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Modelling EROEI and net energy in the exploitation of non renewable resources

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ABSTRACT

Recently, Bardi and Lavacchi (2009) showed that a simple system of coupled differential equations can be used for a quantitative description of the exploitation of non renewable resources in a free market economy. The present paper examines how the model describes the behavior of the system in terms of energy return for energy invested (EROEI) and net energy (energy returned minus energy expended). We show that the model generates a behavior of these factors comparable to the results obtained by other methods, for instance for the case of crude oil production in the US.

1. Introduction

The exploitation of a finite resource must necessarily follow a production cycle that starts with zero and ends with zero. In several historical cases, and in particular for fossil fuels, it has been observed that the shape of the production curve is relatively simple: it is “bell shaped” with a single maximum when approximately half of the resource has been produced. This model was proposed for the first time by Hubbert (1962) as an empirical description of the production of crude oil in the US 48 lower states. The same behavior is often observed for several cases of mineral resources (Bardi and Pagani, 2008) and for slowly renewable resources, such as whale oil (Bardi, 2007).

A reasonable explanation for the decline of production after the peak is related to the declining energy return for energy invested (EROEI or EROI) (Hall et al., 2008; Murphy, 2009). Producers will normally tend to exploit first the “easy” resources, those with high EROEI and must progressively move to lower EROEI ones, with increasing costs of extraction. With lower profits, companies involved in extraction find themselves short of capital and must reduce investments. This process leads, eventually, to “peaking” of production and to its successive decline.

In the present paper we examine how a simple model can describe how EROEI varies as a function of production. The model has been described in a previous paper (Bardi and Lavacchi, 2009) and is related to the well known Lotka–Volterra (LV) model (Lotka, 1925; Volterra, 1926), also known as the “predator–prey” and “foxes and rabbits” model. This model can provide a quantitative fitting of the historical production data for a number of cases of exploitation of non-renewable resources, such as crude oil, or of slowly renewable ones, such as whale oil. We will show here how the model describes the decline of EROEI during the exploitation process and confirms that the Hubbert behavior is related to declining energy yield.

2. EROEI and net energy

Exploiting an energy resource can never been 100% efficient. For instance, in order to exploit the chemical energy stored in an oil well we must expend some energy in operations such as prospecting, drilling, extracting, processing, and transporting. EROEI (energy return for energy invested) is defined as the ratio of the energy obtained from the resource to the energy expended in production (Hall et al., 1986, 2008, 2009). A related concept is that of net energy, defined as the energy produced minus the energy expended. When the EROEI is equal to 1 or lower, the net energy is zero or lower.

EROEI is a useful concept for understanding the real value of a resource in economic and energy terms. Obviously, larger EROEIs are preferable and an EROEI smaller than one corresponds to a net loss of energy. However, some processes may be carried out even at low EROEIs, even smaller than one, as a result of specific choices of the economic system. As an example, biofuels, and in particular ethanol, have a low EROEI (Pimentel and Patzek, 2005) but for political reasons governments (especially in the US) provide finan-

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cial subsidies that result in a net transfer of energy from fossil fuels to ethanol production.

Despite its usefulness, the definition of EROEI suffers of some uncertainty, mainly in terms of the boundaries of the system being considered. These boundaries may be defined according to the "Life Cycle Analysis" (LCA) concept. The related norms are defined in protocols such as, for instance, the ASTM E1991-05. If, however, one wants to take into account everything that is done with an energy source; from producing fuel, to the cars and roads to use it, all the way to cathedrals and poetry then we may speak of "full EROEI" or "societal EROEI" (Hall et al., 2008, 2009). The value of societal EROEI determines the surplus that can be utilized for all those activities that are considered part of what we call "civilization". The problem does not exist as long as consistent EROEI definitions are used when comparing different energy sources, but it must be kept in mind when modelling economic systems.

3. A simple model for resource exploitation

Lotka (1925) and Volterra (1926) developed a well known model of "predator–prey" relationship in simple biological systems. This model is intuitively and mathematically attractive, and is often used in ecology to conceptualize the relation between predator and prey species. The Lotka–Volterra (LV) model works well enough with simple laboratory systems and also appeared to work in nature; however Hall (1988) showed that most examples given in textbooks, including the well known one of hares and lynx, in fact do not support the use of such a simple model in real ecosystems. Nevertheless, models based on the LV approach have found applications in economics. These models are sometimes known as "Free Access" model (see, e.g. Smith, 1968).

Bardi and Lavacchi (2009) developed a modified version of the LV model in order to describe the economic exploitation of non renewable (or slowly renewable) resources where it is assumed that the prey (rabbits) do not reproduce. The model involves two main stock variables: resources and capital. The amount of available resource is defined as the "resource stock", R. The other main variable of the model is the aggregate amount of economic resources being utilized in the exploitation; that is equipment, land, knowledge, human work, and similar. We called this aggregate amount "capital stock", C. R' and C' are defined as the flow (the variation as a function of time) of, respectively, resources and capital. Further parameters of the model are the initial stocks of resource (R_o) and of capital (C_o).

As in the original LV model, it is assumed that resource (the "prey") can be extracted in proportion to the available capital (the "predator") and, at the same time, in proportion to the amount of the resource stock. Implicitly, this assumption involves that resources are "graded" and that the "easy" (less expensive) resources are extracted [or produced] first.

The other fundamental assumption of the model – again corresponding to the original LV model – is that capital is generated in an amount proportional to the amount of extracted resources. In other words, the resource stock is partly transformed into capital stock; let us say that the extracted oil is used to provide the energy necessary to build more oil rigs and other facilities. In more general terms, this transformation is mediated by the market system. That is, the energy re-invested is generated via the sale of the resource on the market and the profits are used to create the equipment and facilities to produce more resource.

A final assumption of the model is that capital is dissipated over time in proportion to the amount of capital itself, the same assumption made in the original LV model. The significance of this assumption is often misunderstood. "Dissipation" might be seen as corresponding to "depreciation," that is the decline in value of the capital stock, mainly in terms of obsolescence. In the biological version of the model, it would mean that it describes how foxes get old and die of aging. But that is only a partial view: the capital stock (or the foxes stock) is an energy stock and this term describes how much of this energy is lost as a function of time without specifying by what mechanism. In practice, the assumption is about the fundamental feedback of the system that has capital allocate some energy in order to create more capital (that is, how foxes expend energy by chasing rabbits). This point is fundamental in the modelling of the system's EROEI, as it will be shown later on.

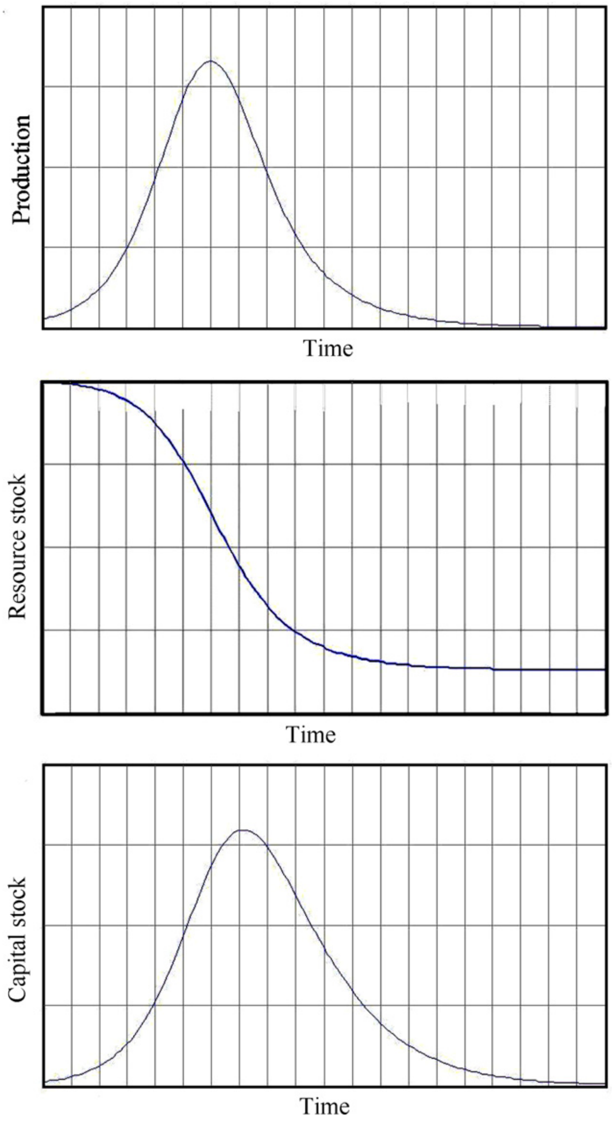

Fig. 1. Qualitative solutions of the model obtained using the Vensim software. The parameters shown are resource, capital and production.

The model can be described in mathematical form as two coupled differential equations. These two equations are basically the same as those of the original Lotka–Volterra model, except that one term is missing, that of the reproduction of the prey. The "ks" are constants which describe the quantitative behavior of the model

$$R' = -k_1CR \quad (1)$$

$$C' = k_2CR - k_3C \quad (2)$$

Qualitative results of the model – obtained using the Vensim software – are shown in Fig. 1. In order for the model to be able to describe historical cases, it is necessary to have data on at least

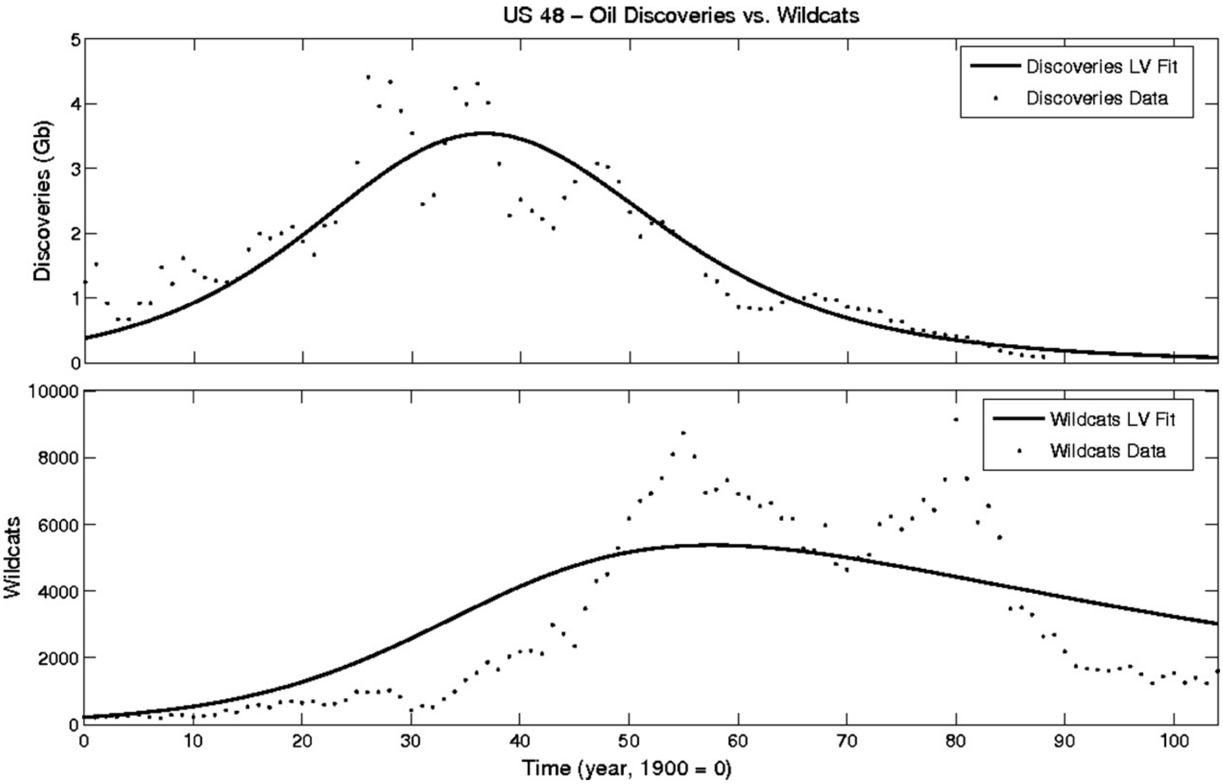

Fig. 2. Fitting of the data for oil discovery in the US 48 lower states and of the number of wildcats. In this case, the number of wildcats is proportional to the capital used by the oil industry in the effort of discovering the resource (oil wells). From Bardi and Lavacchi (2009).

some of the main parameters in the equations. In a previous paper (Bardi and Lavacchi, 2009) we used historical data on production and on aggregate capital accumulation. The latter were measured in terms of "proxies"; e.g. using the tonnage of the whaling fleet as proportional to the total capital available to the whaling industry. In this way, we found that this simplified model can describe a number of historical cases of resource exploitation, when the resource is non renewable (e.g. crude oil) or slowly renewable (e.g. whale oil).

An example of the results obtained for the US-48 lower states historical data on crude oil production is shown in Fig. 1. Here, the "discoveries" parameter is used as a proxy for resource production and the number of wildcats as a proxy for the aggregate capital used by the oil industry for prospecting in the area considered (Fig. 2). Other cases for which the model was found to give a good or acceptable data were gold production in South Africa and in California, whale oil production in the 19th century and crude oil production in Norway (Bardi and Lavacchi, 2009).

4. EROEI and net energy in the exploitation of mineral resources

Any model attempting to describe a physical system must satisfy the laws of physics and, in particular, those of thermodynamics. The Lotka–Volterra model is no exception. In its simplest implementation, that of two biological species (foxes and rabbits), the two stocks involved can be regarded as energy stocks. The same interpretation is possible for energy resources such as crude oil.

In the absence of an external energy flux, the model describes the flow of energy from one stock (resources) to another (capital). The transformation is completely irreversible and it occurs as the result of the increase in entropy of the system (Karnani and Annila, 2009). Eventually, the dissipation term of the model ($-k_3C$) will bring to zero the amount of free energy stored in the capital stock; thus maximizing the entropy in accordance with the second principle of thermodynamics.

Parameters such as EROEI and net energy are not explicitly expressed in the equations of the model, but can be calculated from the available parameters which, as mentioned before, include energy and energy flow. In a previous study (Bardi and Lavacchi, 2009), we defined the "yield" of extraction as (R'/C), that is the ratio of production to capital. However, the concept of EROEI requires a more detailed examination.

If we apply the model to an actual economic process, we are interested in maximizing production and minimizing costs. Production is explicitly defined in the model as "R'". The "costs" in the model are determined by the only term that produces a loss of capital ($-k_3C$). As described earlier on, these costs are the result of the sum of the energy spent in order to exploit the resource and the energy lost because of obsolescence and other factors (depreciation). In other words, the k_3 term is the sum of two terms, one related to exploitation, the other to depreciation. Both these factors should be included in an EROEI calculations based on life-cycle analysis, so it is justified to use the aggregated k_3 factor as proportional to the overall exploitation costs. Hence, we can define the economic yield of the process as the ratio of energy production (k_1RC) to energy loss (k_3C). An alternative definition could be to use capital accumulation (k_2RC) as the numerator of the ratio, but using production appears to be more closely related to the concept of EROEI as it is usually defined in practice.

Therefore we can write:

$$\mathrm{EROEI} = \frac{Rk_1}{k_3}$$

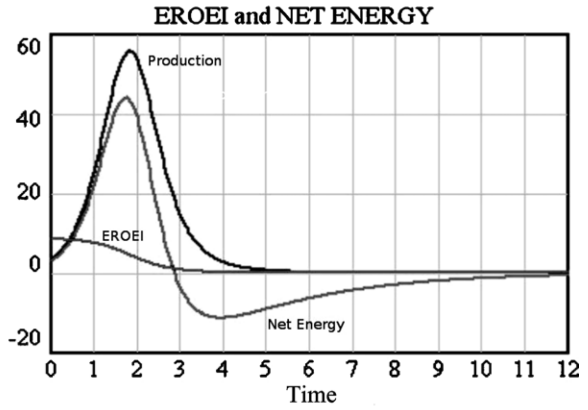

Fig. 3. Qualitative solutions of the model equations system obtained using the Vensim software. The parameters reported are production, net energy and EROEI.

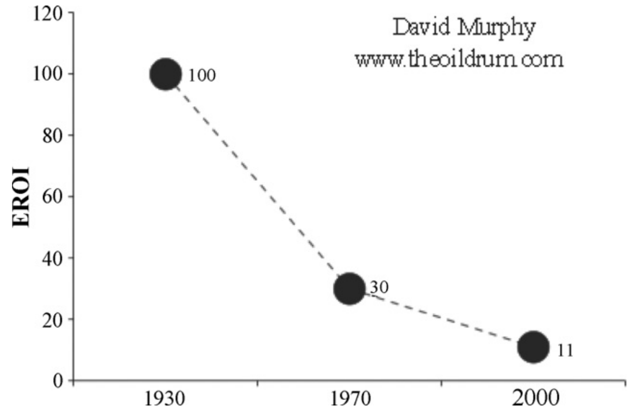

Fig. 4. Historical EROEI of crude oil extraction in the lower 48 US states. Figure from Murphy (2009).

This ratio describes how the EROEI of a non renewable energy source varies with time. For instance, it describes how the average EROEI of single oil wells varies as the oil resources of a region are exploited. Note that the “capital” stock does not appear in this expression. This appears to be correct, since the EROEI derives from the characteristics of the resource being exploited. However, note that the two parameters k_1 and k_3 are defined in the model with respect to both resources and capital, so that the behavior of the capital stock does affect EROEI.

A limitation of this concept is obvious when we apply the concept to a real economic process. The definition of EROEI = Rk_1/k_3 is rigorously valid only for a system where *all* the energy gained from the exploitation of a resource is used for further exploitation. That might be true in a simple biological system, say foxes and rabbits, but surely not for the world’s economy. However, the concept that the EROEI is proportional to R (the resource stock) remains useful in the reasonable assumption that the fraction of profits reinvested by the industry in the exploitation of a resource remains approximately constant over the resource lifetime. This assumption is ultimately justified by the fact that the model can reproduce the historical data on production (Bardi and Lavacchi, 2009) for a number of cases.

Note that there is no element in the formula that would stop processing when the EROEI becomes smaller than one; when that occurs, exploitation will continue utilizing previously accumulated energy resources. Note also that, since production is given by R', a maximum in the production curve will correspond to an inflection point in the EROEI curve.

From this result, we can proceed with the determination of the form for net energy (NE) which we may define as production minus dissipation. That is

$$\mathrm{NE} = C(k_1 R - k_3)$$

We see that for R sufficiently small, that is in the final stages of exploitation, the net energy of the system becomes negative and it remains so. We can also write this relation as:

$$\mathrm{NE} = CR(k_1 - k_3/R)$$

Assuming that R is relatively large, that is we are not at the final stages of the exploitation process, we can approximate NE as equal to $k_1 CR$, that is equal to production. Therefore, we expect net energy to have a maximum that takes place, approximately, near the production peak. Qualitative simulations performed using the Vensim software confirm both this statement and the one that EROEI should have an inflection point in correspondence to the production peak; as shown in Fig. 3.

These calculations qualitatively correlate with the historical data on the EROEI of oil extraction from the US-48 lower states (Murphy, 2009; Cleveland, 2005) as shown in Fig. 4. Despite the small number of points available, it is possible that the inflection point in the EROEI curve occurs around 1970 and therefore it corresponds to the production peak in the region.

These considerations raise the question of whether it is possible to use the model described here in order to determine the EROEI instead of using the standard LCA. There are two problems in this sense: the first is the use of proxy data for the fitting of the historical trends, the second is that EROEI, as defined within the model, implies that all the energy produced by the system is all reused to produce more energy, an obviously non realistic assumption.

Regarding the use of proxy data, it is possible to normalize the equations of the model and to obtain a value of the EROEI as a function of the measured parameters. For the second problem, however, the model cannot say anything about the societal decision of which fraction of the profits from the exploitation of a resource have to be allocated to further exploitation. Indeed, tests made with the US-48 crude oil system studied in a previous paper (Bardi and Lavacchi, 2009) show that the EROEI calculated from the model is smaller than the LCA calculated EROEI (Cleveland, 2005), as expected. In any case, further data and analysis are necessary in order to determine the potential of this method as a tool for EROEI calculations.

5. Conclusions

The model presented here offers useful insights on the mechanism of resource exploitation and it may offer a route for modelling and understanding economic processes which are vital for society. The role and the importance of EROEI are clarified by these results which confirm that, indeed, EROEI is the driving force in the exploitation process. Furthermore, the model shows that, utilizing accumulated resources, the use a non renewable energy resource may continue even for EROEIs smaller than one and – hence – for negative net energy production. Whether this will be the behavior of the real world’s economy remains to be seen, but it is at least a possibility; indicating that the economic mechanisms which are judged appropriate today for determining exploitation priorities may not be such when applied to non renewable resources. Although only qualitative, the model offers a simple mental tool, a “mind sized model” (Papert, 1980), that can be used to understand the mechanism of the exploitation of natural resources (including the ability of the atmosphere to contain CO_2 without overheating the ecosystem.

Understanding (and acting on) these mechanisms is the main problem that our civilization is facing today.

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