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Analysis

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

Robert A. Herendeen

Gund Institute for Ecological Economics, University of Vermont, Burlington, VT 05401, United States

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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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E-mail address: rherende@uvm.edu.

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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 $= (1 - 1/\mathrm{EROI})$.

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):

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

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

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 $\left(\underline{\underline{I}}-\underline{\underline{A}}\right)^{-1}$
3. By Eq. (2), price depends on $\left(\underline{\underline{I}}-\underline{\underline{A}}\right)^{-1}$
4. Therefore price is expressible in terms of EROI.

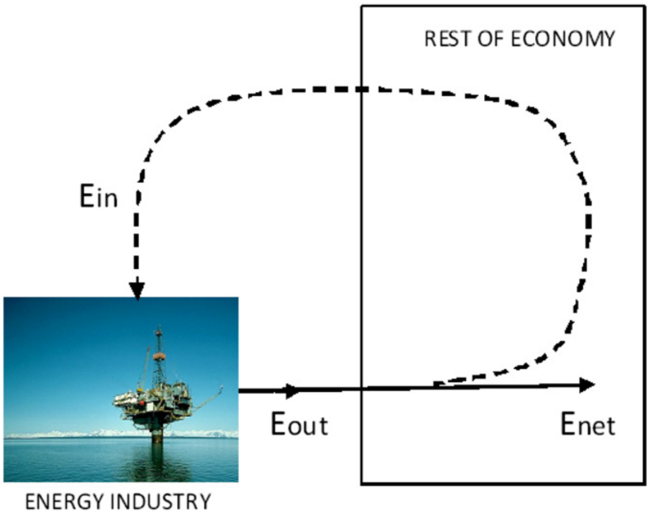

Fig. 1. To define net energy cleanly requires conceptually separating the "energy industry" from the "rest of the economy". E_{in} is the energy embodied in all inputs that the energy sector requires from the rest of the economy. E_{net} is available to the rest of the economy beyond this.

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

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

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

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

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

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.

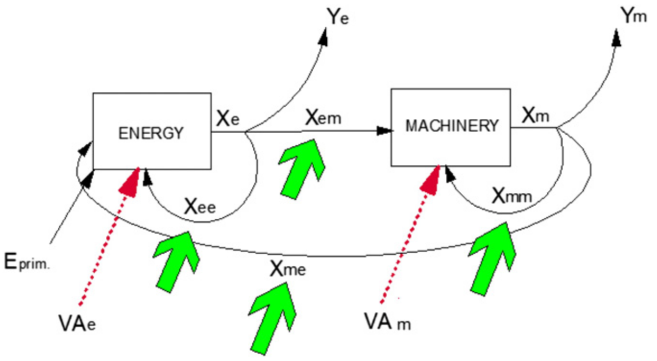

Fig. 2. Flows in two-sector economy, using standard IO notation. "Machinery" is a surrogate for the rest of the economy. X_{**} = intersectoral flow, X_* = total output, Y_* = final demand, VA_* = value added, E_{prim} = primary energy input. Broad arrows indicate flows that, by assumption in this article,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

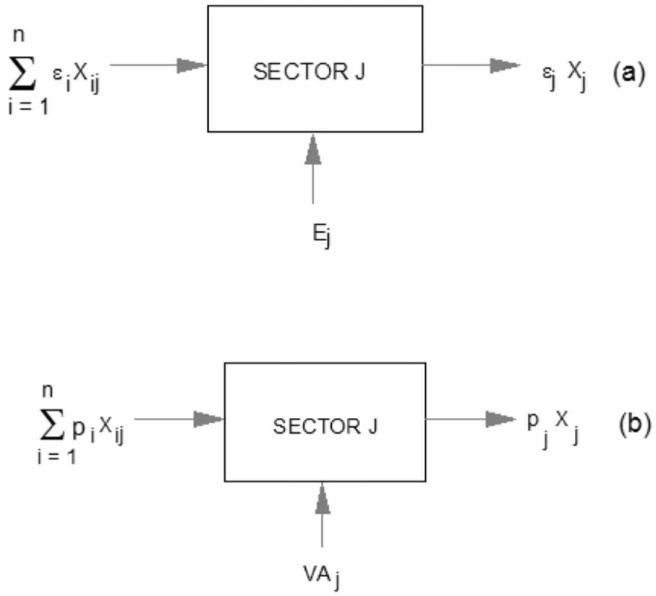

Fig. 3. The assumption underlying Eqs. (1) and (2): each sector is in (a) embodied energy-and (b) embodied value added balance. For each, inflow = outflow. This gives n simultaneous equations to solve for the n energy intensities, and n simultaneous equations to solve for the n prices. ε = energy intensity, p = price. See Table 1 for additional explanation.

4. Connecting EROI to Prices

EROI is usually casually defined; no time period is specified in Fig. 1. Historically it has been defined as (E_{out} over facility lifetime)/(E_{in} over facility lifetime) (Herendeen, 2004; Cleveland, 2010; Hansen and Hall, 2011), i.e., an undiscounted energy benefit–cost ratio (dimensionless), not a return on investment (dimensions = 1/time). Because energy benefits and costs are usually distributed unevenly over time, researchers have also studied net power, referring to a time period shorter than the lifetime. Development and construction usually precede operation, so possibly the summed effect of many young energy facilities could yield negative net power, a problem that would persist as long as a quasi exponential construction program continues. This was claimed for Great Britain's aggressive nuclear plans (which were never realized) in the 1970s (Chapman, 1975). Dale and Benson (2013) conclude that so far, world PV electricity has been an energy sink, though that should reverse before 2020. Today in the literature EROI is usually annual, i.e., (E_{out} for this year)/(E_{in} for this year). In the context of the lifetime of a typical energy facility-several decades-this is effectively net power. The present article deals only with steady state, in which case the distinction is moot: (energy out/energy in) = (power out/power in).

EROI combines two different quantities: E_{out} is actual energy (which is defined solely in terms of the energy sector), while E_{in} is embodied energy (which must be defined in terms of a larger system). Thus in addition to the temporal problem above, there is the conceptual boundary issue: is EROI calculated for a new facility (e.g. gasohol (Chambers et al., 1979) or a solar power satellite (Herendeen et al., 1979)), or for one fully integrated into the economy? The economy as it exists provides the inputs needed to develop/construct a new energy facility; the construction is a delivery to final demand, in effect an export. To obtain the facility's EROI, we then compare the energy embodied in the inputs (characteristic of the present economy) with the (actual) energy which the facility will produce. At this point the new facility is not considered to be integrated; none of its energy output yet flows into the rest of the economy.

Table 2
Terms used to determine energy intensities and prices using Eq. (1). A-matrix and direct requirements vectors $\underline{e}$ and $\underline{v}$ are derived from Table 1. E_{prim}/X_e is usually, but not always, = 1.0; see text.

From/to	Energy	Machinery
Energy	$A_{ee} = X_{ee}/X_e$ Btu/Btu	$A_{em} = X_{em}/X_m$ Btu/$
Machinery	$A_{me} = X_{me}/X_e$ $/Btu	$A_{mm} = X_{mm}/X_m$ $/$
$\underline{e}$	E_{prim}/X_e Btu/Btu	0
$\underline{v}$	VA_e/X_e $/Btu	VA_m/X_m $/$
$\underline{\varepsilon}$	ε_e Btu/Btu	ε_m Btu/$
$\underline{p}$	p_e $/Btu	p_m $/$

Concern over this distinction is motivated by the difference between intermediate and final demand in IO accounting (and national accounts in general), which was explored in an energy analysis context by Brown and Herendeen (1996). After reviewing roughly eight definitions for EROI, including the possibility of different ones for the new and integrated cases, I conclude that a single definition is appropriate for both. The basis is these two observations:

1. In Fig. 1 the net energy is "discretionary"; we do not know how it will be used. The analogous quantity in Fig. 2 is Y_e, the final demand for energy.
2. E_{out} in Fig. 1 is the total energy "put in play" anywhere in the system.

Fig. 4 illustrates the distinction between the new and integrated case. Table 3 lists the expressions for EROI for both. Noting that $\varepsilon_{e,facil} = (\varepsilon_{m,present} Y_{m,present} + Y_{e,facil}) / Y_{e,facil}$, we see that both are of the form

$$\text{EROI} = \frac{\varepsilon_e}{\varepsilon_e - 1} \tag{6}$$

where ε_e = the energy intensity of energy, defined in Eq. (1). Eq. (6) is the connection between EROI and the energy intensity of energy in a steady-state, IO-characterizable economy. Eqs. (1), (2), and (6) can be used to relate prices and EROI for a multi-sector economy as well, though the detailed expressions will be more complicated than Eq. (5) or (8) for the two-sector economy. Eq. (6) assumes that ε_e is dimensionless, which results from using the mixed-unit transactions Table 1. For a purely monetary transactions table, which would give ε_e (but less accurately, Bullard and Herendeen, 1975) in Btu/$, the "1" in the denominator would be replaced by 1/(average energy price).

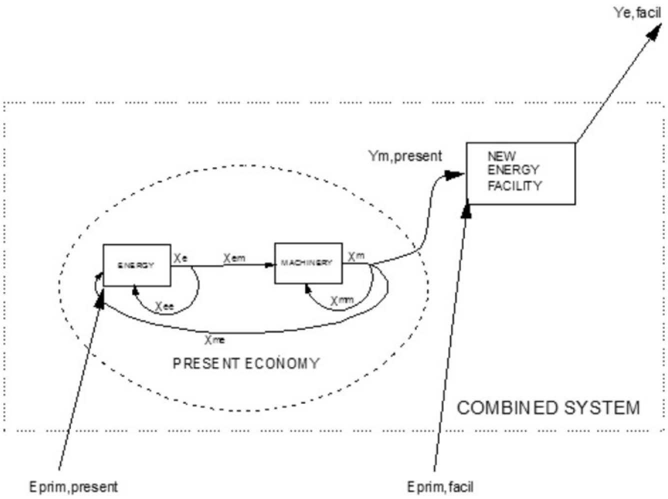

Fig. 4. Evaluating EROI for a new energy facility requires analyzing the (present) economy which supplies the inputs. This is conceptually equivalent to assuming that the present economy produces only machinery needed for the new facility; therefore $Y_{e,present}$ is assumed = 0. In contrast, to evaluate EROI for the energy sector in the present economy (see Fig. 2), we would assume that $Y_{e,present} \neq 0$ and $Y_{m,\ present} = 0$.

Table 3
Expressions for EROI for the energy sector 1. integrated in the present economy, and 2. new but dependent for inputs on the present economy.

Generic, Fig. 1	Integrated (present economy), Fig. 2	New facility, Fig. 4
Eout (usually = Eprim)	$\varepsilon_{e,present}\, Y_{e,present}$	$\varepsilon_{m,present}\, Y_{m,present} + Y_{e,facil}$
E_{net}	$Y_{e,present}$	$Y_{e,facil}$
$E_{in} = E_{out} - E_{net}$	$\varepsilon_{e,present}\, Y_{e,present} - Y_{e,present}$	$\varepsilon_{m,present}\, Y_{m,present}$
$EROI = \frac{E_{out}}{E_{in}}$	$EROI = \frac{\varepsilon_{e,present}}{\varepsilon_{e,present} - 1}$	$EROI = 1 + \frac{1}{\varepsilon_{m,present} \frac{Y_{m,present}}{Y_{e,facil}}}$

EROI in terms of the A-coefficients is obtained by combining Eqs. (4) and (6):

$$EROI = \frac{1}{A_{ee} + \frac{A_{em}A_{me}}{(1 - A_{mm})}} \tag{7}$$

Hoping finally to relate prices and EROI, we can combine Eqs. (5) and (7) to give

$$\underline{p} = (v_e(1 - A_{mm}) + v_m A_{me}, \quad v_e A_{em} + v_m(1 - A_{ee}))\left(\frac{1}{(1 - A_{mm})}\right) \times \left(\frac{1}{1 - 1/EROI}\right). \tag{8}$$

In Eq. (8), EROI has been teased out of the more fundamental Eq. (5). However, this separation is not unique and is generally unjustified, because all the A-coefficients, upon which EROI depends, still appear in Eq. (8). This illustrates that using EROI as a unique "window" to view price changes has a general logical drawback. This conclusion, based on a 2-sector model, will hold for a many-sector IO model as well. However, if only one of the coefficients varies, the role of EROI can be uniquely specified by using Eq. (7) to eliminate that coefficient from Eq. (8). For example, the case often assumed in the literature varies only A_{me}, energy's use of machinery. For this special case, we can write Eq. (8) as

$$\begin{aligned}\underline{p} = (p_e, p_m) = {} & v_e\left(\frac{1}{1 - 1/EROI}\right) \\ & + \frac{v_m}{A_{em}}\left(\frac{1 - A_{ee}EROI}{EROI - 1}\right), \quad \frac{v_e A_{em}}{(1 - A_{mm})}\left(\frac{1}{1 - 1/EROI}\right) \\ & + v_m \frac{(1 - A_{ee})}{(1 - A_{mm})}\left(\frac{1}{1 - 1/EROI}\right)\end{aligned} \tag{9}$$

where A_{ee}, A_{mm}, and A_{em} are held constant. In Eq. (9), the price of machinery is proportional to 1/(1 − 1/EROI), but the price of energy depends on a mix of that factor and (1 − A_{ee}EROI)/(EROI − 1). If $A_{ee} = 0$ (see below for discussion of this coefficient), the latter factor is 1/(EROI − 1), which is more sensitive than 1/(1 − 1/EROI) to changes in EROI. For example, when EROI diminishes from 15 to 10, 1/(1 − 1/EROI) increases by 3.7%, but 1/(EROI − 1) increases by 56%.

Eq. (9) leads to a generalization: when only one of the A-coefficients varies, then the dependence of p_e and p_m on EROI is bounded by 1/(1 − 1/EROI) (less sensitive) and a more complicated function (usually more sensitive), depending on the relative magnitudes of v_e and v_m, and the three remaining A-coefficients. Table 4 summarizes the dependence from changing each coefficient singly. In Table 4 it is evident that the self-use of energy by the energy sector is the reason for the complication. When $A_{ee} = 0$, prices' dependence on EROI simplifies to 1/(1 − 1/EROI) or 1/(EROI − 1). Whatever the specific relationship in Table 4, though, prices become infinite as EROI approaches 1.0. This is expected when the supply of an assumed non-substitutable good approaches zero.

5. Self-use Coefficients A_{ee} and A_{mm}

The coefficients A_{em} and A_{me} are reckoned in terms of gross output. This means that the denominator in A_{me} is the gross primary energy into the U.S. economy. For EROI, we are interested in net figures. The self-flow coefficient A_{ee} accounts for the difference.

1. Under the larger question of relating energy in the ground (or, say, in the wind, to mention renewables) to usable energy, $A_{ee} \neq 0$ would seem appropriate. However, under the standard (economics-like) incremental view of EROI, it is irrelevant how much oil is used/"wasted" at the wellhead, how much gas is flared, or how much coal is left in place to prevent mine collapse. This argues for setting $A_{ee} = 0$ for primary energy sources.
2. Some recent work has gone beyond the incremental view to include onsite use (Cleveland, 2010). By point 1 above I do not favor this, but in any case one does not need to invoke $A_{ee} \neq 0$ for this. Instead, one could adjust E_{prim} to exceed X_e. Then the premultiplying vector in Table 3 and Eq. (1) would be (E_{prim}/X_e, 0) instead of (1, 0). This is called "absolute" energy analysis in Herendeen, 1988.
3. While on-site use or waste in primary energy can increase resource depletion rates, land use impacts, and greenhouse gas generation (Davidson and Andrews, 2013), it will not directly affect price.
4. A stronger reason for a nonzero A_{ee} is to account for conversion losses in secondary energy industries, e.g., in electric plants burning coal, or oil refineries burning natural gas or even crude oil.

In this article all energy sectors, primary and secondary, are aggregated to produce one kind of energy. By point 4, $A_{ee} > 0$ is required. X_e is the sum of primary energies (coal, crude oil and gas extraction, nuclear, and renewable), while X_{ee} is the sum of the energy flows among them, including self flows. $A_{ee} = X_{ee}/X_e$. Similarly, A_{mm} accounts for internal sales and shipments in the aggregated machinery sector.

6. Application to U.S. Economy

The value added coefficients v_e, v_m, and the four A-coefficients can be evaluated for the U.S. economy using various energy and economic data. In order to obtain enough detail, I have had to use the U.S. IO benchmark accounts from 2007 (BEA, 2014a). Updates beyond 2007 were not used because they lack an adequately high level of detail; e.g., coal mining is not separated from all mining. All monetary amounts in this article are therefore expressed in nominal 2007 dollars. Because the IO data are in the make-use format (BEA, 2009), a perfect correspondence is not possible with the commodity–commodity form of the IO table assumed in the model here. In determining U.S. energy intensities for 1977, Hannon et al. (1985) carefully covered this arduous problem, including the assumptions necessary for mathematical tractability. For

Table 4
Dependence of prices of energy (e) and machinery (m) when only one of the A-coefficients varies, in which case dependence on EROI is unambiguous. "Mix" means a weighted sum, depending on the (other three) A-coefficients that do not vary, and on ν_e and ν_m. If $A_{ee} = 0$, all terms in curly brackets reduce to 1.0 (see Eq. (7)).

If vary only this coefficient	p_e varies as	p_m varies as
A_{ee} (energy's self use)	Mix of 1/(1 − 1/EROI) and (1 − {1/EROI − $A_{em}A_{me}/(1 - A_{mm})$})/(1 − 1/EROI)	1/(1 − 1/EROI)
A_{mm} (machinery's self use)	1/(1 − 1/EROI)	1/(1 − 1/EROI)
A_{em} (machinery's energy use)	1/(1 − 1/EROI)	Mix of 1/(1 − 1/EROI) and {1 − A_{ee}EROI}/(EROI − 1)
A_{me} (energy's machinery use)	Mix of 1/(1 − 1/EROI) and {1 − A_{ee}EROI}/(EROI − 1)	1/(1 − 1/EROI)

the purpose of this article, however, a relatively quick approximation is adequate. Sources and results are in Table 5.

In Table 5 the two dominant contributions to A_{ee} are losses (27.77e15 Btu/yr) in fossil and nuclear electricity production (LLNL, 2007a) and energy consumed (3.5e15 Btu/yr) in oil refining. The latter is given in diverse quantities (kWh, barrels, cubic feet, etc.) in Refineries (2007), which I have converted to Btu. In addition there are:

1. electricity, gas, and refined petroleum used in crude oil and extraction and in coal mining,
2. electricity, gas (self-use, countable because this is a secondary energy industry), and refined petroleum used by gas utilities.

Tracking these is a quest for increasingly small quantities subject to increasingly complicated system boundary problems. Based on analyzing monetary flows in the 2007 IO table I estimate that they sum to approximately 0.5e15 Btu/yr. Total primary energy input in 2007 was 106.96e15 Btu, some of which was imported, some of which was ultimately exported (Annual Energy Review, 2007). Then $A_{ee} = (27.77 + 3.5 + 0.5)/106.96 = 0.297$.

Substituting the A-coefficients in Eq. (4) yields $\varepsilon_e = 1.446$ Btu/Btu, while EROI = 3.25 by Eq. (6) or (7) (Table 6 lists this result and others discussed below). EROI is surprisingly low compared with values typically seen in the literature for coal, gas, and most oil. The reason is that EROI calculated here is for primary energy, which is today dominated by fossil fuels. Inevitably a significant portion is lost in conversion, i.e., $A_{ee} > 0$. Eq. (7) indicates that the 2007 U.S. EROI cannot exceed $1/A_{ee}$ (here = 3.37) even if there were no machinery shipped to the energy industry at all, i.e., when $A_{me} = 0$. For comparison, setting $A_{ee} = 0$ yields EROI = 87, which is very likely too high. This may suggest that A_{em} or A_{me}, calculated here as economy-wide averages, are too low, that together they underestimate the embodied energy input to the energy industry. Another possibility is that A_{ee} must exceed 0 because (we decide that) some specific self-use must be included. For example, electricity distribution losses (which I have not included in A_{ee} in Table 5) are roughly 10%, which in 2007 would be roughly 1.2e15 Btu, amounting to a contribution of 0.011 to A_{ee}, which leads to EROI = 45. As usual, a judgment call on a system boundary affects the result. Also evident again is the difficulty of summarizing in “primary energy” the interplay of the several energy types.

Eq. (5) yields energy intensity of machinery, ε_m, =4110 Btu/\$. This is well below the 2007 ratio of energy to GDP, 7400 Btu/\$(2007). The reason is that ca. 40% of U.S. net energy (as in Fig. 1) goes directly to final demand (LLNL, 2007a) but only accounts for ca. 3% of GDP (BEA, 2014a), requiring machinery to produce 97% of GDP using only ca. 60% of net energy.

Eq. (8) yields $p_m = 0.992$ \$/\$ and $p_e = \$12.85/1e6$ Btu. The method used here should give $p_{m.} = 1.0$ exactly. The 0.8% discrepancy is a consequence of approximations in adjusting the make/use IO tables (BEA, 2009, 2014a) to the commodity–commodity approach. p_e is somewhat low; the U.S. Department of Energy 2007 all-energy price is \$18/1e6 Btu (Annual Energy Review, 2009, Tables 3.3, 3.4). As above, if A_{em} were higher than the average value used here, p_e would increase. As well, the Department of Energy price likely includes some trade margins while the IO tables, being expressed in producer prices, do not.

The most useful aspect of these rough estimates for the A-coefficients is how they will vary in the future. Accordingly, I normalize prices to the year 2007. Fig. 5 shows p_e/p_e (2007) and p_m/p_m (2007) as a function of EROI under the assumption that only A_{em} can vary. As predicted by Eq. (9), p_m exactly tracks the function $1/(1 - 1/\text{EROI})$, while p_e shows smooth variation intermediate between this function and $(1 - A_{ee}\text{EROI})/(\text{EROI} - 1)$, but closer to the latter. Because EROI is already so close to 1.0, prices are sensitive to changes in EROI, especially p_e, the price of energy itself.

Before discussing the validity of this apparent sensitivity in the conclusions, I briefly analyze the role of uncertainty. In Fig. 6, for each value of EROI, A_{ee}, A_{mm}, and A_{em} are allowed to vary randomly over a range of ±20%. A_{me} is then calculated to assure that EROI is unchanged. This is done 20 times for each value of EROI, and the resulting 20 values of p_e and p_m plotted in Fig. 6. As one would expect, p_e and p_m are no longer exactly predicted by EROI; rather, the connection is blurred out dramatically. Further, the prices vary beyond the bracketing functions. The blurring is much greater for p_e than for p_m. This is expected from Eq. (9), which shows that p_e depends on the more sensitive factor $(1 - A_{ee}\text{EROI})/(\text{EROI} - 1)$, which is close to zero because A_{ee} here dominates EROI. Additionally, variation in v_e and v_m, which here I ignore, would increase the scatter in Fig. 6.

7. Effect of EROI on GDP Inflator (Price Index)

Changed prices imply inflation or deflation in the nominal (also called current) GDP relative to the real GDP. Assume a constant physical final demand $\underline{Y} = (Y_e, Y_m)$ and initial prices $(p_{e,i}, p_{m,i})$, and final prices $(p_{e,f}, p_{m,f})$. Then the GDP inflator relating the final to the initial situation is

$$\text{inflator} = \frac{\text{GDP}_{\text{nominal, f}}}{\text{GDP}_{\text{nominal,i}}} = \frac{p_{e,f}Y_e + p_{m,f}Y_m}{p_{e,i}Y_e + p_{m,i}Y_m} \tag{10}$$

with the prices given by Eq. (5) or (8). For the special case when only A_{me} varies (see Eq. (9)), Fig. 7 shows the U.S. inflator as a function of EROI. The inflator closely tracks the price of machinery. This is expected, given that only a few percent of GDP is spent for energy.

8. Results of Previous Studies

Defining EROI has received much attention. System boundary is a recurrent issue; an important example is the question of self-use “within the fence” by the energy industry, as mentioned above. Cleveland and O'Connor (2013) argue for its inclusion and show dramatic differences between EROI calculated with and without it for oil shale (a primary energy source). These authors also refer to previous work in which “quality factors” are invoked to account for differences in usefulness of different types of energy, rather than merely combining them Btu-for-Btu.

Table 5

Coefficient values for the U.S. economy in 2007. “Machinery” is a surrogate term for the aggregated IO industry sectors other than the five energy sectors.

Sources: (a) BEA, 2014a; (b) BEA, 2014b; (c) Annual Energy Review, 2007; (d) LLNL, 2007a; (e) LLNL, 2007b; (f) Refineries, 2007.

Coefficient	Value	Units	Notes
v_e	5.137×10^{-6}	\$/Btu	[Sum of values added for sectors 2110, 2121, 2212, 2211, and 3240 (crude oil and gas extraction, coal mining, natural gas utilities, electric utilities, and refined petroleum products, respectively)$^{(a)}$]/[U.S. economy primary energy input$^{(c)}$]
v_m	0.5604	\$/\$	[Sum of values added for machinery]/[machinery total output]$^{(a)}$
A_{em}	1668	Btu/\$	[Machinery energy input$^{(c),(d),(e)}$]/[machinery total output$^{(a)}$].
A_{me}	3.929×10^{-6}	\$/Btu	[Machinery sales to energy sectors$^{(a),(b)}$]/[U.S. economy primary energy input$^{(c)}$]
A_{ee}	0.2970	Btu/Btu	[Sum of inter- and intra sectoral flows for energy sectors$^{(c),(d),(f)}$]/[U.S. economy primary energy input$^{(c)}$] (dominated by thermal losses in fossil fuel electric plants and losses in petroleum refining).
A_{mm}	0.4134	\$/\$	[Sum of inter- and intra sectoral sales for machinery]/[machinery total output]$^{(a)}$

Table 6
Results for energy intensities, prices, and EROI for the U.S. economy for 2007.

Quantity	Value	Units	Notes
ε_e	1.446	Btu/Btu	Excess above 1.0 is dominated by losses in fossil electricity generation.
ε_m	4110	Btu/$	This is less than energy/GDP (=7400 Btu/$) because ca. 40% of usable energy goes directly to final demand, not to industry and commerce.
p_e	1.285e−5	$/Btu	This is $12.85/1e6 Btu ≈ $1.60/gal gasoline equivalent (1 gal = 3.785 l).
p_m	0.992	$/$	This should be exactly 1.0. The 0.8% discrepancy is a consequence of approximations in adjusting the make/use IO tables (BEA, 2014a) to the commodity-commodity approach used here.
EROI	3.25	Btu/Btu	$\text{EROI} = \varepsilon_e/(\varepsilon_e - 1)$.

I see these efforts as arbitrary and revisionist to the original idea of net energy analysis as based on:

1. an incremental interpretation of the energy industries as servants of the larger economy,
2. the putative distinction of energy accounting as separate from economics (which would discourage introducing valuation).

Also, as stated above, within-the-fence self-use or "waste" by primary energy sources should not directly influence price. Indirectly, of course, it can, through the requirement for more machinery, etc.

There have been two recent publications on the price of energy implications of changing EROI. King and Hall (2011) derive an expression for price of U.S. oil and gas (they do not treat coal or electricity) that is proportional to 1/EROI. They use an energy intensity of the economy at large to convert the industry's inputs to E_{in}. Their assumptions in part are equivalent to not accounting for feedback of energy price on the price of non-energy goods, which they acknowledge. Using historical data they find that oil and gas prices roughly have increased proportionally to 1/EROI for 1954–2007, during which time the real price approximately quadrupled. (They use EROI calculated for the U.S. oil and gas industry from various sources, including their own work.) This fit to data justifies trusting the general trend, though there is no error analysis to deal with the considerable uncertainty in method (as discussed in this article) and data. King and Hall also discuss a problem related to the self-use term A_{ee}, mentioned earlier. They note that Cleveland and O'Connor (2013) have reckoned EROI ≈ 1–2.5 for shale oil, with E_{in} dominated by on-site self-use of oil, which leads King and Hall to predict an oil price of $80–$200/barrel. As argued above, I would omit this same-energy self-use, leading to a much higher EROI and hence a lower, more realistic oil price.

Heun and de Wit (2012) obtain an expression for the price of oil that is proportional to 1/(1 − 1/EROI). The first part of their expression (their Eq. (14)) accounts for the energy industry's input costs plus value added ("markup" in their terminology). This is then multiplied by 1/(1-1/EROI) to obtain the price of "delivered" energy. This is equivalent to assuming that all the energy industry's costs are assigned to net energy, so that the price = 0 for energy to support the energy industry, i.e., E_{in}. This is incorrect. There is no market in net energy; everyone buys gross energy, the price of which is affected by net energy. It is necessary to investigate the details of energy production costs, as King and Hall have done approximately and the present article does exactly. Heun and de Wit also test for correlation between U.S. real oil prices and Cleveland's (2005) results for U.S. oil's EROI for 1954–1996. During that period the oil price varied approximately fourfold while EROI varied between roughly 18 and 7. Their best curve fit is price ($2010/barrel) = $12.7 + 467\,e^{-0.359 * \text{EROI}}$. This expression increases by a factor of 3.76 as EROI decreases from 18 to 7, while 1/(1 − 1/EROI) increases by a factor of only 1.10. As well, 1/EROI (King and Hall's expression) varies by a factor of 2.57; 1/(EROI − 1) (one of several possibilities in Table 4), by a factor of 2.83. The familiar factor 1/(1 − 1/EROI) therefore seems the least predictive of energy price.

King and Hall (2011) and Heun and de Wit (2012) thus present evidence that oil/gas prices have an inverse relationship with EROI, though

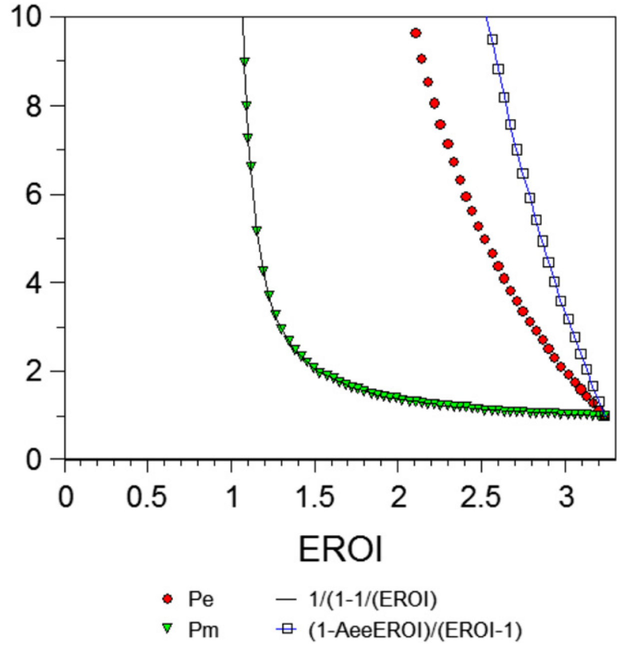

Fig. 5. Variation of the price of energy (p_e) and machinery (p_m) as a function of EROI, assuming that all variation is in coefficient A_{me}. p_e and p_m must lie between the bracketing lines indicated. All quantities are normalized to 2007, when U.S. EROI, as calculated here (primary energy terms), was 3.25.

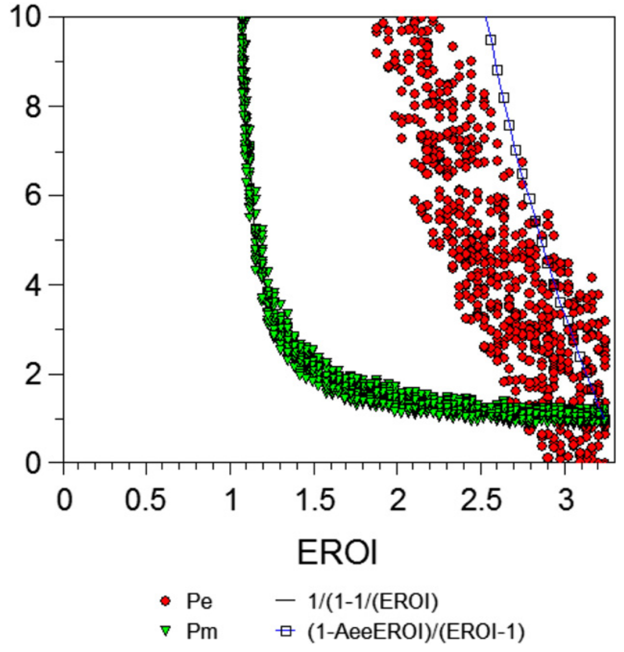

Fig. 6. Effect of randomness on the connection between EROI and prices. For each value of EROI, 20 combinations of the A-coefficients are used to calculate p_e and p_m. A_{ee}, A_{mm}, and A_{em} are allowed to vary randomly ±20%; then A_{me} is calculated to give the desired EROI. Negative values for p_e and p_m are not shown. The bracketing lines are the same as in Fig. 5, i.e., calculated for the unrandomized values of the A-coefficients, assuming that only A_{me} varies.

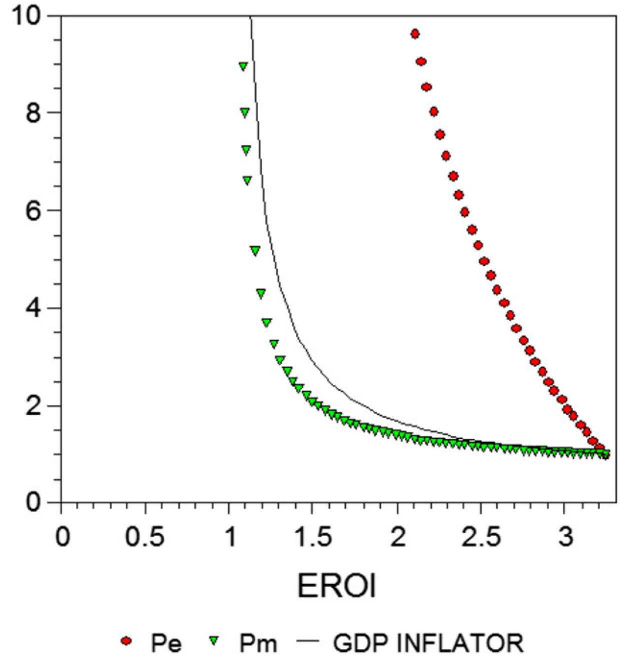

Fig. 7. GDP inflator vs. EROI, normalized to 2007, assuming that only A_{me} varies. The inflation closely tracks the price of machinery because only a few percent of GDP is spent for energy. 2007 final demand in mixed units: $Y_e = 3.372e16$ Btu/yr, $Y_m = \$1.416e13$/yr.

no error analysis was done. King and Hall define price $\propto$ 1/EROI and adhere to this in their data analysis, while Heun and de Wit initially define price $\propto 1/(1 - 1/\text{EROI})$ but must modify that with an expression more sensitive to changes in EROI. This is also seen in Fig. 5 of the present article, where (for total energy, not just oil and gas) energy price closely follows a function of $1/(\text{EROI} - 1)$. Both groups also point out that oil industry markup has varied, peaking in the U.S. around 1976–1982, giving price changes which are not directly attributable to EROI.

It is also possible to compare the results in this article with those of Hannon et al. (1985). These authors analyzed the 1977 U.S. IO data to obtain primary energy intensities (1.03, 0.97, 1.17, 3.65, 1.17 Btu_{prim}/Btu, using the commodity technology assumption) for coal, crude petroleum and gas extraction, refined petroleum, electricity, and natural gas, respectively. As far as I know this is the most recent full mixed-transactions-table IO analysis of the U.S. economy. By Eq. (6) these correspond to individual EROIs of 39, −29, 6.8, 1.4, and 7.0 for the five energy types. For example, $\varepsilon_{\text{refined}} = 6.8\ \text{Btu}_{\text{primary}}/\text{Btu}_{\text{refined}}$. The negative value for crude petroleum and gas extraction is unphysical and results from unavoidable complications of make-use IO bookkeeping. (An example is how to allocate energy inputs in a firm producing several byproducts.) Using these authors' intensities for the industry technology assumption, I obtain EROIs of 26, 15, 6.1, 1.4, and 9.2 Btu_{prim}/Btu, respectively.

One is tempted to calculate a weighted average of these intensities to compare with the energy intensity of the aggregated model used here. Unfortunately the weighting factors are made ambiguous by standard aggregation/system boundary problems. For totally consistent comparison one should create a two sector model from the 1977 data and then determine the energy intensity of the aggregated energy sector. Lacking that, I use a reasonable approximation of weighting the primary energy intensity of each energy type by its output to all non-energy sectors plus final demand. Eq. (6) is then applied to the resulting average intensity to yield EROI = 3.32 (commodity technology assumption) and 3.29 (industry technology assumption) for 1977. This compares well with the value of 3.25 for 2007 found here. Given the many uncertainties in the calculations, and the 30-year separation, this should be considered fortuitous agreement.

9. Effect of Imports on EROI

In 2007 32.3% of U.S. energy consumption plus exported energy ($=E_{\text{out}}$) was imported (Annual Energy Review, 2007, Diagram 1). The method used here implicitly avoids counting the foreign energy inputs to produce this imported energy. While-as usual-the system boundary is blurred, one can interpret this to mean that the domestic E_{in} was used to produce only 67.7% of Eout. This implies that a domestic EROI is $\text{EROI}_{\text{dom}} = 0.677 * \text{EROI}$ (calculated above) $= 0.677 * 3.25 = 2.20$. I do not pursue that issue further here.

10. Conclusions

The two sector mixed-unit IO model used here allows a consistent definition of EROI for a new energy facility or one integrated into a steady state economy (Eq. (6)). It also allows calculating prices for that IO system. Prices approach infinity as EROI approaches 1.0, an expected result for any non-substitutable good as its availability approaches zero. However, even for this very simple, idealized model, EROI does not uniquely determine prices because EROI and prices depend differently on the IO coefficients. On the assumption that only one of the four IO coefficients varies (say the one characterizing material inputs to the energy industry), EROI then does uniquely determine prices, with dependence bracketed by a combination of the factors $1/(1 - 1/\text{EROI})$ and $1/(\text{EROI} - 1)$. Uncertainty in the coefficients blurs the relationship.

Applying the model (and numerous simplifying assumptions) to the US economy for 2007 yields EROI = 3.25 in primary terms. That is, the aggregated energy industry consumed 1 Btu of primary energy (directly and embedded in commodity inputs) to provide a net of 3.25–1.0 = 2.25 Btu to the rest of the economy. This result is essentially, and likely fortuitously, identical with results of Hannon et al. (1985), for the 398 sector IO model of the 1977 U.S. economy. Because this EROI is relatively close to 1.0, prices should be highly sensitive to changes in EROI, so much so that one should be critical about the model's assumptions about constant value added coefficients.

In spite of various conceptual and definitional concerns, there is some consistency between this article and two empirical studies of oil and gas prices. This is that energy price should be a steeper function of EROI than the familiar gross energy/net energy factor $1/(1 - 1/\text{EROI})$. More likely is something like 1/EROI or $1/(\text{EROI} - 1)$.

There is a long list of sub-issues and implied extensions/improvements of this approach. For example:

1. Aggregation: Because at least 29.7% of U.S. primary energy input in 2007 was dissipated in fossil-fuel electric plants, oil refineries, etc., EROI for total energy is immediately constrained not to exceed 1/0.297 = 3.37, and the embedded energy inputs appear to reduce this only slightly. Various other definitions for EROI conceptually bypass these losses. For example, individual primary EROIs, obtained by applying Eq. (6) to results of Hannon et al. (1985), range from 39 (coal) to 1.4 (electricity) for 1977. But as long as we want to consider "total energy" powering the economy, the premise of this article, the problem persists.
2. Different energy types: Besides the familiar, but still ambiguous, issues in aggregating, say, gas and electricity-from-gas, renewable energy further complicates net energy analysis. As we turn to solar and wind electricity, the thermal losses in point 1 will diminish, so that primary EROI will likely increase in the future. This seems to contradict the usual picture of leaner sources leading to decreasing EROI, but is true if we count primary solar and wind energy inputs as free, which may be acceptable while we transition from fossil sources, but will be less so when the transition approaches completion.
3. A realistic pricing model: One could anticipate increased accuracy if one were to apply the IO price method (Eq. (2)) to the full U.S. IO

tables (388 sectors). But the method would still be based on very simplifying assumptions, especially given the world of subsidies, externalities, taxation, international currency manipulation, interest and discount rates, energy efficiency trends and potential, wars (declared or otherwise), national and global business cycles, environmental protection, speculation, corruption, conspiracies, and so on.

Given the issues in point 3, predicting prices is difficult; any models for the purpose will be subject to a similar, likely more complicated list of challengeable assumptions than mentioned or implied here. The present article has demonstrated difficulties in quantitatively involving net energy as an intermediary or "window" to get to prices. Net energy offers powerful insights, compelling justification for concern, and a valid way to evaluate greenhouse gas and other pollution impacts. But when it comes to quantifying prices, it is a laborious and even frustrating tangent, with ambiguous results. More emphasis on more conventional economics, properly done-which is a tall order, admittedly-is warranted, to determine price, which in the end, is the only variable that gets attention and stimulates sustained action.

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