Energy Returns and The Long-run Growth of Global Industrial Society

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ABSTRACT

The extreme interconnectedness of energy and economic systems will tend to confound any attempt to estimate the energy return on investment at anything other than the global scale. Here, I apply a very simple model of global energy use to specify the dynamic characteristics of global-scale Energy Returns On Investment (EROIc). This suggests that the observed long-run relative growth rate of ~2.5% yr⁻¹ in global primary energy use is associated with an equilibrium return from infrastructure investments of 2:1, with returns accruing with a time constant of 40 years. The analysis also attempts to show how growth leads to reductions in the supply efficiency of energy, and how this decline is offset by increases in the efficiency with which industrial society can extract useful work from primary energy flows. This observed preservation of the overall energy efficiency of the global energy system implicates variations in the decay/decommissioning rate of infrastructure in observed ‘long-wave’ like variations in the relative growth rate of global primary energy use, and hence EROIc.

1. Introduction

Because of the way economies co-evolve with their use of energy, it is hard to be precise about the nature of the dependencies between the two (Stern, 2010). However, in standard economic frameworks, energy use is generally assigned around 5% of productivity in line with observed short-term production costs (Dennison, 1979; Ayres and Warr, 2010; Kummel, 2011). This appears to contrast with everyday experience, which suggests that, like food, energy use is central to all socio-economic activity, and if energy was withdrawn, global economic output would cease entirely rather than simply falling by 5% (Ayres and Nair, 1984). The centrality of energy use to the global economy is also underscored by the fact that many of the largest manmade infrastructures on the planet are for energy acquisition, distribution and use, and likewise many of the largest companies in the world (http://fortune.com/global500/list/).

Observations such as these, along with the growing importance of understanding drivers of energy use and resultant greenhouse gas emissions, have encouraged a growing number of researchers to favour placing energy at the heart of their analysis of industrial society. This is also the scale at which the critical impacts of climate change and the required transitions in the global energy portfolio are framed and, as a result, such an analysis might bring some much-needed clarity to an otherwise notoriously complicated but important space. Therefore, although one may sacrifice detail on specific processes at this scale, and some of the...
derived states may become somewhat abstracted from everyday micro-experience, removing internal boundary ambiguities may provide a clearer picture of the systemic drivers of global energy use.

In this paper, I develop a global-scale analysis of energy returns based on recent work by Jarvis et al. (2015). In that work, they present a very simple endogenous growth model that attempts to account for two important observed features of the historic pattern of global primary energy use (GPE): a. that the long-run relative growth rate has been somewhat conserved at $\sim 2.5\% \text{yr}^{-1}$; and b. that the fraction of this energy that is used to acquire and relocate resources has increased as the system has grown. These observations have several important implications for energy return analysis. First, overall rates of return on energy use must be somewhat conserved at the global scale if the relative growth rate of primary energy use is similarly conserved. Secondly, any observed historic declines in specific energy return measures such as EROI (e.g. Murphey and Hall, 2011), may be related to growth-induced increases in resource supply costs, but these declines must be offset by increases in the efficiency of energy use elsewhere in the system, in order to produce a somewhat stationary long-run relative growth rate. Finally, a process experiencing $\sim 2.5\% \text{yr}^{-1}$ growth has a dynamic timescale of 0.025 $\text{yr}^{-1} = 40$ years and, as a result, energy investments on average yield returns over such timescales. Therefore, measures such as EROI need to consider the dynamics operating over these timescales (Dale et al., 2012a). The aim of this paper is to illustrate these three points and relate them to our understanding and management of the global energy system.

The paper is organised as follows: Section 2 sets out the global-scale endogenous growth model. Section 3 then uses this model to develop a dynamic definition of global EROI, EROI$_{G}$. Section 4 explores how growth-induced increases in resource supply costs lead to declining energy returns, but also how these might be balanced by adjustments in efficiency elsewhere in the system such that overall returns and hence growth is maintained. Section 5 explores systematic variations in observed growth rates of GPE about their long-run value, and Section 6 offers some conclusions.

2. Modelling Framework

There are numerous global energy system models (see Jebaraj and Iniyan, 2006; Bhattacharyya and Timilsina, 2010 for reviews) that vary in complexity depending on application. Here I present possibly one of the simplest in that it makes no attempt to resolve any detail beyond what is necessary to describe the observations that a. GPE use has, on average, grown at $\sim 2.5\% \text{yr}^{-1}$ for at least the last century, and b. the efficiency of supplying resources to points of final consumption has fallen consistently as the system has grown (see below). In this framework, energy use is assumed to underpin all economic activity such that the real economy and the global energy system represent one and the same thing over the timescales being considered.

2.1. Components of Primary Energy Use

GPE is the total annual energy consumption (or annual average power demand) of industrial society made up from wood, fossil fuels, renewables, nuclear and food. Estimates of this for 1900 to 2014 compiled by De Stercke (2014) are shown in Fig. 1i, and currently (in 2014) this is around 600 EJyr$^{-1}$ or 19 TW. Let us denote GPE, $x$. Although this energy flow is used for a vast array of differing activities, here I start by considering it as being comprised of just two components: the energy used to acquire resources from the environment and to distribute them within industrial society (or the supply energy use, $x_2$); and the residual that is not available to do things beyond resource acquisition and distribution (or net available energy use, $x_3$).

\[ x = x_2 + x_3 \]  

Defining the partitioning of primary energy use outlined in eq. (1) is nontrivial. This is because energy used for resource supply includes both the running cost (which see instantaneous returns), and investments in the associated infrastructure (which see returns over the investment timescale). The former are commonly accounted for in annual energy input-output statistics such as those reported by the International Energy Agency (IEA). These are associated with the operation of infrastructure for the extraction and relocation of resources from where they are in the environment, to where they are needed within industrial society. Although there are considerable uncertainties associated with the specification of these costs (for example, points of end-use are...
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