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Energy intensity ratios as net energy measures of United States energy production and expenditures

C W King

Center for International Energy and Environmental Policy, The University of Texas at Austin,
1 University Station, C1100, Austin, TX 78712-0254, USA

E-mail: careyking@mail.utexas.edu

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Abstract

In this letter I compare two measures of energy quality, energy return on energy invested (EROI) and energy intensity ratio (EIR) for the fossil fuel consumption and production of the United States. All other characteristics being equal, a fuel or energy system with a higher EROI or EIR is of better quality because more energy is provided to society. I define and calculate the EIR for oil, natural gas, coal, and electricity as measures of the energy intensity (units of energy divided by money) of the energy resource relative to the energy intensity of the overall economy. EIR measures based upon various unit prices for energy (e.g. \$/Btu of a barrel of oil) as well as total expenditures on energy supplies (e.g. total dollars spent on petroleum) indicate net energy at different points in the supply chain of the overall energy system. The results indicate that EIR is an easily calculated and effective proxy for EROI for US oil, gas, coal, and electricity. The EIR correlates well with previous EROI calculations, but adds additional information on energy resource quality within the supply chain. Furthermore, the EIR and EROI of oil and gas as well as coal were all in decline for two time periods within the last 40 years, and both time periods preceded economic recessions.

Keywords: energy, net energy, energy return on energy invested, energy intensity, energy economics

 Online supplementary data available from stacks.iop.org/ERL/5/044006/mmedia

1. Introduction

Since the oil crises of the 1970s so heavily affected economic output in the industrialized world, various researchers have confirmed the dependence of the modern economy on the environment, energy, and sometimes more precisely energy or exergy services (Ayres 2008, Ayres and Warr 2005, Cleveland *et al* 1984, 2000, Costanza and Herendeen 1984, Georgescu-Roegen 1971, Kaufmann 1994, Odum 1996, Soddy 1926). Part of this pursuit revealed an understanding of not only the quantity of energy resources produced over time but also the quality. Quality is measured in many ways (e.g. energy density, cleanliness, etc), but one key measure of the systemic quality of energy resources and systems is the energy return on energy

invested (EROI). That is to say, with all other characteristics of two energy systems, technologies, or resources being equal, the one with higher EROI will have a higher value to society than the other. Societies and natural systems also organize themselves differently depending upon the EROI of their resources (Tainter 1988, Tainter *et al* 2003).

For fossil energy resources, analysts usually calculate EROI at the mine mouth as the energy content of the produced resource (e.g. oil) divided by the sum of energy inputs required to extract the resource (Hall *et al* 1986, 1981). Energy price and the total expense of purchasing end-use forms of energy also act as system-wide economic indicators describing the role of energy in the broader economy. Because energy is an inelastic good and increased energy prices are passed along to

other consumer goods, increases in energy price tend to reduce purchases of these more elastic discretionary goods more than energy itself (Hall *et al* 2008). In the US, over the past four decades since peak US oil production, economic growth was slow or the US was in recession whenever total energy expenditures were both increasing and above 10% of gross domestic product (GDP). For example, in the United States from 1971 to 1981 total expenditures on energy increased by an average of 5%/yr, and from 1974 to 1985 over 10% of GDP was spent directly on the purchase of energy (EIA 2008). From 1973 to 1974 and 1979 to 1980 the political motivations of the oil embargos drove the price of oil up quickly such that there were annual increases of 26% and 16%, respectively, in the per cent of US GDP spent on energy. The combination of both high levels and sharp increases in energy expenditures resulted in no real GDP growth for 1973–1975 and 1980–1982. While the events of the 1970s were politically motivated, their effectiveness in causing high prices was enabled by the physical reality of peak US oil production in 1970. Rising energy prices, driven by lower EROI, could certainly prevent economic growth independent of political factors. From 2003 to 2008, energy prices and US energy expenditures rose precipitously without any singular causal political event to restrict supplies, and these increases in energy prices played a major role in causing the latest recession (Hamilton 2009).

Thus, the motivation for this letter is to understand how measures of net energy relate to broader economic indicators of energy such as energy price and expenditures. I hypothesize that prices of energy largely reflect their EROI. EROI from US energy data is not easy to calculate, and the appropriate data from the US government sources are available only every five years at best. Thus, if the hypothesis is true, then a readily available EROI proxy can be estimated every year. In order to test this hypothesis, I derive and compare a proxy measure of EROI based upon prices and expenditures for energy. I call this proxy measure the energy intensity ratio (EIR). By calculating EIR at different points in the supply chain, I provide insight into the energy required to produce and distribute different forms of energy. For EROI calculations I use Cleveland (2005) for US oil and gas and Hall *et al* (1981, 1986) for US coal. I show that the EIR is a simply calculated indicator that is a proxy for EROI but uses readily available data of price, energy content, and energy intensity, energy consumption, and energy expenses of the overall economy. Because I show that EIR is a proxy for EROI, EIR must be greater than one for any energy sector, resource, and technology to be a net contributor of energy to the economy—just as is the case with EROI.

2. Definition and calculation of energy intensity ratio (EIR)

I define the EIR as the energy intensity of a fuel or energy resource divided by the aggregate economic energy intensity of a country (e.g. the US). Generically, energy intensity is energy consumed divided by some output or service provided. Throughout this letter I use a definition of energy intensity with units of energy per dollar, and I use annual average monetary

and energy data for computations. For the economy-wide, or aggregate, energy intensity (EI_{GDP}) of the US I use the definition as its total annual energy consumption divided by its annual gross domestic product (GDP) as in (1). These US-wide values of economic energy intensity are reported for each year by the US Energy Information Administration (EIA) in the Annual Energy Review in units of British thermal unit (Btu) per dollar (EIA 2008). A low value of economic energy intensity indicates that a relatively low quantity of energy enables a relatively high amount of economic value. In units of chained 2000 dollars¹, the US economic energy intensity dropped from 19 500 Btu/\$ in 1950 to 8500 Btu/\$ in 2008 (EIA 2008).

$$EI_{GDP} = \frac{\text{total energy consumption}}{\text{gross domestic product}} \sim \frac{\text{'energy input'}}{\text{'economic output in units of money'}} \quad (1)$$

I calculate the fuel energy intensity in two ways. I define one way using fuel price ($EI_{f,p}$) and the other way using the total expenditures for purchasing that fuel ($EI_{f,e}$) (see (2) and (3), respectively). As I show in this letter, using both formulations enables a broader understanding of the value of energy to the economy. Price-based fuel energy intensity is the energy content per unit of that fuel divided by its price per unit (see (2)). The EIA records the combined fuel price per Btu (e.g. inverse of fuel energy intensity) as well as the price and energy content of fuels separately (EIA 2008). If the fuel energy intensity is high, then fuel is cheap, and vice versa. Expenditure-based fuel energy intensity is the total US energy consumption of that fuel divided by the total US expenditures for that fuel for a given year. The total energy consumption for each fuel is estimated as the number of units of that fuel consumed multiplied by the average energy content per unit of fuel (see (3)).

$$EI_{f,p} = \frac{\text{Btu/unit}}{\text{\$/unit}} \sim \frac{\text{'energy output'}}{\text{'input price in units of money'}} \quad (2)$$

$$EI_{f,e} = \frac{(\text{total units of fuel consumed})(\text{Btu/unit})_{\text{avg}}}{(\text{total money spent on fuel})} \sim \frac{\text{'energy output'}}{\text{'input expenditures in units of money'}} \quad (3)$$

From (1), economic energy intensity is 'energy input to the economy divided by dollars given from the economy to the fuel sector'. From (2) and (3), energy firms within the economy 'produce an energy output to the economy for a given dollar input from the overall economy'. Thus, by dividing (2) and (3) by (1), I obtain unitless ratios that are proportional to 'energy output from energy-producing firms divided by energy input to energy-consuming firms', and I call these *energy intensity ratios* (EIR). Economic energy intensity is often used as a measure of increasing efficiency of the economy in terms of converting energy to value via technical change and economic restructuring (USDOE 2010). Thus, EIR is proportional to

¹ From EIA (2008): the chained dollar is a measure used to express real prices. Real prices are those that have been adjusted to remove the effect of changes in the purchasing power of the dollar; they usually reflect buying power relative to a reference year. The chained dollar is based on the average weights of goods and services in successive pairs of years.

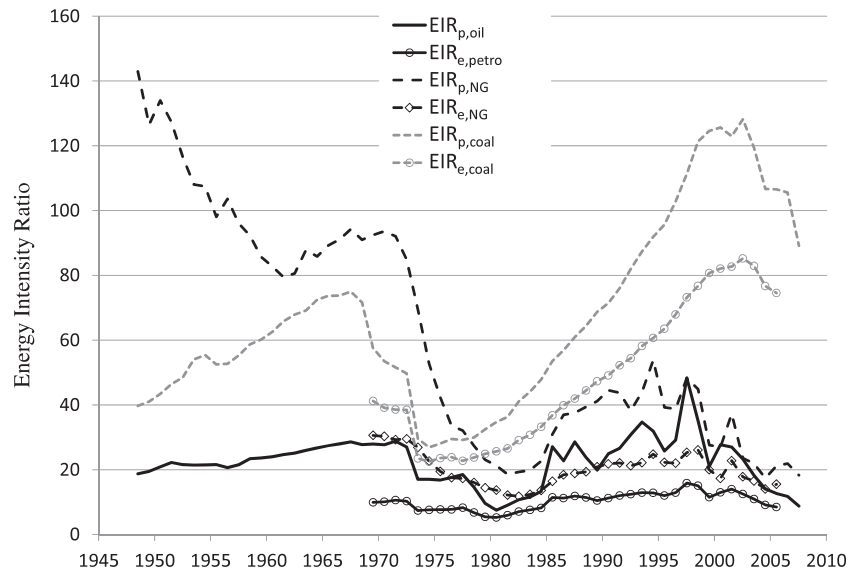


Figure 1. The US energy intensity ratios (EIR) for natural gas, coal, and oil show cyclical behavior, and all indicators were decreasing after 2003.

EROI (e.g. energy output over energy input) and measures the fuel energy provided to the economy relative to the effective use of all energy in the economy (i.e. output of all goods and services). Because EIR is normalized by economic energy intensity, it effectively measures the technical change of the energy sector relative to the technical change of the overall economy. For fossil fuels EIR is a measure of the net effect of resource depletion plus or minus the effect of technology.

I calculate the price-based annual EIR, EIR_p , of the United States for each major primary fossil fuel as in (4)–(6) (see figure 1). I also calculate the expenditures-based annual EIR, EIR_e , as in (7)–(9). The data used for GDP, energy consumption, expenditures on energy, energy content of fuels, and energy price are obtained from the US Department of Energy’s Energy Information Administration (EIA) Annual Energy Review (EIA 2008). Fossil fuel prices taken from the 2008 Annual Energy Review are the US first purchase price of oil (table 5.18), the NG wellhead price (table 6.7), and total coal price (table 7.8). As reported by the EIA, I adjust the energy content of each fuel to account for fluctuations over time; however, typical values are 5.8 MMBtu for each barrel (BBL) of oil, 1.03 MMBtu for each thousand cubic feet (Mcf) of natural gas (NG), and 20–24 MMBtu per short ton of coal. As the EIA reports GDP in units of chained 2000 dollars (EIA 2008), I use energy prices and expenditures in year 2000 chained US dollars. Figure 1 plots the values of EIR_p for oil, EIR_e for petroleum, and EIR_p and EIR_e for NG and coal in the United States. Petroleum includes crude oil and natural gas liquids used directly or refined into other final consumer products such as gasoline and diesel.

$$EIR_{p,oil} = \frac{EI_{f,p(oil)}}{EI_{GDP}} = \frac{\text{Btu}/\$ \text{ of oil}}{\text{Btu}/\text{GDP of economy}} = \frac{\frac{\text{Btu}}{\text{BBL}} \text{ of oil/oil price}(\frac{\$}{\text{BBL}})}{\text{Btu}/\text{GDP of economy}} \quad (4)$$

$$EIR_{p,NG} = \frac{EI_{f,p(NG)}}{EI_{GDP}} = \frac{\text{Btu}/\$ \text{ of natural gas}}{\text{Btu}/\text{GDP of economy}} = \frac{\frac{\text{Btu}}{\text{Mcf}} \text{ of natural gas/natural gas price}(\frac{\$}{\text{Mcf}})}{\text{Btu}/\text{GDP of economy}} \quad (5)$$

$$EIR_{p,coal} = \frac{EI_{f,p(coal)}}{EI_{GDP}} = \frac{\text{Btu}/\$ \text{ of coal}}{\text{Btu}/\text{GDP of economy}} = \frac{\frac{\text{Btu}}{\text{ton}} \text{ of coal/coal price}(\frac{\$}{\text{ton}})}{\text{Btu}/\text{GDP of economy}} \quad (6)$$

$$EIR_{e,petro} = \frac{EI_{f,e(petro)}}{EI_{GDP}} = \frac{\{\text{total petroleum consumption (Btu)}/\text{total expenditures on petroleum}(\$)\} \{\text{Btu}/\text{GDP of economy}\}^{-1}}{\text{Btu}/\text{GDP of economy}} \quad (7)$$

$$EIR_{e,NG} = \frac{EI_{f,e(NG)}}{EI_{GDP}} = \frac{\text{total NG consumption (Btu)}/\text{total expenditures on NG}(\$)}{\text{Btu}/\text{GDP of economy}} \quad (8)$$

$$EIR_{e,coal} = \frac{EI_{f,e(coal)}}{EI_{GDP}} = \frac{\text{total coal consumption (Btu)}/\text{total expenditures on coal}(\$)}{\text{Btu}/\text{GDP of economy}} \quad (9)$$

Per (4)–(9) EIR is an analog of EROI, and trends of EIR_p and EIR_e indicate the same impacts from EROI—namely that with all other aspects being equal, energy systems with higher EROI and EIR are of more benefit to society. The higher EIR becomes, the higher the value of the resource to the overall economy. The corollary is that low EIR presents a higher burden to economic growth. A few major trends appear in figure 1, and a comparison of these trends to those of EROI in section 3 indicates that there is justification in using EIR as an analogous measure to EROI.

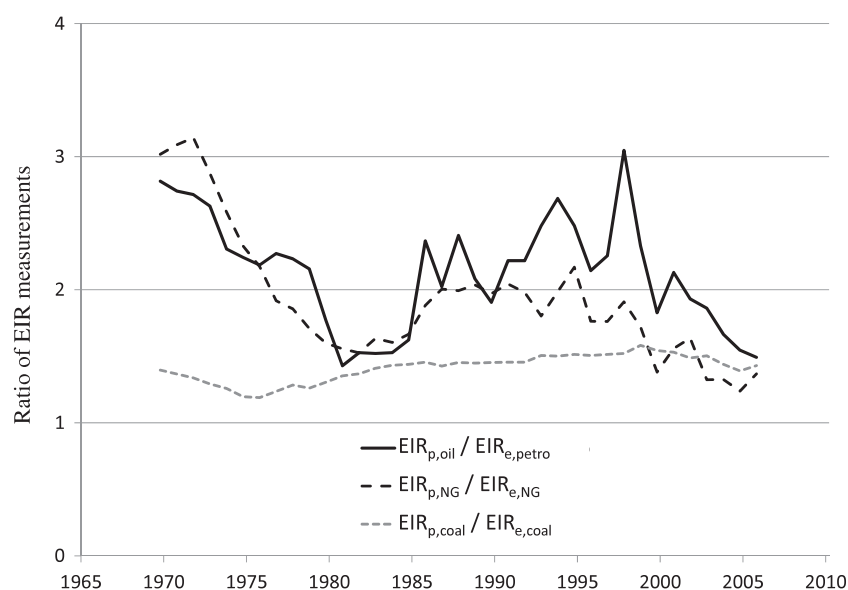


Figure 2. The ratios of $EIR_p:EIR_e$ were considerably lower during the recession of the early 1980s and moving to the latest recession that started in late 2007.

It is important to investigate both EIR measures. While the price of energy represents the marginal cost of a particular fuel at some point in the supply chain, the total expenditures on energy represent how much the total economy depends upon total energy consumption, or average cost of refined energy products (e.g. diesel and gasoline), at final purchase locations. One clear pattern from figure 1 is that $EIR_e < EIR_p$ for all fuels. This is to be expected because EIR_p uses prices at the point of production, energy hubs, or trading points whereas EIR_e uses expenditures that include final consumers far from energy hubs and production locations. Thus, they are measures at different points in the supply chain, with EIR_e representing the end of the energy supply chain. For example, $EIR_{p,oil}$ represents net energy of oil before refinement into gasoline, diesel, and other products. $EIR_{e,petro}$ represents net energy after petroleum products have been refined and delivered. Thus, one can view the difference between EIR_p and EIR_e as the difference between net energy from energy after production and energy after delivery, and EIR_e inherently includes labor costs factored into delivered prices.

Another important pattern emerges from comparing EIR_p to EIR_e : the lower the measures become, the closer they come to the same value (see figure 2). As the two EIR measures approach each other, it signals lower profit margins for fossil fuel refining and distribution versus fossil fuel extraction. Although the definitions of EIR dictate that both approach zero as energy prices and expenditures increase, the ratio of EIR_p to EIR_e cannot viably be less than one as this would indicate hub (or producer) prices are less than prices to final consumers. Thus, the EIR_p to EIR_e ratio could be an important economic indicator in addition to the nominal values of EIR and EROI. The two EIR measures are most similar during the US recession of the early 1980s as well as during the years leading to the recession starting in 2008.

2.1. EIR of oil and petroleum

The $EIR_{p,oil}$ typically lies between 10 and 30, but from 1949 to 2008 it ranges from 7.5 (1981) to 48 (1998) with a value of 8.8 in 2008 marking the year of the highest oil price in history and the beginning of the latest time period of US economic recession. The minimum $EIR_{p,oil}$ of 7.5 in 1981 also coincided with the peak of an economic recession in the US as well as the time of the highest overall cost of petroleum as a percentage of GDP at 8.5% (EIA 2008). $EIR_{e,petro}$ from 1970 to 2006 ranged from 5.3 in 1981 to 15.9 in 1998, the same years for the lowest and highest $EIR_{p,oil}$. In 1981 $EIR_{p,oil}:EIR_{e,petro}$ was 1.43:1 (minimum) and in 1998 3.05:1 (maximum). The $EIR_{p,oil}$ from 1949 to 1972 gradually increased from 19 to 29 with little volatility in the value. This lack of volatility can possibly be attributed to the Texas Railroad Commission (TRC) acting as an oil cartel by prorationing oil production in Texas from 1935 to 1973 to create a price floor for balancing supply and demand (Prindle 1981). With Texas as the swing state oil producer until US peak production in 1970, this balancing on the price was possible.

After 1972, the increased oil prices in 1973, caused by the Arab oil embargos, and again in 1979, impacted by the Iranian Revolution, forced the $EIR_{p,oil}$ to drop (e.g. lower Btu/\$ in the numerator of (1)). After the mid-1980s, the $EIR_{p,oil}$ follows a general rise and fall, with increased volatility and a steady declining trend since 1994 (with one anomalously high value in 1998). Due to the dramatic drop in the price of oil from 2008 to 2009, the $EIR_{p,oil}$ is higher in 2009.²

2.2. EIR of natural gas

The $EIR_{p,NG}$ is three to four times higher than $EIR_{p,oil}$ from 1949 until 1971, but dropped significantly from over 140 in

² $EIR_{p,oil} \sim 14$ in 2009 with oil price of \$51/BBL in 2000 US\$. The continuation of EIA data for 2009 was not yet available at the time of this writing.

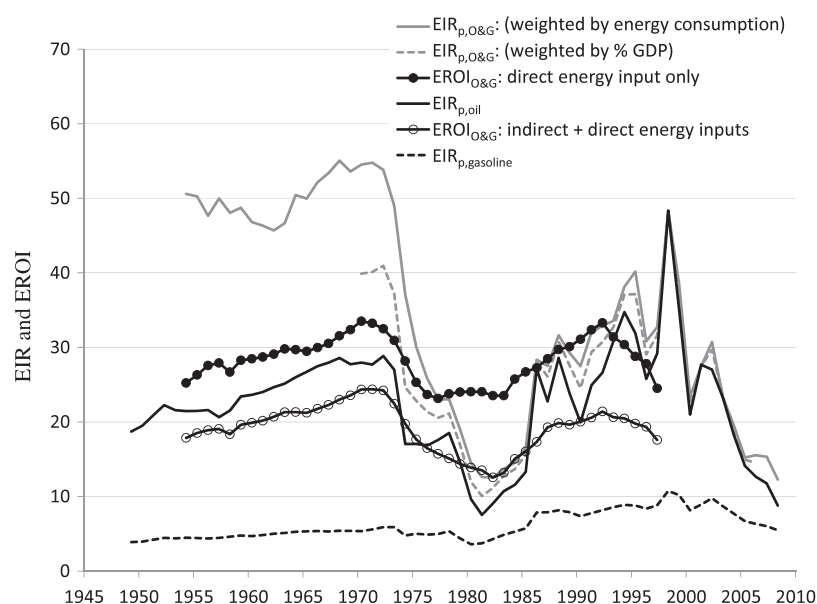


Figure 3. EIR_p and EROI for US oil and natural gas (O&G). The $EROI_{O\&G}$ from Cleveland (2005) is shown when considering only direct energy inputs (solid circles) as well as including indirect energy inputs (open circles). The EIR_p is shown for oil only ($EIR_{p,oil}$: solid black line), for both oil and gas ($EIR_{p,O\&G}$) when weighted according to two methods—the respective energy consumed from oil and NG (solid gray line) and percentage of GDP spent on petroleum and natural gas (dashed gray line), and for gasoline ($EIR_{p,gasoline}$: dashed black line).

1949 to 79 in 1962. The $EIR_{p,NG}$ also shows a steep decline from 94 in 1971 to 19 in 1982, driven by both a greater than 500% increase in the real price of NG as well as economic stagnation in the 1970s. Until the late 1970s the Federal Power Commission regulated the NG price at relatively low values. The Natural Gas Policy Act of 1978, effectively ending regulation of wellhead NG prices, allowed producer prices to rise and incentivized new production and interstate trade. $EIR_{e,NG}$ from 1970 to 2006 ranged from a low of 11.8 in 1983 to a high of 31 in 1970, and it was most certainly higher before 1970 following the pattern of $EIR_{p,NG}$. From the mid-1980s, the $EIR_{p,NG}$ began to follow a similar trend as the $EIR_{p,oil}$ and eventually came into alignment at nearly the same values after the mid-1990s. Starting in 2005 the $EIR_{p,NG}$ separated from $EIR_{p,oil}$, and this could indicate that unconventional natural gas resources (e.g. shale gas) are enabling some decoupling of $EIR_{p,NG}$ from that of oil. The ratio of $EIR_{p,NG}:EIR_{e,NG}$ has similar values to that for oil except after 1990 this ratio maintains a lower value (minimum of 1.24 in 2005) with slightly less volatility.

2.3. EIR of coal

The $EIR_{p,coal}$ shows two periods of increasing and decreasing values, and the pattern closely follows that of the production efficiency measure of tons of coal produced per employee hour (EIA 2008). Starting at a value of 40 in 1949, $EIR_{p,coal}$ rose almost continuously to 75 in 1968. From 1968 to 1975 $EIR_{p,coal}$ dropped quickly to 27 before starting a long rise to the range of 110–125 at the years around the latest turn of the century. In section 3 I compare EIR_p , EIR_e , and EROI to discuss how technology shifts and decline of resource quality explains much of the pre-1977 trends for coal. In the

early 1970s, appreciable production of sub-bituminous Powder River Basin coal began in the Western US, and this use of a new coal resource facilitated the rise in the $EIR_{p,coal}$ starting in the 1970s. It took almost a decade more for sub-bituminous coal to reach annual production of over 100 million short tons at 121 million short tons in 1979, or 16% of US production. Because of Western US coal production, $EIR_{p,coal}$ begins to rise almost immediately starting in 1975. Since peaking at 128 in 2003, $EIR_{p,coal}$ dropped 39 points to 89 in 2008 at nearly the same rate it rose 39 points from 82 in 1993 to 121 in 1999. The $EIR_{e,coal}$ smoothly follows the same trend as $EIR_{p,coal}$, and there is less volatility in the $EIR_{e,coal}$ than for either oil or NG. The minimum and maximum $EIR_{e,coal}$ were 23 and 85 in 1975 and 2003, respectively. The ratio of the two EIR measures is also relatively stable between 1.2 and 1.6, but began to drop after the peak ratio of 1.58 in 1999 (see figure 2).

3. EIR compared to EROI

In this section I compare EIR to past estimates of EROI for oil and natural gas ($EROI_{O\&G}$) and EROI for coal ($EROI_{coal}$). Figure 3 compares $EROI_{O\&G}$ to price-based EIR, EIR_p , for oil and natural gas while figure 4 compares $EROI_{O\&G}$ to expenditures-based EIR, EIR_e , for oil and natural gas. For each year tabulated for oil and natural gas (O&G), I use $EROI_{O\&G}$ estimated from Cleveland (2005) as he defined in (10). Cleveland (2005) calculated $EROI_{O\&G}$ for the combined O&G sector and included energy inputs from two basic categories: (1) direct energy—the direct consumption of fuels as well as in final energy carriers (e.g. electricity) and (2) an estimate of indirect energy—the energy required to make the materials and infrastructure (e.g. steel, concrete, etc) used during O&G operations. The energy output includes

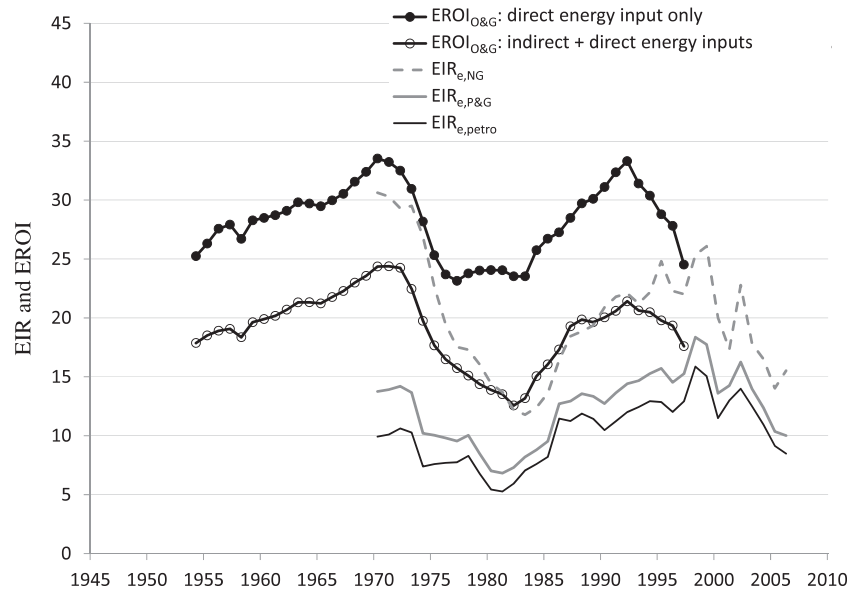


Figure 4. EIR_e and EROI for US oil and natural gas. The EROI from Cleveland (2005) is shown when considering only direct energy inputs (solid circles) as well as also indirect energy inputs (open circles). The EIR_e is shown for petroleum ($EIR_{e,petro}$: solid black line), for natural gas ($EIR_{e,NG}$: dashed gray line), and for combined petroleum and natural gas ($EIR_{e,P\&G}$: solid gray line).

the thermal energy of produced oil, natural gas, and natural gas liquids (NGL) (Cleveland 2005). Figures 3 and 4 show two $EROI_{O\&G}$ values for US O&G production. The closed circles represent $EROI_{O\&G}$ when considering only direct energy inputs (inferred from Cleveland (2005)), and the open circles represent $EROI_{O\&G}$ when considering both direct and indirect energy inputs. Note that the original calculations for $EROI_{O\&G}$ only exist for ten of the years (approximately every year ending in ‘2’ and ‘7’) shown as Cleveland (2005) estimated additional values by interpolation.

$$EROI_{O\&G} = \frac{E_{out}}{E_{in}} = \left\{ \left(\frac{Btu}{BBL} \text{ of oil} \right) (BBL \text{ of oil}) + \left(\frac{Btu}{Mcf} \text{ of NG} \right) (Mcf \text{ of NG}) + \left(\frac{Btu}{BBL} \text{ of NGL} \right) \times (BBL \text{ of NGL}) \right\} \{E_{in,direct} + E_{in,indirect}\}^{-1}. \quad (10)$$

I plot four values of EIR_p for comparison in figure 3:

$EIR_{p,oil}$: oil only—these are the values calculated from (1) as displayed in figure 1.

$EIR_{p,O\&G}$: oil and natural gas, weighted by two methods. To more effectively compare EIR_p of O&G to the $EROI_{O\&G}$ calculated by Cleveland (2005), I create a combined $EIR_{p,O\&G}$ for oil and natural gas as follows:

Percentage of GDP spent on each fuel: these values are the average of $EIR_{p,oil}$ and $EIR_{p,NG}$ weighted according to the total expenditures of US GDP on each fuel each year (EIA 2008). As an example, in 2006, 5.2% and 1.4% of US GDP were spent on purchasing petroleum and NG, respectively. Thus, for 2006, $EIR_{p,O\&G} = (EIR_{p,oil})(5.2\%/6.6\%) + (EIR_{p,NG})(1.4\%/6.6\%) = (12.7)(5.2\%/6.6\%) + (21.2)(1.4\%/6.6\%) = 14.5$.

Percentage of energy consumed of each fuel: these values are the average of $EIR_{p,oil}$ and $EIR_{p,NG}$ weighted according to the total energy consumed from each fuel for each year (EIA 2008).

$EIR_{p,gasoline}$: leaded and regular unleaded gasoline—these are the values substituting the price and energy content of gasoline for oil in (1). The price of leaded gasoline is used for 1949–1975, and the price of regular unleaded gasoline is used for 1976–2008 (EIA 2008).

I plot three values of EIR_e for comparison in figure 4:

$EIR_{e,petro}$: petroleum only—these are values calculated from (4) as displayed in figure 1.

$EIR_{e,NG}$: natural gas only—these are values calculated from (5) as displayed in figure 1.

$EIR_{e,P\&G}$: petroleum and natural gas—to more effectively compare EIR_e of O&G to the $EROI_{O\&G}$ calculated by Cleveland (2005), I create a combined EIR_e for petroleum (~oil) and natural gas. These data are calculated by dividing the sum of the numerators of (4) and (5) by the sum of the denominators of (4) and (5).

While the two $EIR_{p,O\&G}$ measures vary substantially before 1980, they mostly converge by the mid-1980s driven by increased incorporation of NG into the economy as a substitute for oil (e.g. for electricity) and deregulation of NG prices. From 1954 to 1972, the $EIR_{p,oil}$ measured approximately midway between the two $EROI_{O\&G}$ measures as the two $EROI_{O\&G}$ values appear to represent approximate upper and lower limits for $EIR_{p,oil}$ during the dates for which both measures are calculated. During this time the Texas Railroad Commission (TRC) was setting oil production limits and prorationing oil production in Texas. Thus, it is possible that the value of $EIR_{p,oil}$ between the EROI indicators is evidence that the TRC was effective at setting the oil price to

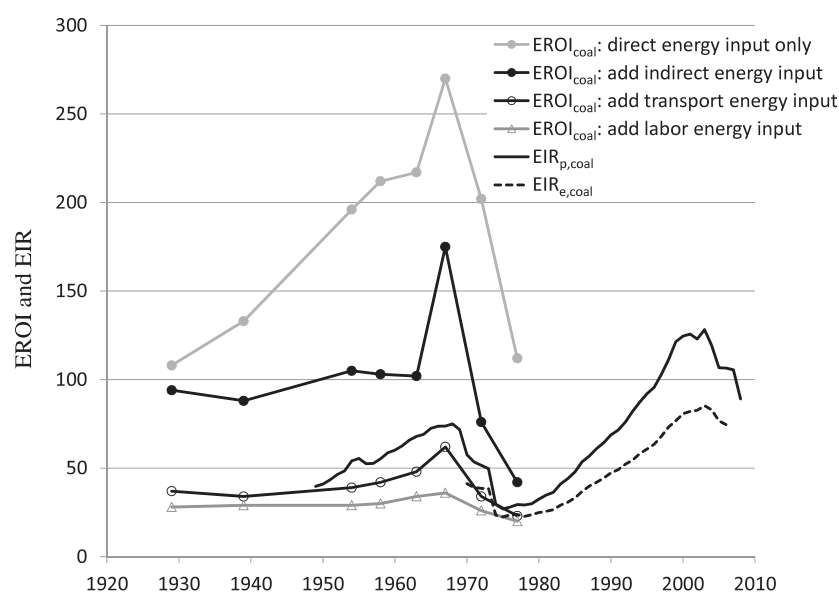


Figure 5. Energy intensity ratio and EROI (bituminous only per (Hall *et al* 1986)) for US coal production. The $EROI_{coal}$ from Hall *et al* (1986) is shown when considering only direct energy inputs (gray solid circles), adding indirect energy inputs (black solid circles), adding transport energy (black open circles), and adding an energy input for labor (gray open triangles). The $EIR_{p,coal}$ (solid line no markers) and $EIR_{e,coal}$ (dashed line no markers) are shown for total US coal consumption.

balance supply and demand in a forward-looking manner—as long as US production could easily outpace demand before US peak oil production in 1970.

After 1985 there is little difference between the $EIR_{p,O\&G}$ values in figure 3. Additionally, beginning in 1998, all EIR_p measures for oil and NG dropped quickly through 2008, and only the values of the early 1980s are lower. The $EIR_{p,gasoline}$ is expectedly lower than the EIR_p measures for oil and NG as delivered gasoline is the end of the supply chain before consumption in consumer vehicles. The $EIR_{p,gasoline}$ peaked at 10.8 in 1998 and had a low of 3.6 in 1980. In 2008 $EIR_{p,gasoline} = 5.5$, a value surpassed for all other years since 1985. For statistically comparing $EROI_{O\&G}$ to the two $EIR_{p,O\&G}$ calculations, there are only six overlapping years ($N = 6$) of calculations (1972, 1977, 1982, 1987, 1992, and 1997) due to data limitation from the US government (Cleveland 2005). However, calculating the Pearson correlation coefficient shows that there is high correlation between $EROI_{O\&G}$ including direct and indirect energy inputs with the $EIR_{p,O\&G}$ weighted by the percentage of GDP spent on petroleum and NG ($r = 0.93$), the $EIR_{p,O\&G}$ weighted by the energy consumed of petroleum and NG ($r = 0.93$), and $EIR_{p,oil}$ ($r = 0.84$). The first two correlations at $r = 0.93$ are statistically significant at the $p = 0.005$ level (i.e. less than 0.5% chance that the values are not correlated), and $r = 0.84$ is significant at the $p = 0.025$ level. Because both EIR and EROI are wholly or partly derived from economic rather than pure energy data, the correlation test indicates only that EROI and EIR capture the same changes in energy and economic phenomena rather than one value or the other is more correct.

As seen in figure 4 $EIR_{e,petro}$ and $EIR_{e,P\&G}$ are well below the indirect $EROI_{O\&G}$. Because $EROI_{O\&G}$ most closely represents net energy at production, it should most closely

resemble EIR_p rather than EIR_e , and this is verified in figures 3 and 4. Both EIR_p and EIR_e indicators for oil/petroleum and combined O&G/P&G follow the same trend as $EROI_{O\&G}$. In calculating the correlation coefficient for $EROI_{O\&G}$ and $EIR_{e,P\&G}$ I obtain $r = 0.80$, significant at the $p = 0.05$ level. However, $r = 0.69$ between $EROI_{O\&G}$ and $EIR_{e,petro}$ —too low for significance with $N = 6$. Due to the correlations between $EROI_{O\&G}$ and both $EIR_{p,O\&G}$ and $EIR_{e,P\&G}$, it is very likely that the $EROI_{O\&G}$ indicator dropped by the same relative amount (40%–60%) as those EIR indicators from 1997 to 2008.

In figure 5 I compare $EROI_{coal}$ to both $EIR_{p,coal}$ and $EIR_{e,coal}$ where the various $EROI_{coal}$ calculations are obtained from Hall *et al* (1986) who estimated $EROI_{coal}$ for US bituminous coal from 1929 to 1977. For the six years with comparable data $EIR_{p,coal}$ follows the trends of $EROI_{coal}$ and lies between the $EROI_{coal}$ measure that includes only direct and indirect energy inputs (solid black circles) and that which additionally includes transport energy inputs (open circles). Because over 90% of coal production was bituminous before 1973, the $EIR_{p,coal}$ before 1973 effectively represents a measure for bituminous coal comparable to the $EROI_{coal}$ presented by Hall *et al* (1986). The correlation coefficients from comparing the six overlapping years of data for $EROI_{coal}$ and $EIR_{p,coal}$ are 0.89, 0.96, 0.99 for the $EROI_{coal}$ measures including only direct and indirect energy inputs, additionally including transport energy, and additionally including labor energy, respectively. The first coefficient is statistically significant to the $p = 0.01$ level, and the last two at the $p = 0.005$ level showing a very high confidence in correlation. There are not enough overlapping data points to effectively compare $EIR_{e,coal}$ with $EROI_{coal}$, but it should match best with the lowest $EROI_{coal}$ that accounts for labor inputs to the point of delivery to power plants and industrial facilities.

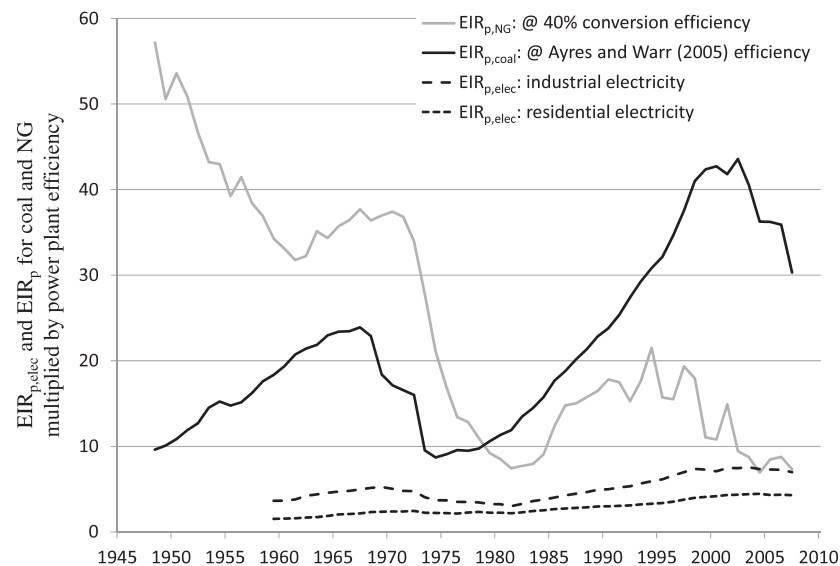


Figure 6. The $EIR_{p,elec}$ of industrial and residential electricity rose steadily from 1960 to 2005 after which both began declining. For quick comparison of $EIR_{p,elec}$ to electricity generated using NG or coal, the $EIR_{p,NG}$ and $EIR_{p,coal}$ are multiplied by a power plant conversion efficiency.

For $EROI_{coal}$ including all energy inputs, Hall *et al* (1986) attribute the relatively constant value from 1929 to 1954 to a time of constant mining technology and little to no exploration. During the 1950s and 1960s, the substantial introduction of mechanized mining increased indirect costs but decreased labor costs more substantially. However declining resource quality and increased energy inputs embodied in machinery most contribute to the $EROI_{coal}$ decline from 1969 to 1977 (Hall *et al* 1986).

The price used to calculate $EIR_{p,coal}$ from table 7.8 of EIA (2008) is the free-on-board (FOB), or undelivered, average price of coal. Today the difference between FOB and delivered coal price varies substantially across the US, and future work should estimate $EROI_{coal}$ after 1977 to reveal if $EIR_{p,coal}$ continues to correlate well with $EROI_{coal}$. Nonetheless, just as with oil and gas, $EIR_{p,coal}$ follows the same trends as $EROI_{coal}$ providing a quick, easy, and useful proxy measure of net energy.

4. EIR of electricity

With section 3 showing that EIR provides an accurate proxy measure for EROI for O&G and coal, I use EIR as an estimate for the overall system that produces and delivers electricity, a secondary energy carrier. This system inherently includes fuel production, power plant conversion, electricity distribution and transmission, and retail sales (for residential electricity). I calculated the EIR_p of electricity ($EIR_{p,elec}$) just as done for the primary fuels, as shown in (11). Because (11) is based upon consumer sales price rather than expenditures, the equation calculates $EIR_{p,elec}$. Thus, $EIR_{p,elec}$ represents net energy of electricity delivered to the consumer.

Figure 6 displays the results using both US residential and industrial electricity prices. Additionally, because NG and coal are commonly burned to generate electricity, I compare

$EIR_{p,elec}$ to the $EIR_{p,coal}$ and $EIR_{p,NG}$ multiplied by a standard conversion efficiency of a coal and natural gas combined cycle (NGCC) power plant, respectively. This qualitative comparison of presents only a first-order look at how to envision the supply chain of fuel to electricity, and future work can focus on more rigorous comparison. The conversion efficiency of a coal plant is taken from Ayres and Warr (2005) until 2000, and assumed at 34% after 2000. The conversion efficiency for a NGCC is assumed at 40%, a typical value for NGCC power plants operating on the grid even though NGCC plants can operate at higher efficiencies. Multiplying $EIR_{p,coal}$ and $EIR_{p,NG}$ by a conversion efficiency provides a comparison to the full $EIR_{p,elec}$. $EIR_{p,elec}$ inherently includes all costs associated with selling electricity, whereas the values obtained by multiplying $EIR_{p,coal}$ and $EIR_{p,NG}$ by conversion efficiencies should be larger in that they do not include the capital and operating costs of converting, distributing, and selling of electricity.

$$EIR_{p,elec} = \frac{EI_{f,p(elec)}}{EI_{GDP}} = \frac{\text{Btu}/\$ \text{ of electricity}}{\text{Btu}/\$ \text{ of economy}} = \frac{\frac{3410 \text{ Btu}}{\text{kWh}} \text{ of electricity} / \text{electricity price}(\frac{\$}{\text{kWh}})}{\text{Btu}/\$ \text{ of economy}}. \quad (11)$$

Because the industrial electricity price is lower than the residential price, its $EIR_{p,elec}$ is always greater. Industrial facilities use higher voltages and thus have less transmission and distribution costs. From 1960 to 2008, the $EIR_{p,elec}$ of residential and industrial electricity rose from 1.5 to 4.3 (peaking at 4.5 in 2005) and 3.6 to 7.0 (peaking at 7.6 in 2004), respectively. These trends imply that over the last 50 years investments in electricity infrastructure have returned increasingly more energy per that invested. The more significant downturn of the industrial $EIR_{p,elec}$ from 5.0 in 1971, to 3.0 in 1982, and back to 5.0 by 1991 shows the more

heavy reliance of industrial electricity on oil and NG than residential electricity.

The last 10 years of $EIR_{p,elec}$ data present particularly interesting information. The industrial $EIR_{p,elec}$ in 1998, at a value of 7.0, is the same as in 2008. Furthermore, the 2008 $EIR_{p,NG}$ multiplied by an assumed power conversion efficiency of 40% is at the same value as industrial $EIR_{p,elec}$ for that year. This comparison shows that NGCC-powered electricity may have difficulty continuing the trend of increasing industrial $EIR_{p,elec}$. However, my first-order comparison does not include the energy value of industrial facilities using excess heat in combined heat and power (CHP) applications. For a CHP comparison, I could use a higher energy conversion efficiency, but a full analysis is beyond the scope of the present work.

5. Conclusion

I have defined the measure of energy intensity ratio as a proxy measure for energy return on energy invested that is easily calculated for a country by using energy price, fuel energy content, total energy expenditures, total energy consumption, and energy intensity of the overall economy. The calculated EIR measures have high correlation with existing calculations for EROI of US oil and gas as well as US coal. Thus, the hypothesis of this letter is true: prices of energy resources, scaled by the energy intensity of the overall economy, do largely reflect their EROI (or at least existing measures of EROI). This is not too surprising given that the indirect energy input estimates for EROI involve the use of financial cost information that is scaled by energy intensity. Additionally, an important conclusion of the present work is that by using different EIR measures one obtains net energy information at different points in the energy supply chain (e.g. at oil production, at gasoline sales, as delivered electricity) to provide insight into the energy requirements for the overall energy system rather than a single technology or resource.

In the post-World War II era, the EIR and EROI of the US oil and gas industry and coal production have risen and fallen for two cycles. The last decade corresponds to the latest downward cycle for all three fossil fuels. This begs the question as to how long this trend could have continued without significant structural changes to the economy. Indeed recent studies suggest that the most recent oil price shock of 2007–2008 played no small part in the current economic downturn (Hamilton 2009). Because the US has had economic downturns (1970s to early 1980s) characterized by high percentages (>10%) of expenditures going to direct purchase of energy, it is possible that EIR and EROI can be forward-looking measures of the onset of economic difficulties caused by energy price rises. That is to say, EIR and EROI could represent bounding constraints on the percentage of energy expenditures that can occur without inducing economic recession. Because energy infrastructure changes slowly (e.g. power plants operate for over 40 years), investments made today affect energy prices several decades into the future, and EROI and EIR may present sound bases for projecting future energy production scenarios.

The EIR calculations of this letter also shed light into the nature of energy efficiency in the US. The economic energy intensity is often used as one measure of economy-wide energy efficiency. By calculating EIR in a manner that is normalized by economic energy intensity, we are able to track how well energy is produced relative to technological change. For example, in 1972 $EIR_{p,gasoline}$ was 5.9 and in 2008 $EIR_{p,gasoline}$ was 5.5. But during this time period the US average car fuel efficiency changed from 0.073 (13.7 mpg) to 0.044 (22.6 mpg) gallons of gasoline per mile traveled—an increase in efficiency of 39% (Davis *et al* 2010). Thus, even though there was significant improvement in car fuel efficiency, the net energy contribution of gasoline to economy was essentially the same in 2008 as three and a half decades earlier. Technology advancement and economic restructuring have only allowed the US economy to tread water with respect to net energy for petroleum (Charles 2009). Efficiency investment thus far has not significantly eliminated the need for fuels with high net energy.

In this letter I analyzed data describing only fossil fuels and aggregate electricity. But in the long term, the development of renewable energy technologies is a race to install them with the high EROI of past and current fossil energy resources before fossil resources are depleted to lower EROI. It is also likely insufficient to have energy resources with EROI just greater than unity, and researchers to date have given very little attention to the minimum EROI that may be required for a modern complex society (Hall *et al* 2009, Tainter *et al* 2003). For example, debates about whether or not corn-based ethanol has $EROI > 1$ (Farrell *et al* 2006, Patzek and Pimentel 2005, Pimentel 2003) rarely discuss how or when it is supposed to compete with petroleum and gasoline characterized by EROI and EIR many multiples higher.

It is important to guide future research to understand the meaning of crossover values of EIR and EROI from renewable and fossil alternatives as the use of more land for capturing renewable energy flows has a similar negative effect on long-run economic growth as depletion of fossil resources (Jones 2002). Thus, a need exists to calculate the trends of EROI and EIR for renewable energy technologies starting in the lab and continuing through commercialization. These early assessments will teach us better how to measure the pace of innovation in energy technologies. However, the lack of specific renewable energy prices or sector energy input data presents a difficulty for long term tracking. Future research should be directed at deriving methods and data for effectively comparing EROI of fossil and renewable technologies, on equal footing and over time. In this way, we can measure the innovation, or lack thereof, of both fossil and renewable energy systems.

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