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Energy Return on Investment (EROI) of China's conventional fossil fuels: Historical and future trends

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ABSTRACT

One of useful metrics for analyzing the production of fossil fuels in China is Energy Return on (Energy) Investment (EROI). Various measures of this index are declining. The EROI for China's oil and natural gas production sector fluctuated from 12 to 14:1 in the mid-1990s, and declined to 10:1 in 2007–2010. EROI for the coal production sector has declined from 35:1 in 1995–1997 to about 27:1 in 2010. We used a multi-cyclic generalized Weng model and a linear trend extrapolation method to predict that the EROI of either sector will continue to decline until 2020. We predict that the average $EROI_{stnd}$ for oil and natural gas extraction will be about 10:1 in 2015, 9:1 in 2020, and that for the coal production sector will be about 28:1 in 2015, 24:1 in 2020. EROI for coal extraction are and will continue to be higher than that for oil and natural gas extraction, indicating that coal is likely to continue being the most dominant fossil fuel resource for China in the future, ensuring some degree of energy security.

1. Introduction

EROI (Energy Return on Investment) is a method to calculate the energy returned to the economy and society compared to the energy required to obtain that energy [1]. It is calculated as energy outputs divided by energy inputs used in the same production process. The units of EROI are either dimensionless or maybe Joules per Joule, Calories per Calorie, barrels per barrel etc. EROI is one measure of the value of an energy production system which allows one to evaluate the energy production physically rather than monetarily. It is a good indicator when one deals with the same type of energy in the input and the output, e.g. how much fossil fuels are used to produce one joule of renewable energy. It can be modified to reflect differences in quality of input and output energies. Because it evaluates the efficiency of energy extraction and production, and it gives a sense of the net energy useful to society obtained from a resource reserve, rather than simply accounting for the gross energy it contains.

The concept of net energy can be found in anthropology, describing the importance of energy to the degree of cultural development [2]. EROI as a concept originated from ecology [3], and it was implicit in Hall and Cleveland's 1981 paper on petroleum yields per effort although the term net energy was not used there. The first publication that used the term EROI was Hall et al. in 1981 [4], and it subsequently received significant attention in the journal Science [5] and a subsequent book [6]. In recent years, many researchers and public officials have shown considerable interest in EROI. Almost all current analyses have shown that the EROI for conventional oil and natural gas is high but decreasing [7–10]. Most of EROI results for alternatives, including oil shale [11], wind [12] or bio-fuels [13–15] have a large range due for example to the inconsistent boundaries used between studies [16] and whether corrections for the quality of energy are employed [17].

Changes in EROI have important implications to society. Hall [1] calculated the EROI hierarchy for energy use, and gives the following descriptions:

> "*Think of a society dependent upon one source: its domestic oil. If the EROI for this oil was 1.1:1 then one could pump the oil out of the ground and look at it. If it were 1.2:1 you could also refine it and look at it, 1.3:1 also distribute it to where you want to use it but all you could do is look at it … if the energy included was enough to build and maintain the truck and the roads and bridges required to use it (i.e., depreciation), one would need at least a 3:1 EROI at the wellhead. Now if you wanted to put something in the truck … and deliver it that would require an EROI of, say, 5:1. If you wanted to include depreciation on the oil field worker, the refinery worker, the truck driver and the farmer you would need an EROI of say 7 or 8:1*

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to support the families. If the children were to be educated you would need perhaps 9 or 10:1, have health care 12:1, have arts in their life maybe 14:1 and so on."

EROI and net energy for oil and other fuels need to be calculated for different regions, countries and fields [18]. However, currently there exist no published papers on the EROI of China's conventional fossil fuels, even though China is the largest producer and consumer of coal in the world by far, accounting for almost half of the world's total coal consumption [19]. Coal use meets about 70% of China's total energy needs [20]. If the Chinese economy continues to expand the way it has in the last decade, China's annual coal production would inevitably decline. However, most Chinese government officials do not seem worried about the coal supply even though in recent years China has had to face a rapid increase in coal prices. China is the fifth largest producer and the second largest consumer of oil in the world [19]. Oil currently represents 20% of China's total energy consumption. As its onshore oil fields mature, the country is increasingly turning towards buying international oil assets, and drilling offshore, the latter creating conflict with countries sharing ownership of the South China Sea. Meanwhile, China is the seventh largest conventional natural gas producer in the world, and tenth in terms of consumption. As a fossil fuel, natural gas is also limited and non-renewable, and will also have a production peak.

2. Methods

Our objective is to analyze patterns in EROI for Chinese conventional fossil fuels and predict what these will be in the future. We calculated EROI using the standard method of EROI given by Murphy et al. [21] and projected the amount of fuels delivered to the Chinese society from fossil fuels by extrapolating trends in EROI in conjunction using Weng's peak production model and several different estimates of the Ultimate Recoverable Resource (URR).

2.1. Time series EROI

2.1.1. Standardization of EROI analysis

The basic equation for calculating EROI is as follows [21,22]:

$$\mathrm{EROI} = \frac{\text{Energy return to society}}{\text{Energy required to get that energy}} \tag{1}$$

However, some previous EROI analyses have generated a wide variety of results, even when applied to the same energy resource. The reasons behind these differences were not limited only to intrinsic variations in energy resources quality, extraction technology, varying geology, and geography; but also include methodological issues. Common methodological problems in EROI analysis include: (1) different boundaries of analysis; (2) different methods used to estimate indirect energy inputs (including monetary expenditure converted into energy using different assumptions), and (3) issues related to energy quality, e.g. should different forms of energies be weighted differently because of different physical characteristics and different economic utility (e.g. electricity vs. coal).

In an attempt to formalize the analysis of EROI and to reduce or at least understand the discrepancies, Mulder and Hagens [23] put forward a consistent framework for EROI analysis. Murphy et al. [21] proposed a more explicit standard formula, $\mathrm{EROI}_{\mathrm{stnd}}$, and they used a two-dimensional framework for EROI analysis. The horizontal dimension is "what do we count as energy outputs?" and uses three system boundaries: mine mouth, refined fuel and costs up to and including point of use. The vertical dimension is "what do we count as inputs?" which they divide into five levels (see Table 1).

Table 1
Two-dimensional framework for EROI analysis.

Levels for energy inputs	Boundary for energy outputs		
	1. Extraction	2. Processing	3. End-use
Direct energy and material inputs	$\mathrm{EROI}_{1,d}$	$\mathrm{EROI}_{2,d}$	$\mathrm{EROI}_{3,d}$
Indirect energy and material inputs	$\mathbf{EROI_{stnd}}$	$\mathrm{EROI}_{2,i}$	$\mathrm{EROI}_{3,i}$
Indirect labor consumption	$\mathrm{EROI}_{1,lab}$	$\mathrm{EROI}_{2,lab}$	$\mathrm{EROI}_{3,lab}$
Auxiliary services consumption	$\mathrm{EROI}_{1,aux}$	$\mathrm{EROI}_{2,aux}$	$\mathrm{EROI}_{3,aux}$
Environmental consumption	$\mathrm{EROI}_{1,env}$	$\mathrm{EROI}_{2,env}$	$\mathrm{EROI}_{3,env}$

In Table 1, the numbers "1", "2", and "3" describe the boundary for energy analysis, i.e. where the analysis is terminated (mine mouths, refinery or point of use), while the letters and abbreviations "d", "i", "lab", "aux", or "env" refer to the different types of inputs considered: direct energy used on site, indirect energy used to purchase material inputs constructed offsite such as steel forms and pipes, embodied energy in the wages of labor, energy afforded by governmental services in the public sector, and energy embodied in environmental costs for assessment. $\mathrm{EROI}_{\mathrm{stnd}}$ represents the direct and indirect energy inputs and outputs from boundary 1.

2.1.2. Formulas for EROI

Most EROI analyses account for both direct and indirect energy inputs, but not for labor or environmental costs. For this reason, Murphy et al. [21] named the ratio between energy outputs at the mine mouth and direct plus indirect energy inputs as the "standard EROI" (see $\mathrm{EROI}_{\mathrm{stnd}}$ in Table 1, second row). Other approaches (e.g. including labor) can be done as a sensitivity analysis, which is seeing how changing variables affect the outcome. Using the "standard" calculation, we have the following equation:

$$\mathrm{EROI}_{\mathrm{stnd}} = \frac{E_o}{E_d + E_i} \tag{2}$$

The challenge is that the indirect energy inputs are rarely available as physical energy units. Rather, the data is available in monetary units as e.g. investments in industrial equipment. Thus we employ Eq. (3), to complete the EROI analysis:

$$\mathrm{EROI}_{\mathrm{stnd}} = \frac{E_o}{E_d + (M_i \times E_{ins})} \tag{3}$$

where M_i expresses indirect inputs in monetary terms and E_{ins} is the energy intensity of a dollar inputs for indirect components.

The above equations give the energy performance metrics for a single point in time (like an annual balance sheet), but it is usually more interesting to generate results to evaluate the dynamic productivity of an energy supply process over time. One difficulty with this type of time series analysis is assigning the period over which inputs generate outputs. Usually the energy outputs data should be for the same period as that of energy inputs. Some of the fuel produced at a given time came from investments long ago, and today's investments are likely to be generating fuel well into the future. In reality, the largest part of costs is for immediate production (such as natural gas used to pressurize or pump an oil field) or the constant maintenance and replacement of equipment that has worn out over the past years. Therefore, in time series EROI calculations, it usually makes sense to simply compute energy costs and gains on an annual basis.

2.1.3. Energy conversion

It is easy to convert physical energy units to joules because they have a fixed, if approximate, conversion factor (see Table 2). Different grades of fuels may vary considerately from the average.