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Emergy analysis of emerging methods of fossil fuel production

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ABSTRACT

The production of energy from unconventional sources of fossil fuels, (e.g., tar sands, shale or sandstone formations where oil or natural gas is tightly bound), is forming an increasingly large proportion of global energy use. This research evaluates three of the most prominent emerging methods of fossil fuel production—oil from oil/tar sands, shale oil and shale gas, both produced through hydraulic fracturing. In 2013, 42% of natural gas production and 41% of oil production in the United States was produced through hydraulic fracturing and ~60% of new oil and gas wells use the method. In 2013, the Alberta region of Canada produced 1.7 million barrels per day of synthetic crude oil from oil sands, exporting 1.3 million barrels to the US every day, comprising ~7% of daily US oil consumption. Results from this work show that natural gas obtained through hydraulic fracturing has an emergy yield ratio (EYR) between 4.23 and 9.18, depending on well productivity and whether the gas is "wet" (contains other hydrocarbons) or "dry" (pure or nearly pure methane). Synthetic crude oil from oil sands was found to have an EYR of 3.38–4.06 (in situ vs. mined production, respectively). The EYR of tight oil was found to be 3.43–4.73, dependent on the productivity of the well. Given the relatively high current market price of oil and relatively low market price of natural gas the observed results (i.e., similar or higher EYR for natural gas than past observations and a lower EYR for oil than past observations) are expected.

1. Introduction

As traditional fossil fuel reserves and rates of production begin to decline around the world the deficit is being made up for through "unconventional" methods of acquiring fossil fuels. Global production of oil has increased by 3.1 million barrels per day (mbpd) since 2008, but production of oil from OPEC (Organization of the Petroleum Exporting Countries) has fallen by 0.7 mbpd and production from all nations other than the US and Canada has fallen by 1.0 mbpd over that time period (Kopits, 2014). This drop has largely been made up for by an increase of 3.0 mbpd in the U.S. and 0.9 mbpd in Canada since 2008 (EIA, 2014; CAPP, 2014). The increase has been nearly entirely comprised of oil produced through hydraulically fractured wells in the U.S. (i.e., "tight" or "shale" oil) and extraction of oil from oil sands (i.e., "tar" sands) in Canada. It should be noted that "oil" sands can be used interchangeably with "tar" sands, although tar sands is often used as a pejorative so this document will use oil sands. "Tight" oil/gas will be used interchangeably with "shale" oil/gas.

When considering the potential utility of an energy resource two important aspects must be accounted for: the quantity of resource and how efficiently the resource can be exploited. This research addresses the latter aspect, using environmental accounting to quantify the net benefit being provided by three sources of unconventional fossil fuels. Environmental accounting (i.e., emergy synthesis) is an appropriate method for evaluating energy alternatives; it allows the work of the environment, humanity, and nonrenewable resources to be put on the same baseline and considered together (see Brown and Ulgiati, 2004 for additional information on emergy). When only considering energy or money the work of the environment is not considered and the value of the non-renewable resource is only partially realized (the economy only values the work to extract the energy, and energy accounting does not consider the work required for resource formation).

Previous work (Odum, 1996)[1] has suggested that unconventional methods of fossil production have comparatively low emergy yield ratio's (EYR, the primary measure used in environmental accounting to suggest viability of an energy resource) when compared to traditional methods of oil and natural gas production. However, the recent trend of rising energy costs (in the case of oil

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[1] Odum 1996 included analyses of oil shale and oil sands but did not analyze hydraulic fracturing for natural gas or oil.

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Nomenclature

Emergy	The available energy (exergy) of one kind that is used in the transformations directly and indirectly to make a product or service.
Emjoules	The unit of emergy accounting. Sunlight, fuel, electricity, and human service and all other resource flows can be put on a common basis by expressing them in the emjoules of solar energy required to produce them.
Transformity	The ratio of emergy input to available energy (exergy) output. The solar transformity of sunlight absorbed by the earth is defined as 1 sej/J.
Specific emergy	The emergy per unit mass output. This is usually expressed as solar emergy per gram (sej/g).
Emergy per unit money	The emergy supporting the generation of one unit of economic product (expressed as currency). The average emergy/money ratio (sej/$) can be calculated by dividing the total emergy use of an economy by its gross economic product (e.g., GDP), known as the Emdollar Ratio.
Empower	The flow of emergy per unit of time. Emergy flows are usually expressed in units of solar empower (i.e., sej/yr).
Emergy Yield Ratio (EYR = Y/F)	Emergy yield produced ($Y = R + N + F$) per unit of emergy contributed from the economy (F) (sej/sej).

sands and shale oil) and technological advancements/discovery (in the case of shale gas) have made exploitation of these resources financially viable (EIA, 2014).

The primary goal of this research is to use emergy analysis (i.e., environmental accounting) to evaluate the three prominent unconventional fossil fuels—oil sands, tight oil, and tight gas, answering the questions of the degree to which these fuels contribute net emergy to society and how these resources compare to previous estimates of fossil fuel emergy yield. The net yield of emergy is of primary importance in evaluating fuel sources because it indicates the contribution the fuel source is making to the greater economy/society. Fuel sources with higher EYR can support more economic activity and a more complex societal structure (Odum, 1996). Essentially, fuel sources with higher EYR's provide a greater "energy surplus" than lower EYR energy sources, meaning there is more energy available for supporting societal structure after accounting for what is needed to extract, process, and transform the energy source to a useful state.

Beyond the net contribution these energy resources are providing, the pertinent question, giving context to this analysis, is the quantity of these unconventional fossil fuels in the ground. Fossil fuels have declined in their net benefit over time (Guilford et al. (2011), measured by EROI, energy return on investment) as the most accessible resources are exploited first and remaining resources require increasing investment to acquire. The algorithm determining proven reserves takes into account both what exists in the ground with reasonable certainty (i.e., 90%) and what can be recovered economically given current market price and technology (EIA, 2012; EIA, 2014). This is the most restrictive definition of reserves, with "technically recoverable" and "estimated ultimate recovery" (EUR) reserve estimates being much more inclusive, but also speculative, relying on imprecise projections of future discoveries. Past being precedent, yield of fossil fuels will decrease over time, along with the EYR of fossil fuels produced.

Recent economic growth has separated from the ratio of GDP growth to fossil fuel use seen in the previous century (Kopits, 2014). Prior to 2004 oil demand increased at 75% of the rate of GDP growth. From 2004–2013 global GDP has risen by 39%, while Oil demand has only risen 7.5%, 20% of the rate of GDP increase. Essentially, this implies that the economic growth experienced over this period was largely not based in "real wealth", i.e., tangible benefits to society like built infrastructure.

No work on the net contribution of a fuel source can be complete without, at minimum, acknowledging the finite nature of fossil fuel reserves and that they are in the process of being exhausted. It is only because more readily accessible, higher net energy/emergy fossil fuels have been exploited that the unconventional sources evaluated here have started to be utilized. These resources have already begun to have an impact on "peak oil" or "peak energy", extending the timeline for when these events are thought to occur. Recent work by Hughes (2013) projects shale resources in the United States, predicting a peak in tight oil production at 2.4 million barrels per day in 2017 and a peak in domestic shale gas production in approximately 10 years (~2023). Both shale gas and oil wells tend to produce the majority of their resource within the first four years (~60%) and decline rapidly, producing the remainder over 10–15 years. There are more than 30 shale gas "plays" (producing regions) in the United States, but the top six account for over 80% of production, and of those six only two are increasing production, the Marcellus (3rd largest) and Eagle Ford (5th) (Hughes, 2013). The Marcellus region is highlighted in this work because it is projected to have the largest increase in future production.

2. Methods

2.1. System description

Emergy analysis accounts for the cumulative energy used in generating a good or service in a studied system. In this case, the three studied systems are an average hydraulically fractured well for natural gas in the Marcellus shale region of the United States (Fig. 4), with processed natural gas being the end product an average hydraulically fractured well for oil in the United States, and 1 barrel of synthetic crude oil produced from oil sands in Alberta, Canada. Figs. 2 and 3 depict the energy systems language diagrams of the hydraulic fracturing and oil sand extraction processes, respectively. We base the emergy of fossil fuel formation considered in this work on Bastianoni et al. (2005). The yield evaluated for natural gas is the average amount of natural gas derived from a hydraulically fractured well in the Marcellus shale geologic region of the United States (Marcellus shale underlies