Methodology for figure 1-3 in *Reinventing Fire*

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This graph plots the actual global output of the three major classes of hydrocarbons through 2009, then projects the remaining amounts of each believed likely to be recovered if there are no above-ground constraints. The historic data are taken from the sources noted in the respective coal, liquids, and gas sections below. The smoothed illustrative projections are approximate, reflecting leading resource experts' knowledge in early 2011 but subject to many uncertainties. The projections include unconventional resources such as shale gas, heavy oil, tar sands, and shale oil, but not methane hydrates, potential Arctic and Antarctic resources, or Alaskan North Slope and central Siberian coal. The basic methodology for generating these projections is described in the following section, with specifics given for coal, liquids, and gas in their respective sections below.

GENERAL PROJECTION METHODOLOGY

The projections shown apply techniques and logic similar to and refined from those developed by Shell geophysicist M. King Hubbert (1903–89). These techniques are well documented in the liturature.[1,2] Long-term projections reflect statistical best fits to the historic production curves, as opposed to more conventional, geological-survey-based estimates. They are primarily intended to predict only the total amount and the general contours of cumulative production; annual production can be much more volatile, so the vertical axis is accurate only for the historic data shown for 1799–2010.

More conventional reserve and resource calculations are taken from geological survey data and are generally more optimistic than those found by Hubbertian analysis.

For example, let's look at Caltech Professor David Rutledge's recently published analysis of global coal production and resources[3]. For the case of coal especially, reserve estimates tend to underestimate the economic challenges of production, and more detailed coal exploration tends to reduce reserves[4]. For mature coal regions, historic survey-based long-term production forecasts can be compared to the now-known recovery. In four of the world's major mature coal regions, historic survey-based estimates have overstated actual output by an average of fourfold (and by far more in a fifth region). Rutledge has developed techniques, similar to those used by

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[1] Campbell, C. J, and J. H Laherrère. 1998. "The end of cheap oil." *Scientific American* 278 (3): 60–5; Laherrere, J.H. 2000. The Hubbert Curve: Its strengths and weaknesses. http://dieoff.org/page191.htm; Deutsche Bank. 2009. *The Peak Oil Market: Price Dynamics at the End of The Oil Age*. Deutsche Bank, October 4. www.petrocapita.com/attachments/128_Deutsche%20Bank%20-%20The%20Peak%20Oil%20Market.pdf; Association for the Study of Peak Oil & Gas. http://www.peakoil.net/.
[2] Rutledge, D. 2011. "Estimating long-term world coal production with logit and probit transforms." *International Journal of Coal Geology* 85 (1) (January): 23-33. doi:10.1016/j.coal.2010.10.012.
[3] Ibid.
[4] Rutledge, David. 2010. Personal communication with author. March 7.

Hubbert[5], based on historic production data, which fully reflect market-clearing prices and the complex geological and logistical details of production. His method has proven accurate in predicting both 90%-depletion dates and ultimately recoverable resources (±15%). Using the recovered reserves inputs for liquids and gas noted below, annual production curves were generated using Rutledge's method.

Assumed Ultimately Recovered Resources (total area under curves) used for Projections

Coal: Ultimate recovery of ~2,500 Gboe (680 gigatonnes or Pg of mixed rank)

Coal historic production data and projections are taken directly from Rutledge's analysis[6,7] (described above), which is much less optimistic than some others'; Rutledge's recovered reserves are less than half of WEC's assessments[8] (used by the Intergovernmental Panel on Climate Change (IPCC)) as well as Laherrère's suggestion.[9] We converted coal to Gboe (billion barrels of oil equivalent) using 1850–2010 annual conversion factors.[8] and for 2010 onward using the recent typical value of 0.5 toe per coal tonne. We didn't include 1750–99 British coal output[10] because the amounts would be invisible in this graph, as would (probably) Chinese Song Dynasty coal use if the data were available. Future resources omit unknown fields and undeveloped ones (for good reasons), chiefly on Alaska's North Slope and in central Siberia.

Liquids: Ultimate recovery of 3,000 Gboe (1 boe ~ 308 GJ)

The recovered-liquids projection was suggested by Laherrère[11] and is slightly below that used by the IPCC. Liquids are defined as by the U.S. Energy Information Administration (EIA) (but excluding renewables such as biofuels) to include all petroleum products, natural gas liquids,

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[5] Sharing common logic with Hubbert's techniques, but perhaps most similar to those used by his colleague Kenneth S. Deffeyes. Deffeyes, K. S. 2006. *Beyond oil: The view from Hubbert's Peak*. Hill & Wang; ———. 2008. *Hubbert's peak: the impending world oil shortage*. Princeton Univ.
[6] Rutledge, D. 2011. "Estimating long-term world coal production with logit and probit transforms." *International Journal of Coal Geology* 85 (1) (January): 23-33. doi:10.1016/j.coal.2010.10.012.
[7] Rutledge, David. 2010. Personal communication with author. March 7.
[8] World Energy Council. 2010. *Survey of Energy Resources*. http://www.worldenergy.org/publications/3040.asp.
[9] Laherrère, J.H. 2010. Personal communication with author. December; bio at www.oilcrisis.com/laherrere/bio.htm, see recent talks at aspofrance.viabloga.com/texts/.
[10] Pollard, S. 1980. "A New Estimate of British Coal Production, 1750–1850," *Ec. Hist. Rev.* **33**(2):212–234 (1980), doi:10.1111/j.1468-0289.1980tb01824.x, kindly provided by Rutledge.
[11] Laherrère, J.H. 2010. Personal communication with author. December; bio at www.oilcrisis.com/laherrere/bio.htm, see recent talks at aspofrance.viabloga.com/texts/.

and liquids derived from other hydrocarbon sources (coal-to-liquids and gas-to-liquids); liquids do not include compressed natural gas (CNG), liquefied natural gas (LNG), or hydrogen.

GAS: ULTIMATE RECOVERY OF 3,700 GBOE (~19,000 TCF)

Taken from a Massachusetts Institute of Technology (MIT) report,[12] the recoverable mean includes unconventional gas such as shale gas, but not methane hydrates[13]. The number is larger than Laherrère's 13,000 Tcf. Because natural gas does not yet exhibit a clear historic period of decreasing annual production, curve-fitting is not directly applicable, so RMI used the MIT study's recovered reserves; this number is significantly larger than that suggested by Laherrère, but is less than half of IPCC's.

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[12] Massachusetts Institute of Technology. 2010. *The Future of Natural Gas: An Interdisciplinary MIT Study*. Massachusetts Institute of Technology. http://web.mit.edu/mitei/research/studies/naturalgas.html.
[13] Pollard, S. 1980. "A New Estimate of British Coal Production, 1750–1850," *Ec. Hist. Rev.* **33**(2):212–234 (1980), doi:10.1111/j.1468-0289.1980tb01824.x, kindly provided by Rutledge)