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Energy return on (energy) invested (EROI), oil prices, and energy transitions

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ABSTRACT

Very little work has been done so far to model, test, and understand the relationship between oil prices and EROI over time. This paper investigates whether a declining EROI is associated with an increasing oil price and speculates on the implications of these results on oil policy. A model of the relationship between EROI and oil market prices was developed using basic economic and physical assumptions and non-linear least-squares regression models to correlate oil production price with EROI using available data from 1954–1996. The model accurately reflects historical oil prices (1954–1996), and it correlates well with historical oil prices (1997–2010) if a linear extrapolation of EROI decline is assumed. As EROI declines below 10, highly non-linear oil price movements are observed. Increasing physical oil scarcity is already providing market signals that would stimulate a transition away from oil toward alternative energy sources. But, price signals of physical oil scarcity are not sufficient to guarantee *smooth* transitions to alternative fuel sources, especially when there is insufficient oil extraction technology development, a declining mark-up ratio, a non-linear EROI–cost of production relationship, and a non-linear EROI–price relationship.

1. Introduction

The economical and sustainable provision of energy to run modern economies and meet human development goals (UN, 2000) is one of the Grand Challenges facing the world today (NAE, 2008). However, an emerging consensus indicates that physical scarcity of energy resource supplies is, or soon will be, upon us, in the absence of a concerted effort to develop and implement fossil fuel substitutes (Brandt, 2007; Hubbert, 1956; Nashawi et al., 2010; Sorrell et al., 2010). Friedrichs (2010) reviewed case studies of nation-states that experienced energy supply shortages and noted many possible responses, including predatory militarism, totalitarian retrenchment, and socioeconomic adaptation. The energy supply shortages that trigger such responses deserve closer scrutiny.

One proposed physical indicator of energy supply scarcity is *energy return on* (*energy*) *invested* (EROI), which, like its well-known financial counterpart *return on investment* (*ROI*) is a ratio of outputs to inputs (Cleveland et al., 1984). We define EROI as the ratio of gross energy delivered by an energy production process to input energy required to obtain that gross energy. Basic economic theory leads to the expectation that a declining EROI may be associated, all other things such as costs of capital, labour, and technology being equal, with a increasing marginal costs of production and, ultimately, an increasing price at which the commodity (energy) is traded.

Despite some very useful work on EROI (as discussed below), investigations of the interactions between physical indicators (such as EROI) and economic indicators (such as oil prices) are in short supply. Furthermore, very little has been done to determine if price signals of physical scarcity will be sufficient to cause transitions to alternative fuel sources. Finally, the speed and orderliness of such transitions is of the utmost importance for policy makers, yet there is little work available on the topic of EROI and energy transitions. The questions addressed in this paper are as follows:

- "How is EROI related to energy prices?"
- "What implications do EROI trends over time have for economic and energy policy?" and
- "What is required to ensure a smooth transition away from oil toward substitutes?"

After reviewing the available literature on these topics, we analyse the interactions between EROI and oil pricing in the markets, through a combination of historical data analysis, mathematical modelling, and statistical analysis. We then compare the models with recent market price data to show good correlation. We end by indicating policy implications and discussing transitions.

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2. Literature review

We begin with the relationship between physical scarcity of energy resources and market prices of energy commodities, as documented in the literature. We focus on oil, because it is most often cited as facing physical scarcity in the coming decade. The resource economics literature emphasises the important roles of supply, demand, and prices in the allocation of resources (Sweeney, 1993). Every market has different factors that affect supply and demand, but generally it is expected that increasing physical scarcity is associated with rising prices, all other things being equal (Sweeney, 1993). This means that current prices play an important role in the evaluation of the future of the energy market. The EROI literature, however, doubts this claim and argues for the use of a separate physical indicator in the evaluation of the energy market future. The rationale in the EROI literature for the use of EROI as an indicator for physical scarcity is a deep suspicion that market signals and cost-benefit analyses based on current prices are insufficient to guide decisions about future energy markets (Hall et al., 2009).

In the next section we briefly review the literature on the oil market, focused on the forces of demand and supply, and the interactions between them. We continue with an overview of the problems of these markets and review the arguments for the development of EROI as a physical indicator of the contest between scarcity and technology. We conclude that the relationship between prices and EROI needs to be empirically tested as this has not been done to date.

2.1. The oil market and signals of physical scarcity

In the oil market specifically, global oil production rates were stable in the 2000s and failed to grow as demand increased and prices rose during the period 2005–2007 (Hamilton, 2009). This combination of increasing demand and flat production led to oil price increases in recent years (Hamilton, 2009). When price increases are the result of rising demand rates in the context of stagnant production rates, the relationship between physical scarcity and the rising marginal cost of production may be an important driver. This warrants further research into the permanence and expected impact of this scarcity over time.

Before turning to the literature on EROI addressing this issue of physical scarcity, the question remains whether oil prices are a reliable indicator of what is happening in oil markets. In the market for gasoline and crude oil, for example, price is strongly influenced by both supply and demand factors. The present value of depletable resources such as oil is based on price expectations going forward. Price expectations are based on historical and spot prices. Efficient markets may be a sufficient guide for action, but when no or only patchy information is available and expected prices do not reflect scarcity (user costs), expected extraction costs, and search costs, prices are not a sufficient guide for making decisions. Energy markets today exhibit significant distortions. Victor (2009), for example, points out that global fossil fuel subsidies amount to US$500 billion annually thereby stimulating over-consumption, undermining energy security, and worsening environmental impacts. Such energy market distortions increase the risk of sudden shocks to the market as new, undiscounted information becomes available.

2.2. EROI as a physical indicator of scarcity

Because it takes energy (usually in the form of diesel fuel and electricity) to make energy available for consumption (as a liquid fuel or electricity), the relationship between energy input and energy made available for use is an important indicator. EROI is defined for an energy production process such as a well or a mine as the ratio of gross energy produced by the process to energy required to run the process. EROI functions as a proxy for the contest between the depletion of fossil fuel energy sources and the development of technology for fossil fuel extraction (Hall et al., 2009) because the "easiest" to reach (in an energy sense) oil and coal deposits are the first to be exploited with minimal energy input. As wells and mines go offshore and deeper, it takes increasingly more input energy to make the same amount of energy available to society, and EROI declines.

Hall et al. (2009) contend that today's market prices do not adequately discount geological (depletion) or political factors, are greatly influenced by various subsidies, and do not adequately account for externalities. Hence, to Hall et al., markets cannot be trusted as an indicator for decision-making. The presumption is that additional decline of EROI will have large economic effects in the future (Hall et al., 2008), especially with looming peak oil dynamics. The important question for this paper is whether the relationship between EROI and market signals, notably prices, has been modelled and tested. This question is especially relevant in the aftermath of the meteoric rise and subsequent fall of oil prices in recent years. King and Hall (2011) started addressing this question by analysing the financial and energy return on investment of energy businesses. Murphy and Hall (2010) reviewed empirical work in the field of EROI during the past few years, but none had a focus on the possible relationship between EROI and market prices. Murphy and Hall speculate on the unlikely prospect of indefinite economic growth in the face of declining EROIs and fossil energy supplies and question the impact of current debt-based fiscal stimulus by governments around the world. Such speculation places further emphasis on the critical importance of understanding the role of market signals for future energy availability and use.

There are very few estimates of global or country-specific EROI values. One of the first estimates of EROI for a country was performed by Cleveland et al. (1984). Cleveland (2005) later estimated the EROI for oil and gas in the United States during the period 1954–1997 and found that a U.S. EROI peak occurred at approximately EROI=25 in about 1970. Gagnon et al. (2009) estimated a worldwide EROI for oil and gas production during the period 1992–2006 and found that a worldwide EROI peak occurred in 1999 at approximately EROI=32. Although EROI cannot be measured easily and little data is available, there is some consensus that EROI for oil and gas has declined substantially from the 1930s up to now (Cleveland, 2005; Gagnon et al., 2009). Hall et al. (2009) estimate that an EROI of 3 or greater is required at the well-head or mine mouth to provide fossil fuels to society, because delivery and use of the fuels consume substantial energy.

A similar but different way to assess the depletion-technology contest comes from a related area of research that focuses on the concept of "Emergy" (Odum, 1996). Emergy is a contraction of the phrase "embodied energy", and its use as a physical concept appears in a wide variety of contexts including ecosystems, material flows, recycling, thermodynamics and policy (Center for Environmental Policy, 2010). In contrast to EROI (which typically focuses on human-produced energy), emergy is quantified by equivalent solar energy. One metric for analysing an energy production system is emergy yield ratio (EYR), which, for an energy production process, is an energy-quality-corrected ratio of energy output to energy input. Brown (2009) shows that EYR has been decreasing for the U.S. economy from 1949 to the present and the EYR for U.S. oil production has decreased from 17 in 1953 to 6 in 2000. Both areas of research are saying the same thing: over time it is costing more energy to get energy. For this paper, we use EROI instead of emergy, because it focuses on human-chosen energy rather than natural embodied energy.