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Analysis

Connecting net energy with the price of energy and other goods and services

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ABSTRACT

Net energy is intuitively compelling and useful in calculating total impacts (e.g., primary energy, greenhouse gases, land use, and water requirements.) of delivering useful energy to the larger economy. However, it has little policy impact unless connected quantitatively to the price of energy and other goods and services. I present an input–output (IO)-based method to do this. The method is illustrated by a two-sector model fitted to U.S. IO economic data. In an IO-characterized system, the energy returned on energy invested (EROI) and the energy intensity of energy are directly related. However, EROI and prices are not uniquely related because they depend differently on four independent IO coefficients representing internal structure of, and the relationship between, the energy sector and the rest of the economy. If only one of these coefficients varies, then EROI does uniquely determine prices. Uncertainties in the IO coefficients, as well as persistent issues of choosing system boundary and aggregating diverse energy types, further complicate the EROI-price connection. In this context I review two recent empirical comparisons of U.S. oil and gas prices and EROI for 1954–2007.

1. Introduction

Net energy is a compelling, intuitive concept: a comparison of the energy produced with the energy required to produce it. It has been in the literature for a half-century (Cottrell, 1955; Odum, 1970; Georgescu-Roegen, 1971). The Odum book, “Environment, Power, and Society” was a key stimulus in a wave of explicit calculations for various energy technologies which continues through today (Herendeen et al., 1979; Chambers et al., 1979; Herendeen and Plant, 1981; Herendeen, 1988, 2004; Hansen and Hall, 2011; Hall and Klitgaard, 2011; Cleveland and O'Connor, 2013; Lambert et al., 2014; Hall et al., 2014; Weissbach et al., 2013). The general conclusion of many studies is that the net energy payoff from our energy-source technologies has decreased over the past 75 + years. This is a potential cause for serious concern, as the improvement in energy-use efficiency might not be able to compensate for poorer energy-source efficiency.

Net energy is also an illuminating and useful window through which one can view other issues such as greenhouse gas emissions and land use requirements. Intuitively, one would think that it is useful in determining the monetary price of energy itself and of all other goods and services. On one hand this is cumbersome; if price is the question, why not use whatever tools are needed to address it directly and not force a reference to net energy (Leach, 1975). On the other hand, in the real world of subsidies, lags, externalities, etc., a spiraling dance between a plurality of indicators is (often claimed to be) appropriate.

Unfortunately, in its details net energy analysis is a complicated concept that renders it inaccessible to laypersons and vexing to analysts (Herendeen, 1988, 2004; Cleveland, 2010), requiring complicated qualifiers and a proliferation of situation-specific variants (Murphy et al., 2011). In energy policy, for significant and lasting response at the societal and personal level, monetary price is the question. Therefore net energy is policy-relevant largely to the degree that it can be tied predictively to the price of energy and all goods and services. There are two recent attempts (King and Hall, 2011; Heun and de Wit, 2012), which I will review below. Neither of these has completely closed the causal loop from the rest of the economy to the energy sector and back to the rest of the economy. This article describes a simple, input–output (IO)-based method to close the loop. The specific question addressed here is: “For a stable, steady state economy whose energy industry is characterized by energy return on energy invested (EROI), how do the prices of energy, and of non-energy goods and services, depend on EROI?”

2. Model

There are persistent difficulties in formulating and answering net energy questions (Herendeen, 1988), arising mostly from system boundary issues and attempts to aggregate different kinds of energy. Additionally there are generic problems with any IO economic model, including aggregation again, assumptions of linearity and steady state, and the roles of byproducts and imports. Acknowledging these problems, I represent the U.S. economy with two sectors: one, the energy industry; and the other, “machinery”, which here is used as a surrogate

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for the remainder of the economy. (Net energy analysis is based on the feasibility of this separation.) The use of machinery by the energy sector represents a feedback of (embodied) energy. This is expressed as E_{in} in Fig. 1. EROI is defined as E_{out}/E_{in}. Net energy return $= E_{out} - E_{in}$, and net energy/gross energy $= (1 - 1/\text{EROI})$.

E_{in} can be related to energy intensity calculated from standard IO-based energy analysis, which allows one to convert economic flows of all goods and services to embodied energy flows (Bullard and Herendeen, 1975). In parallel, the IO framework allows calculating the prices charged by each sector (Herendeen and Fazel, 1984). I use a mixed units approach; flows are expressed in Btu/yr for energy, \$/yr for machinery, and \$/yr for value added. (1 Btu = 1055 J). Value added could also be expressed in labor units = job-yr/yr = jobs. Table 1 lists the transactions table; the corresponding flow diagram is in Fig. 2. Steady state is assumed.

3. Energy Intensities and Prices

Fig. 3 shows, and its caption explains, the assumed balance condition used to calculate energy intensities and prices, leading to the standard matrix equations for energy intensities, $\underline{\varepsilon}$ (Bullard and Herendeen, 1975) and prices, $\underline{p}$ (Herendeen and Fazel, 1984):

$$\underline{\varepsilon} = \underline{e}\left(\underline{I} - \underline{\underline{A}}\right)^{-1} \tag{1}$$

$$\underline{p} = \underline{v}\left(\underline{I} - \underline{\underline{A}}\right)^{-1}. \tag{2}$$

The A-matrix and premultiplying vectors used in Eqs. (1) and (2) (defined in Table 2) are obtained from the transactions table, Table 1.

One is tempted to think that Eqs. (1) and (2) will facilitate connecting EROI and price, as follows:

1. Eq. (1) in conjunction with Figs. 2 and 3 yields embodied energy flows.
2. EROI is a function of some of these flows and hence expressible in terms of elements of $\underline{\underline{A}}$ and $\left(\underline{I} - \underline{\underline{A}}\right)^{-1}$
3. By Eq. (2), price depends on $\left(\underline{I} - \underline{\underline{A}}\right)^{-1}$
4. Therefore price is expressible in terms of EROI.

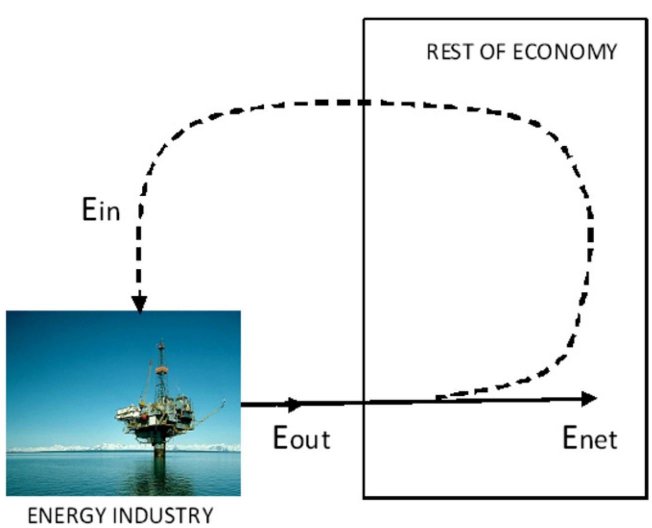

Fig. 1. To define net energy cleanly requires conceptually separating the "energy industry" from the "rest of the economy". E_{in} is the energy embodied in all inputs that the energy sector requires from the rest of the economy. E_{net} is available to the rest of the economy beyond this.

Table 1
Mixed-unit transactions table. X_{ee} is nonzero to account for self-use by the energy sector. X_{mm} is nonzero to account for the fact that machinery is an aggregation of many intertrading sectors.

From/to	Energy	Machinery	Final demand	Total output	Units
Energy	X_{ee}	X_{em}	Y_e	X_e	Btu/yr
Machinery	X_{me}	X_{mm}	Y_m	X_m	\$/yr
Value added	VA_e	VA_m			\$/yr
Primary energy	E_{prim}	0			Btu/yr

We will see, however, that the connection is not unique because EROI and prices depend differently on the elements of $\underline{\underline{A}}$.

The matrix inverse is

$$\left(\underline{I} - \underline{\underline{A}}\right)^{-1} = \begin{pmatrix} 1-A_{ee} & -A_{em} \\ -A_{me} & 1-A_{mm} \end{pmatrix}^{-1} = \begin{pmatrix} 1-A_{mm} & A_{em} \\ A_{me} & 1-A_{ee} \end{pmatrix}\left(\frac{1}{(1-A_{ee})(1-A_{mm})-A_{em}A_{me}}\right). \tag{3}$$

Substituting Eq. (3) in Eqs. (1) and (2) yields the energy intensities and prices, expressed in vector notation:

$$\underline{\varepsilon} = (\varepsilon_e, \varepsilon_m) = (1-A_{mm}, \quad A_{em})\left(\frac{1}{(1-A_{ee})(1-A_{mm})-A_{em}A_{me}}\right) \tag{4}$$

$$\underline{p} = (p_e, p_m) = (v_e(1-A_{mm}) + v_m A_{me}, \quad v_e A_{em} + v_m(1-A_{ee})) \times \left(\frac{1}{(1-A_{ee})(1-A_{mm})-A_{em}A_{me}}\right) \tag{5}$$

In Fig. 2, and in Eqs. (4) and (5), there are six coefficients that affect EROI:

1. A_{me}, machinery in/energy out for the energy sector (units = \$/Btu),
2. A_{em}, energy in/machinery out for the machinery sector (units = Btu/\$),
3. A_{ee}, self-use/output for the energy sector (units = Btu/Btu),
4. A_{mm}, self-use/output for the machinery sector (units = \$/\$),
5. v_e, value added/output for the energy sector (units = \$/Btu),
6. v_m, value added/output for the machinery sector (units = \$/\$).

Eq. (5) gives prices of both energy and machinery in terms of these six coefficients. This method tracks indirect effects in both directions: the price of energy changes, which affects the price of machinery, which affects the price of energy, and so on in a converging infinite series which is captured by matrix inversion in Eqs. (1) and (2). I will assume that the value added factors are constant, and investigate responses to changes in the four A-coefficients.

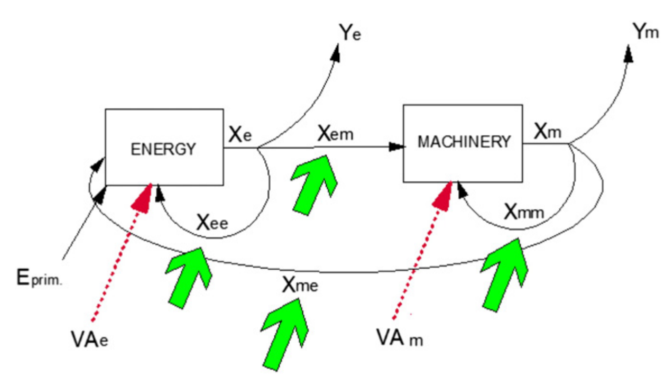

Fig. 2. Flows in two-sector economy, using standard IO notation. "Machinery" is a surrogate for the rest of the economy. X_{**} = intersectoral flow, X_* = total output, Y_* = final demand, VA_* = value added, E_{prim} = primary energy input. Broad arrows indicate flows that, by assumption in this article, can be varied to influence energy intensities, prices, and EROI.