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Emergy-based energy return on investment method for evaluating energy exploitation

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ABSTRACT

To consider the environmental impacts of energy resource exploitation and better estimate the energy return of investment (EROI), this paper establishes a new emergy-based method (EmEROI) that can capture the essence of energy resource exploitation. The EmEROI method treats environmental impacts and labor as particular forms of energy, and all forms of energy can be quantified by solar transformity, which is expressed in emjoules as a common unit. The Daqing oilfield is used as an example, and the corresponding EmEROI value is calculated via the proposed method. The results are then compared with standard EROI estimates. Our EmEROI result is much lower than the standard EROI result and presents a more pronounced declining trend. Our results also indicated that the EmEROI estimates conform well to actual conditions and are not as affected by industrial energy intensity levels as the standard EROI. Thus, EmEROI has the potential for use as an integral aspect of energy resource exploitation project evaluations.

1. Introduction

Historically, the development of modern society has predominantly been fueled by the use of conventional hydrocarbons [1]. The continued growth of conventional oil outputs represents a growing challenge, and peak conventional oil outputs have essentially been reached [2,3]. In the wake of this phenomenon, producers have shifted to the use of unconventional petroleum resources. In particular, the “*shale revolution*” occurring in the USA represents a clear illustration of the changing oil supply landscape. Unconventional oil differs greatly from conventional oil in terms of reservoir characteristics, processing and mining methods, energy quality levels and other aspects [4,5]. Considerable environmental impacts and high costs of shale gas exploitation aggravate the contradiction between energy resource exploitation and environmental protection. As a result, the suitable handling of environmental and energy efficiency issues in the evaluation of energy resource exploitation has become increasingly important [6,7].

Current economic evaluation methods, such as the discounted cash flow method and real option method, use economic benefits as a sole criterion and pursue the maximization of economic benefits [8–11]; thus, these evaluation methods have been criticized by scholars because of their inadequate consideration of environmental impacts and energy efficiency concerns. For example, economic evaluations of oil and gas fields merely focus on fuel prices while failing to consider the environmental impacts of fuel consumption [11–13]. Coal-to-liquids (CTL) constitute another example. Financial analyses of CTL plants are largely unconcerned with process energy efficiency levels, which can be as low as 30%–50% [14]. Therefore, more holistic methods that consider economic, energy-focused and environmental perspectives are needed for energy project assessments.

Several methodologies consider economic factors, environmental impacts and energy efficiency issues simultaneously, such as environmental input-output (I/O) methods, life cycle assessments (LCA) and various multi-criteria analysis methods [15–17]. However, increased levels of complexity arising from the need to consider the entire life cycle constitutes a major drawback and constrains practical applications of such models. For example, LCA can be defined as “*the compilation and evaluation of the inputs, outputs and potential environmental impact of a product system throughout the life cycle*” [18]. A life cycle inventory (LCI) of all inputs and outputs for the entire life cycle is estimated according to the chosen system boundaries and methods [19]. LCA frequently

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include impacts that are not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.) [20–22], and cumulative energy demand (CED) or embodied energy is a frequently used performance metric that describes the total amount of primary energy that must be extracted from the environment to deliver a product or to support a process. In general, LCA involve the use of a large amount of scientific and reliable statistical data as well as materials and details on each stage of the entire life cycle, thereby constraining practical applications of this method.

An energy company represents a social operating unit based on energy resources, and its fundamental role is to provide energy from a social development perspective. Because the true value of energy is represented by the net energy value, net energy analysis (NEA) methods have been proposed as a method of studying energy systems [23]. The energy return on investment (EROI) approach is one of the most suitable methods of measuring net energy [24], and EROI methods are more frequently mentioned in the literature than NEA methods. The energy investment derived from NEAs is related to the CED obtained from LCA, and the CED is used to determine the EROI, although supply chain losses and other adjustments must be made [25]. Therefore, to understand how effective a system is or the level of environmental impact a system has in terms of exploiting societal energy uses to upgrade environmental stocks and flows into societally useful forms, we need to conduct only a partial LCA when evaluating energy resource exploitation. However, this process creates a problem regarding the calculation of the EROI. Although the EROI method takes environmental impacts into consideration in theory [26], most studies using the standard EROI method merely consider direct and indirect energy inputs [26–30].

In this article, we extend the EROI concept by combining it with an emergy analysis, and the result is a fairly simplistic energy-centered evaluation method that can be used to conduct holistic assessments of environmental impact and energy efficiency. The method is tested using empirical data on the Daqing oilfield in China. The remainder of the paper is organized as follows. Section 2 presents a literature review. Section 3 presents the emergy-based EROI evaluation method. Section 4 describes our case study of the Daqing oilfield to show the feasibility of the method, and Section 5 concludes the paper.

2. Literature review

2.1. EROI theory

The EROI represents the energy gained from an energy-obtaining effort divided by the energy used to obtain this energy, and the results are used to measure the net energy level [31,32]. Net energy is the amount of energy left over from the gross energy extracted (and processed and delivered) from a primary energy source (or a mix of PES) after the energy needed to sustain extraction, processing and delivery processes has been subtracted [33].

In 1955, Cottrell proposed the "*net energy production*" principle and noted that a portion of the total energy production is focused on energy resource development while the remainder contributes to societal and economic development [34]. The latter is "*net energy production,*" which is also known as the "*energy surplus*" as shown in Fig. 1. In 1973, Odum proposed a similar definition of net energy [23]. In the United States, net energy was given a legislative imprimatur through the "*Federal Non-nuclear Energy Research and Development Act of 1974,*" which resulted in a flurry of net energy studies [29]. In 1975, Gilliland published an article praising the EROI concept for its merits in relation to public policy [24]. In 1984, Cleveland et al. proposed a theoretical formalization of the EROI as the ratio of gross fuel extracted to economic energy directly and indirectly needed to deliver fuel to society in a useful form [35].

Recently, a number of EROI studies have been performed with a focus on fossil fuel depletion and measuring renewable energy quality levels. Examples of such studies are shown in Table 1, and further information on these studies can be found in Hall et al. [28] and Xu et al. [36].

From an energy economics perspective, the EROI can be viewed as equivalent to the "*ore grade*" in mineral resource economics and has the advantage of being a physical measurement with uniform units across different energy sources [41]. Hall et al. concluded that declining EROI values of primary fuels have had a considerably negative economic impact [28]. Lambert et al. concluded that when

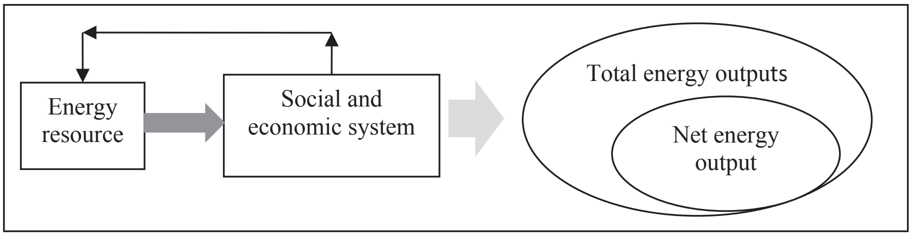

Fig. 1. Relationship between total energy output and net energy output.

Table 1
Published EROI values for various fuel sources and regions.

Resource	Year	Country	EROI	Reference
Oil and gas	1990	USA	16	Guilford et al. [37]
Oil and gas	2010	USA	10	Guilford et al. [37]
Oil and gas	1996	China	14	Hu et al. [32]
Oil and gas	2011	China	11.5	Hu et al. [32]
Coal	1996	China	35	Hu et al. [32]
Coal	2011	China	27	Hu et al. [32]
Tight gas	1960s-1980s	Pennsylvania, USA	87	Sell et al. [38]
Tight gas	2003	Pennsylvania, USA	67	Sell et al. [38]
Wind energy	n/a	Global	20	Kessides and Wade [39]
Solar energy	n/a	Global	5.4–10	Kessides and Wade [39]
Wind turbine	n/a	n/a	18	Kubiszewski et al. [40]