Energy Policy 86 (2015) 562–573

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Net energy analysis in a Ramsey–Hotelling growth model

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HIGHLIGHTS

- A neoclassical growth model with EROI ("Energy Return on Energy Invested") is shown
- All concepts linking neoclassical economics and net energy analysis are discussed
- Any EROI decline can be compensated increasing gross activity in the energy sector.
- The economic impact of EROI depends on some non-energy cost in the energy sector.
- Comparative steady-state statics for different EROI levels is performed and discussed.
- Policy implications are suggested.

ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form
4 June 2015
Accepted 29 July 2015

JEL Classifications:
Q01
Q43
Q41
Q57 O13

Keywords:
EROI
Net energy analysis
Growth
Ramsey–Hotelling
Depletion

ABSTRACT

This article presents a dynamic growth model with energy as an input in the production function. The available stock of energy resources is ordered by a quality parameter based on energy accounting: the "Energy Return on Energy Invested" (EROI). In our knowledge this is the first paper where EROI fits in a neoclassical growth model (with individual utility maximization and market equilibrium), establishing the economic use of "net energy analysis" on a firmer theoretical ground. All necessary concepts to link neoclassical economics and EROI are discussed before their use in the model, and a comparative static analysis of the steady states of a simplified version of the model is presented.

1. Introduction

The impact of energy resources depletion has been a classical issue in economics at least since "The Coal Question" (Jevons, 1865) was published, introducing the problem of the sustainability of a productive system significantly reliant on non-renewable resources. The description of the optimal path of depletion of a non-renewable resource was a problem solved using variational calculus in the earlier years of neoclassical economics (Hotelling,1931), but early neoclassical growth theory (Koopmans,1965) was based on production functions that only included capital and labour as inputs. In the seventies, non-renewable natural resources were incorporated in neoclassical growth models (Dasgupta and Heal, 1974; Solow, 1974), and the long-run trends of production and consumption with and without productivity growth were characterized, but the mainstream narrative of neoclassical economics has identified technological progress and the institutional environment as the core drivers of the economic growth process.

On the other hand, in the two hundred years of the Industrial Revolution, economic growth has been related not only to an increasing level of productivity and capital accumulation, but also to *an equally sustained increase on energy use*. This happened in a feedback process, where the same technical progress (let us take the invention of the steam engine as the canonical example)

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http://dx.doi.org/10.1016/j.enpol.2015.07.028

created an increasing demand for energy (coal) and provided the means to accordingly increase supply (the steam engine was, first of all, used in coal mining).

As a reaction to the perceived neglect of the relevance of the extensive use of natural resources (specially energy) as a determinant of economic growth by neoclassical economics, a theoretical body of economic thought emerged (Ecological Economics) stating that economic growth after the Industrial Revolution was based on the depletion of the stock of fossil fuels (Cottrell, 1955; Hubbert, 1956; Georgescu-Roegen, 1971; Odum and Odum, 1976; Cleveland, 1999; Mayumi, 2001), and defending that economic scarcity was at least partially derived from thermodynamic constraints.

A main tool used by ecological economists was "net energy analysis", that is defined (Cleveland, 1992) as a "*technique for evaluating energy systems […] which compares the quantity of energy delivered to society by an energy system with the direct and indirect energy used in the delivery process*". The technical development of net energy analysis was done by engineers to compute the energy life cycle of some products and installations (Thomas, 1977; Hendrickson, et al., 2006) and by ecological scientists expanding to the human civilization the energy flow analysis developed for ecosystems (Odum, 1983). A relevant measure derived from net energy analysis is the EROI ("Energy Return on Energy Investment") defined as "*the ratio of energy delivered to energy costs*". These costs are the direct energy costs (fuel and electricity used in the process to obtain the final useful energy) and the indirect energy costs (the energy embedded in the capital goods used by the energy production sector).The economic relevance of "net energy analysis" and particularly of EROI is still a controversial issue (Cleveland, 1991, 2001) that is discussed in Section 2 of this article.

The efficiency in energy use and production is a relevant growth driver: The amount of useful work performed per unit of exergy (a physical measure of free energy in a fuel) steadily improved in the nineteenth and twentieth century, being a relevant growth driver for that period (Ayres and Warr, 2003, 2005). In Stern and Kander (2010) a Solow growth model with an energy sector is fitted for Swedish data: the model is sensitive to quality improvements in the fuels used by the Swedish economy and improvements in the efficiency of energy use in the Swedish economy, but depletion of energy sources and improvements in energy production are not considered (a sensible decision for the small open Swedish economy, but a limitation to understand a closed economic system as the global economy). The "exergy conversion" paradigm provides a measure of how physically efficient is the use of delivered energy by the economic system, while EROI is a synthetic measure of how difficult is to deliver that energy into the economic system with the given technology and resources. EROI and exergy conversion efficiency provide useful and complementary measures of physical efficiency for the energy producing and energy consuming sectors of the economy, respectively.

The first advantage of EROI is being a physical measure (instead of a monetary one). The classification of natural resources by "monetary costs" (Hotelling, 1931; Chakravorty et al., 1997) is a reasonable first approach to describe quality-heterogeneous natural resources, but it cannot be directly used in a general equilibrium model, because monetary costs should be the result of the market interaction between demand (derived from subjective preferences) and supply, derived from the endowments of resources and production functions, that are the mathematical description of technologically feasible transformations of commodities in other commodities (Mas-Collel et al., 1995). Physical descriptions of resource scarcity (as "ore grade") are the natural inputs in general equilibrium models, while "monetary costs of extraction" based models are making hidden hypothesis that can lead to significant biases when production conditions change significantly from present ones. For example, energy resources depletion could impact the replacement cost of capital or the cost of labour (wages), that are significant determinants themselves of energy production costs; in a model where energy resources are classified by (fixed) production costs, second round effects of energy resources depletion in the cost of energy goods are not considered (Stern, 1997; Pearce, 2008; Kenny et al., 2010).

The second advantage of EROI is being comparable across energy sources: a more detailed description of the physical quality of the different energy sources (the ore grade of uranium mines for nuclear fuel, the thickness of seam for coal mines, the size and deepness of oil and gas fields) can be used in a Ramse–Hotelling model to predict depletion paths of natural resources and the impact of natural resource depletion in consumption.[1]

Being comparable across different energy sources, the average EROI of currently energy sources can be computed and used as an aggregated measure of the quality of energy resources in use. As it is usual in economics, there is a trade off between low-level modelling (where detailed descriptions of physical scarcity and technology are used) and a high-level description of the relations between the economy and the energy system. In low-level descriptions, the exactness, precision and more realism of the model imply more sensitivity to modelling choices and the description of the technology, while high-level models are less sensitive to particular technology and modelling choices (but still depend on high level assumptions) and their results are more transparent and understandable. EROI is a useful concept and measure for high level modelling of the impact of physical constraints in the economy.

The use of net energy analysis in neoclassical economics has been unusual with only a few interesting applications, mainly concentrated in international trade: Baumol and Wolff (1981) used input–output analysis and the concept of energy yield to prove that targeted subsidies increase energy dependence, and Hong et al. (2007) analysed the energy transactions "embodied" in Chinese merchandise trade and their consequences. On the other hand, the academic interest in EROI has remained substantial in the latest years, including a few peer-reviewed articles and some books about the methodology and economic applications of EROI (Cleveland, 2001; Hall and Day, 2009; Pimentel 2008). The interest in economic applications of EROI by environmental scientists has been reflected in an array of publications in natural science reviews, including publications in Nature (Hall et al., 2003), the American Scientist (Hall and Day, 2009), the Annals of the New York Academy of Sciences (Murphy and Hall, 2010) and "Ambio" (Mulder, Hagens, 2008) and a special issue of "Sustainability" (Hall, 2011).

This article makes two original contributions: first in the conceptual realm, we point out that EROI is a leverage ratio between energy as an input and energy as an output for the energy production sector of an economy, and its economic impact depends in the non-energy costs of running the energy sector. Second, the previous observation allows us to naturally include EROI in a neoclassical growth model.

To summarize the conceptual contribution, the economic impact of a change in the EROI of the energy sector of a society depends on some non-energy cost of the expansion and maintenance of the energy production sector of that society, because if the energy production sector could be expanded for free, any decline (not below one) in the EROI of the available energy sources (which

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[1] See Chakravorty et al. (1997) for a similar model, but based on monetary extraction costs.