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Modeling the point of use EROI and its implications for economic growth in China

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ABSTRACT

Energy return on energy invested (EROI) might be considered a measure of net energy, and most current studies focus on standard EROI ($EROI_{ST}$). If the energy inputs required to obtain a fuel was extended from a wellhead to the point of use, the energy delivered decreases, and the energy input of delivering the fuel increases. These factors combine to reduce the $EROI_{ST}$ to what is referred to as the point of use EROI ($EROI_{POU}$). This study calculates the direct and indirect energy (embodied energy) inputs for energy production sectors (including extraction, processing and delivery) by means of an Input-Output table to calculate China's $EROI_{POU}$ and the net energies from 1987 to 2012. Based on calculations in this study, the $EROI_{POU}$ of China's energy production sector declined from 11.01:1 to 5.26:1 between 1987 and 2012. In 1987, the energy production sectors consumed 1 ton standard coal equivalent (TCE) energy inputs for every 10.01 TCE of produce net energy. However, in 2012, this number declined to 4.25. Additionally, this study simulates and forecast economic Gross Domestic Product (GDP) trends in China using net energy production function. The results reveal how declining $EROI_{POU}$ for Chinese fossil fuels influence China's GDP growth.

1. Introduction

Energy production sectors (including energy extraction, processing and delivery) require energy inputs (also known as energy costs) from themselves for energy outputs because a significant amount of energy is needed for processing. An approach that does not consider the costs of energy (including energy inputs) cannot provide a proper assessment of energy consumed at the final end (i.e., the point of use). A comprehensive evaluation should focus not only on energy resources but also on both the energy input that is part of the energy production process and the net energy contribution to this process, particularly the impact of its size on the economic system [1].

Energy return on investment (EROI) is a concept that originated in ecology [2] and represents the ratio of the energy output to the energy input during the process of energy production [3]. This metric, which evaluates energy and its related problems from the perspective of the “ratio of net energy”, transforms the gross energy by positing that what is important to society is the available net energy [4]. Economic development is actually supported by net energy, as opposed to gross energy, because energy is used in the production of energy itself. The EROI is significant in both theory and reality because net energy supports economic development. However, net energy is associated not only with extraction but also with the entire energy industry (including the energy extraction, processing and delivery sectors) that delivers useful energy to a location at which it is used to generate economic goods and services.

In recent years, significant research has been performed on EROI, but these studies have tended to not be comparable with one another because the difference between the boundaries is the most important and most easily overlooked variable. Most research on EROI involves calculations based on the extraction of fossil energy; however, net energy is influenced not only by extraction but also by the entire energy industry chain. For example, when the EROI of extraction decreases, the EROI of the entire energy industry chain may nonetheless be decreasing, stable or increasing based on the technological development status (the determinants of EROI include a technological component and a physical depletion component [5]). Hall further clarified the boundaries used in EROI calculations into the following categories

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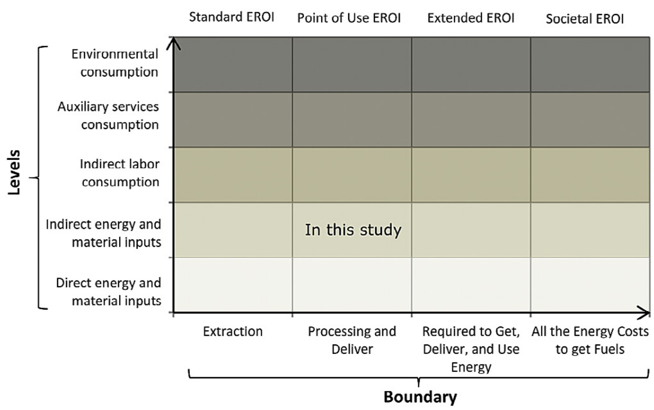

Fig. 1. Different boundaries used to calculate the different EROIs.

[6,7]: standard EROI ($EROI_{ST}$), point of use EROI ($EROI_{POU}$), extended EROI ($EROI_{EXT}$), and societal EROI ($EROI_{SOC}$). The calculation of the $EROI_{ST}$ divides the energy output for a project, region or country by the amount of energy used to generate that output per year. The $EROI_{POU}$ is more comprehensive than the EROI because the $EROI_{POU}$ includes the energy consumed in extracting, processing and delivering the energy. The $EROI_{EXT}$ is an expanded analysis that considers the energy required not only to extract but also to consume the energy at the final end use of a unit of energy.(see Fig. 1).

Hall [8] gives the following description:

> “A reasonable question is what would be the EROI of a fuel at the point where it is used, since there may be very different efficiencies for different fuels between the source and the point at which it is used. Unfortunately, such studies are rare, and we must remember to always start with a source of energy from nature.”

A lower EROI value indicates that a smaller ratio of net energy is provided for the socio-economic system that is defined outside of the boundary of the EROI analysis. Using a gross output of 100 units of energy, if, for example, the EROI is 1.2:1, only 16.7% of the gross output can be consumed [9]. Lower net energy describes numerically greater input and thus less net energy remaining to power society after fossil energy extraction, processing and delivery. Unsurprisingly, lower net energy negatively affects whether the economy continues to grow. Researchers generally study the connection between economic growth and the gross energy supply as opposed to the net energy [10–13]. However, considering the long-term structural scarcity in net energy supplies, the energy cost of obtaining the energy is necessary to calculate the energy constraints on economic growth. Thus, net energy plays an important role in spurring economic growth.

This study aims to build a model to calculate the $EROI_{POU}$ from embodied energy perspectives in China. Next, using a simulated production function, predicts the effects of $EROI_{POU}$ changes on China's economic growth from 2016 to 2030 (flowchart see Fig. 2).

2. Methods and data

2.1. Modeling point of use EROI with embodied energy analysis

2.1.1. The relationship between net energy and EROI for fossil fuels

The basic equation for EROI is as follows:

$$\mathbf{EROI} = \frac{\textbf{Energy Output}}{\textbf{Energy Input}} = \frac{\textbf{Total Primary Energy Supply}}{\textbf{Energy Required to Get That Energy}} \tag{1}$$

The EROI is defined as the total energy output divided by the sum of all direct and indirect energy inputs, the energy output is the energy returned to society and the economy, and the energy input is the energy required to acquire that energy [6]. The energy input includes direct and indirect energy, i.e., the energy “embodied” in the energy production process or “embodied energy”. “Embodied” indicates the sum of all goods and services (direct and indirect) that are required to produce any goods or services considered as if the goods and services are incorporated or “embodied” in the product itself.

Consider the case of a single fuel in which this fuel is used by the entire economic system. The baseline variables are *F*, *G* and *C*. Variable *F* is the total primary energy supply by the entire economy. *G* represents the final energy consumption at the point of use that also could be defined as the net energy that is used at the final end. *C* is the sum of all energy inputs in each energy production sector, and this energy cannot be used by the non-energy portion of the economic system (see Equation (2)).

$$G = F - C \tag{2}$$

The definition of the EROI includes the energy inputs necessary to invest in producing the net energy. Thus, the EROI can also broadly be described as the ratio of the energy made available to society through a certain process to the energy inputs necessary to implement this process [14,15].

Notably, much research on EROI involves calculating the oil and gas field extraction processes and does not include final use at the end, which can lead to a problem, i.e., the EROI and net energy will be overestimated. The EROI has primarily been used to estimate changes in the net energy productivities of oil and gas fields [16–18]. However, the energy inputs not only include oil and gas extraction but also include separation, washing, coking, and transport. Many studies on EROI find it difficult to calculate the net energy at the point of use because the input data for fossil fuels are difficult to collect.

A metric can be defined in this study that is calculated at different boundaries if “delivered to society” as the total energy consumption (i.e., the net energy plus what is used in the energy production sectors) and assume that the energy “used in the energy production sectors” is the sum of the energy inputs of the energy extraction, processing and delivery sectors. Based on these definitions, the ratio of the energy production sectors EROI (point of use EROI) is

$$\mathbf{EROI_{POU}} = \frac{\sum_{i=1}^{n} \mathbf{F_i}}{\sum_{i=1}^{n} \mathbf{C_i}} = \frac{\sum_{i=1}^{n} \mathbf{F_i}}{\sum_{i=1}^{n} \mathbf{F_i} - \sum_{i=1}^{n} \mathbf{G_i}} \tag{3}$$

where $EROI_{POU}$ is the point of use EROI of all energy sectors, and the net energy from all primary energy is $\sum_{i=1}^{n} G_i$. $\sum_{i=1}^{n} F_i$ is the total energy used by the entire economy (including the energy used in extraction, processing and delivery). The variable *i* represents the different types of energy. $\sum_{i=1}^{n} C_i$ represents all the types of energy inputs in the different processes throughout the entire energy industry chain. Therefore, the equation of net energy can be derived as follows: