affect these temperature increases?

Depending on the rate of fossil fuel consumption, it is possible that the decay of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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 2175. This short timescale suggests that we can, to a first approximation, ignore the decay of CO<sub>2</sub> concentrations over time.

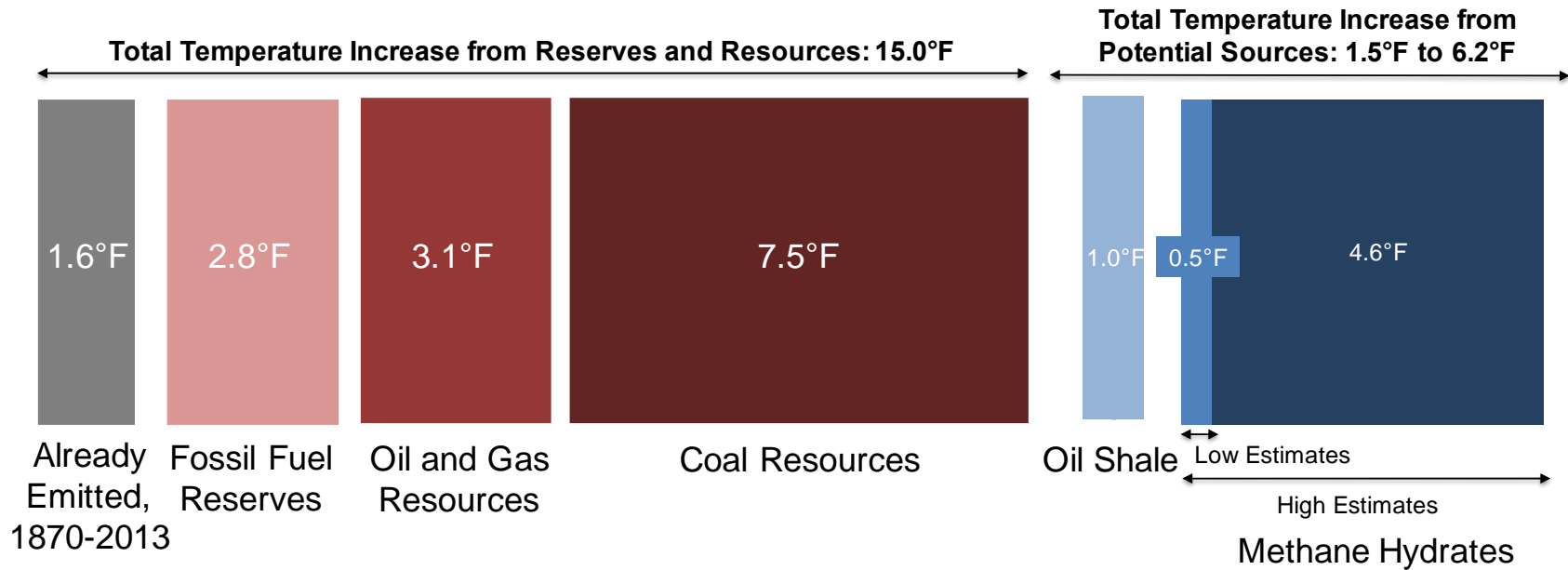
### 3. Do these calculations include carbon trapped in the permafrost?

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](#)).

## BIBLIOGRAPHY:

- BP. 2014. “BP Statistical Review of World Energy 2014.”  
<http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy/using-the-review/Conversionfactors.html>. Accessed March 23, 2015.
- CDIAC. 2012. “Carbon Dioxide Information Analysis Center - Conversion Tables”.  
<http://cdiac.ornl.gov/pns/convert.html>. Accessed April 12, 2015.
- EPA. 2004. “UNIT CONVERSIONS, EMISSIONS FACTORS, AND OTHER REFERENCE DATA”. <http://www.epa.gov/cpd/pdf/brochure.pdf>. Accessed March 23, 2015.
- GCP. 2015. “Global Carbon Project.” <http://cdiac.ornl.gov/GCP/>. Accessed December 2015.
- IPCC. 2013. “2013: Technical Summary.” In: “Climate Change 2013: The Physical Science Basis.” Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, page 102.
- IPCC. 2014. “The SRES A1FI Emissions Scenarios ”[http://www.ipcc-data.org/sim/gcm\\_clim/SRES\\_TAR/ddc\\_sres\\_emissions.html](http://www.ipcc-data.org/sim/gcm_clim/SRES_TAR/ddc_sres_emissions.html). Accessed April 12, 2015.
- Matthews, H Damon and Ken Caldeira. 2008. “Stabilizing climate requires near-zero emissions.” *Geophysical Research Letters* 35 (4): 1944-8007.
- Matthews, H Damon, Nathan P. Gillett, Peter A. Stott and Kirsten Zickfeld. 2009. “The proportionality of global warming to cumulative carbon emissions.” *Nature* 459 (7248): 829-832.
- Matthews, H Damon. 2014. “A growing commitment to future CO<sub>2</sub> emissions.” *Environmental Research Letters* 9: 111001.
- McGlade, Christophe and Paul Ekins. 2015. “The geographical distribution of fossil fuels unused when limiting global warming to 2 °C.” *Nature* 517 (7533): 187-190.
- National Research Council. 2011. “Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia.” Washington, DC: The National Academies Press, pages 97-104.
- Nordhaus, William. 2014. “DICE-2013R Model as of November 15, 2013”  
<http://www.econ.yale.edu/~nordhaus/homepage/Web-DICE-2013-April.htm>. Accessed April 13, 2015.
- Schuur et al. 2015. “Climate change and the permafrost carbon feedback.” *Nature* 520 (7546): 171–179.
- USGS. 2006. “Geology and Resources of Some World Oil-Shale Deposits”.  
[http://pubs.usgs.gov/sir/2005/5294/pdf/sir5294\\_508.pdf](http://pubs.usgs.gov/sir/2005/5294/pdf/sir5294_508.pdf). Accessed December 2015.
- USGS. 2012. “Potential of gas hydrates is great, but practical development is far off”.  
<http://www.eia.gov/todayinenergy/detail.cfm?id=8690>. Accessed December 2015.

**Figure 1:**



*Notes:* This figure depicts potential temperature increases from different sources of fossil fuels, as in **Table 1**. Carbon potential is calculated using manual conversion factors and temperature responses are calculated using the “carbon-climate response” model. See **Table 2** and **Table 3** for a comparison across different carbon conversion factors and climate models. The following carbon conversion factors are used from [Matthews \(2014\)](#) and [BP](#): 1) 7.33 barrels per tonne of oil and 3.07 tonnes of CO<sub>2</sub> per tonne of oil 2) 0.9 tonnes of oil equivalent per 1000 cubic meters of gas and 2.35 tonnes of CO<sub>2</sub> 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<sub>2</sub> per tonne of oil equivalent. Following the [National Academy of Sciences \(2011\)](#), we take 1.75°C per 1,000 GtC emitted as the central best estimate for the relationship between cumulative carbon emissions and global mean temperature.

**Table 1:****Calculations for the Temperature Potential of Fossil Fuels**

Carbon Source	Reserves	Resources	Carbon Potential, Reserves (GtCO <sub>2</sub> )	Carbon Potential, Resources (GtCO <sub>2</sub> )	Temperature Increase, Reserves (°F)	Temperature Increase, Resources (°F)
Total Oil	1294	5070	542	2123	0.466	1.824
Total Gas	192	675	406	1428	0.349	1.226
Total Coal	1004	4085	2286	8778	1.964	7.541
Hard Coal	728	2565	1922	6772	1.651	5.817
Lignite	276	1520	364	2006	0.313	1.724
Oil Shale	-	2826	-	1184	-	1.017
Methane Hydrates (Low Estimate)	-	283	-	599	-	0.514
Methane Hydrates (High Estimate)	-	2831	-	5987	-	5.143
Already Emitted, 1870-2010	-	-		1844		1.584

Notes: Reserve and resource estimates for oil, gas, and coal come from Extended Data Table 1 of [McGlade and Ekins \(2015\)](#). Oil shale resource estimates come from [USGS \(2006\)](#). Low and high resource estimates for methane hydrates come from [USGS \(2012\)](#). The reserves/resources are expressed in units of trillion cubic meters for gas/methane hydrates, giga-barrels for oil/oil shale and gigatonnes for coal. Carbon potential is measured in gigatonnes of carbon dioxide 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<sub>2</sub> per tonne of oil 2) 0.9 tonnes of oil equivalent per 1000 cubic meters of gas and 2.35 tonnes of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> to GtC, we use the following conversion factor: 3/11 GtC to GtCO<sub>2</sub> ([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 CO<sub>2</sub> emissions from fossil fuels, cement and land use change and is measured in GtCO<sub>2</sub> ([GCP, 2015](#)).

**Table 2:****Carbon Potential Comparison, Manual Conversion Factors versus McGlade and Ekins (2015)**

Carbon Source	Manual Conversion Factors				McGlade and Ekins (2015)			
	Carbon Potential, Reserves (GtCO <sub>2</sub> )	Carbon Potential, Resources (GtCO <sub>2</sub> )	Temperature Increase, Reserves (°F)	Temperature Increase, Resources (°F)	Carbon Potential, Reserves (GtCO <sub>2</sub> )	Carbon Potential, Resources (GtCO <sub>2</sub> )	Temperature Increase, Reserves (°F)	Temperature Increase, Resources (°F)
Total Oil	542	2,123	0.47	1.82	523	1,513	0.45	1.30
Total Gas	406	1,428	0.35	1.23	359	900	0.31	0.77
Total Coal	2,286	8,778	1.96	7.54	1,985	5,620	1.71	4.83
Hard Coal	1,922	6,772	1.65	5.82	1,728	4,442	1.48	3.82
Lignite	364	2,006	0.31	1.72	257	1,178	0.22	1.01
Totals	3,234	12,329	2.78	10.59	2,867	8,033	2.46	6.90

Notes: This table compares carbon potential and temperature estimates using manual conversion factors and the Table 1, Panel D estimates reported by [McGlade and Ekins \(2015\)](#). The following manual conversion factors come from [Matthews \(2014\)](#) and [BP](#): 1) 7.33 barrels per tonne of oil and 3.07 tonnes of CO<sub>2</sub> per tonne of oil 2) 0.9 tonnes of oil equivalent per 1000 cubic meters of gas and 2.35 tonnes of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> to GtC, we use the following conversion factor: 3/11 GtC to GtCO<sub>2</sub> ([EPA, 2004](#)). To convert from Δ°F to Δ°C, we use the following conversion factor: 9/5 °F to 1 °C.

**Table 3:****Cumulative Carbon-Related Temperature Change, By Climate Model**

	(1)	(2)	(3)	(4)
Carbon Sources	( $\Delta$ GtCO <sub>2</sub> )	( $\Delta$ PPM)	( $\Delta$ °F)	( $\Delta$ °F)
Already Emitted, 1870-2010	1,844	236	1.6	1.5
Total Reserves and Resources, Manual Conversion Factors	17,407	2,229	15.0	11.9
Total Reserves and Resources, McGlade and Ekins (2015)	12,744	1,632	10.9	10.0
Carbon-climate response model			X	
DICE model				X

*Notes:* Column 1 reports cumulative CO<sub>2</sub> emissions in gigatonnes, Column 2 reports cumulative atmospheric CO<sub>2</sub> 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<sub>2</sub> = 2.13 GtC ([CDIAC, 2012](#)).