ON RELATING US AND UK ENERGY EXPENDITURES (NET ENERGY), DEBT, AND INTEREST RATES

Carey W. King

Assistant Director - Energy Institute, University of Texas at Austin
2304 Whitis Ave., C2400, Austin, Texas
Phone: +1 512 471 5468/E-mail: careyking@mail.utexas.edu

Abstract

Anthropologist Joseph Tainter has posited a theory on the role of energy in describing the ability of a society to organize itself and solve social and environmental problems. Accordingly, in order to solve new problems and maintain existing services, societies tend to become more complex. In order to become more complex, societies need more energy and resources to coordinate this additional complexity. In this paper I explore long-term trends in net energy, debt, and interest rates in the United Kingdom (UK) and United States (US) to investigate relations between the relative cost of energy (and food) as a measure of net energy to that of economic growth and debt. If energy consumption increases along with increasing economic and societal complexity, I postulate that if debt does not accumulate then society is able to pay for its increased complexity. However, if debt accumulates, then I postulate that society is not able to pay for its current state of complexity. In many instances in the historical data, debt accumulates when the net energy of the US or UK economy is decreasing. For the most of the last 60-100 years, the net energy of the economies been increasing (i.e., the fraction of gross domestic product needed to purchase energy (and food) has normally been decreasing). However, the last decade is characterized by the trend of decreasing net energy and debt accumulation. The past decade is unique within the history of the time period of central banking, going back 300 years for the UK, in that this situation also occurs at a time of near zero interest rates. This suggests that the current time might mark a fundamental turning point in this history of the US and UK (or the world) that is characterized by the passing of the year of the cheapest energy in the history of mankind. If increased energy consumption is required to solve new problems and add complexity, and given increased energy consumption has been associated with decreasing costs, this poses the question of whether our modern economies will be able to increase in complexity to solve future challenges.

1 Overview

Anthropologist Joseph Tainter has posited a theory on the role of energy in describing the ability of a society to organize itself and solve social and environmental problems (Tainter and Patzek, 2012, Tainter, 1988, Tainter et al., 2003). Accordingly, in order to solve new problems and maintain existing services, societies tend to become more complex. In order to become more complex, societies need more energy and resources to coordinate this additional complexity. In a different approach for a similar purpose, Hall has contemplated a minimum value of net energy ratio (or minimum 'energy return on energy invested' ~ energy output/energy input) required for liquid fuel energy commodities to continue operation of our present transportation and economic system (Hall et al., 2009). *Tainter's compelling theory (based upon pre-industrial societies), needs quantification within the context of our modern society* powered by industrial energy technologies that depend upon and impact a variety of natural resources and other systems.

Energy prices and the total expense of purchasing end-use forms of energy act as system-wide economic indicators describing the role of energy in the broader economy. In recent history since the end of World War II, energy has largely been viewed as an inelastic good such that when prices increase, consumer consumption does not change very much. Thus, increased energy prices are passed along to other consumer goods, and increases in energy price tend to reduce purchases of these more elastic discretionary goods more than energy itself (Hall et al., 2008). However, United States (US) primary energy consumption peaked in 2007 (at 101.3 quadrillion Btu (EIA, 2014)) before the onset of the "Great Recession" that roughly is defined (globally) as mid-2008 to early 2009. Much of the reason for the slightly reduced US (and United Kingdom, UK) energy consumption, as well as the lack of continued increase in energy consumption, is the high price of energy post-2007 relative to the previous two decades. In particular, post-2007 oil prices have stayed higher than most of history due to higher marginal cost supplies such as from tight sands and shale formations.

Over the past four decades since US peak oil production and the 1973 Arab Oil Embargo, economic growth was slow or the US was in recession whenever total energy expenditures (measured as consumer prices with taxes by the Energy Information Administration, see the Annual Energy Review, 2012, Table 1.5) were both increasing and above 9% of gross domestic product (GDP). Recent work supervised by the author suggests that the energy expenditure trends for the US parallel those of other industrialized economies and the world overall (Maxwell, 2013). That is to say, both the early 1980s and late 2000s were times periods of world recession or very slow growth and time periods of high expenditures for energy as a fraction of world GDP. These are only two data points such that statistical methods might not account for their severity.

However, high debt has played a large role in the Great Recession following the financial crisis started in 2008. It is important that we understand the relationship(s) between the cost of energy (e.g. as a fraction of GDP) and debt accumulation over the long term. This paper focuses on the US and UK economies by relating the following energy-economic aspects for those countries:

- the Energy Intensity Ratio (EIR_p): a metric based on inverse energy prices as a proxy measure of net energy ratio of energy commodities,
- the fraction of GDP for energy (and food) expenditures and its inverse,
- public and private debt, and
- central bank interest rates.

This paper explores how the rates and types of investments in energy systems feedback to the macroeconomy. The evidence supports the view that if the fraction of GDP spent on energy (particularly oil (Kopits, 2009, Hamilton, 2013)) is large enough and occurs too quickly, then that situation either induces or coincides with major recessions (e.g., early 1970s, late 1980s, late 2000s) and can act as a limit, at least temporarily, on economic growth. While some debate these findings that energy can be a limit, most of the discussion is only within the context of the modern economy of the last several decades. There is a need to bridge economic theories and historical analyses of pre-industrial societies to that of the modern global economy. ***In essence the goal is to understand the nonlinear feedbacks of energy expenditures on societal economic growth and organizational complexity through time***.

This paper proceeds as follows. Section 2 describes the data sources and methodology for calculating the net energy metrics for individual energy commodities as well as the overall economy. Section 3 describes results in a series of figures that plot the time series of the metrics of interest as well as plotting the economic metrics versus those of net energy to look for patterns. Section 4 draws the major conclusions from the paper.

2 Methodology

2.1 Data Sources

2.1.1 Energy

I use data for US and UK energy production, consumption, and prices from the International Energy Agency (1978-2010) Energy Prices and Taxes, Energy Balances, and Energy Statistics available (for purchase) in the Beyond 20/20 Global Database. Other data on US energy consumption and types (e.g., electricity) are from the website of the Energy Information Administration (1980-2011). For long-term (1300-2008) energy time series (prices, consumption for energy services) data for the UK I use data from the works of Roger Fouquet (Fouquet, 2011, Fouquet, 2014, forthcoming).

2.1.2 Food

For US food expenditures data I use data from the Bureau of Economic Analysis (BEA) Table 2.3.5[1] annual personal consumption expenditures from 1929-2012. These expenditures include taxes for energy and food purchases as well as food purchases inside and outside of the home (e.g., at hotels and restaurants). For UK food expenditures from 1974-2011 I use data in the UK Family Food Survey[2] that includes household and 'eating out' expenditures on food and drink.

2.1.3 Interest rates, GDP, and GNP

Interest rate data are from the Federal Reserve of the United States[3] and Bank of England[4]. US GDP and gross national product (GNP) data are from the US Federal Reserve Bank of St. Louis[5]. UK GDP per capita and population data are obtained courtesy of Roger Fouquet and originally from the UK Office of National Statistics[6] and other references (Mitchell, 1988, Broadberry et al., 2011).

2.1.4 Debt

Debt data are from the Reinhart and Rogoff data set[7]. The core data are debt as a percentage of GDP and GNP, and I convert as needed to total debt in real US dollars and British pounds using real GDP data. One of the debt data sets for the UK is of external debt as a ratio of Gross National Product (GNP), rather than GDP, and I use the Penn World Tables[8] to convert UK GNP to GDP for some comparisons.

[1] http://www.bea.gov/iTable/iTable.cfm?ReqID=9&step=1#reqid=9&step=3&isuri=1&903=65
[2] https://www.gov.uk/government/statistical-data-sets/family-food-datasets
[3] http://www.federalreserve.gov/econresdata/statisticsdata.htm
[4] http://www.bankofengland.co.uk/boeapps/iadb/repo.asp
[5] http://research.stlouisfed.org/fred2
[6] http://www.statistics.gov.uk/hub/index.html
[7] http://www.reinhartandrogoff.com/data/
[8] https://pwt.sas.upenn.edu/

2.2 Metrics

2.2.1 Net Energy - EIR_p of energy commodities

As a proxy metric for the 'net energy' for energy commodities I use the calculation of the dimensionless price-based ("p") Energy Intensity Ratio (EIR_p) as previously defined and used in (King, 2010). The EIRp is a proxy for the net energy metric often referred to as 'energy return on energy invested' (EROI) for energy carriers, or the net energy ratio (NER). Roughly speaking, EROI and NER for energy carriers is the energy output from the economy for consumption divided by the energy inputs, via intermediate demands, required to provide that energy output (Cleveland et al., 1984, Hall and Cleveland, 1981, Hall et al., 1986, Modahl et al., 2013). In other words, EROI = (energy output) / (energy input), a dimensionless ratio. Just as when comparing energy prices (e.g., levelized cost of energy) among different energy technologies, there are important details about specifying boundaries for comparing EROIs of different technologies and resources. For the purposes of this paper, it is most important to understand that EROI and NER are inversely related to energy prices (King, 2010, King and Hall, 2011). EROI and NER are calculated using 'energy output' in the numerator, and energy prices (e.g., \$/kWh) are derived with energy output in the denominator. Thus, EIR_p scales in same manner as EROI and NER calculations, hence my calling it a price-based proxy.

Equation 1 shows the calculation for EIR_p as the ratio of two energy intensities (EI): $EI_{p,n}$ of energy commodity *n* at price *p* is the energy content of the fuel divided by its price, and $EI_{country}$ is the total primary energy supply (TPES) divided by the GDP of the country of interest. King (2010) showed that for the US, the EIR_p of oil, natural gas, and coal had the same general trends of the time series of EROI as calculated in the existing literature (Cleveland, 2005, Hall et al., 1986). This comparison showed that EIR_p is effectively a proxy metric for net energy ratio.

$$EIR_{p,n} = \frac{EI_{p,n}}{EI_{country}} = \frac{\left(\text{energy content}/\$\right)_n}{\left(\text{TPES}/\text{GDP}\right)_{country}} \qquad (1)$$

Thus, EIR_p can be a useful 'system wide' net energy metric that is effectively a scaled energy price affected by both production and consumption technologies and trends. Because energy prices are more available than net energy calculations, particularly for countries that do not produce much primary energy, the metric can be applied to all energy commodities and all countries as energy price data are available. For example, there are effectively no net energy calculations for grid electricity because it is by definition a mix of generation technologies and fuel sources, but calculation of EIR_p for electricity is straightforward. Further, by noting that net energy metrics such as EROI and NER are inversely related to energy prices (e.g., they are two sides of the same coin), we can potentially use forward looking EROI and NER calculations as complements to thinking of energy prices. This is important because there are not traded energy prices for all primary energy resources and technologies (e.g., solar photovoltaic panels), but there are life cycle assessments of many technologies that calculate EROI and NER.

2.2.2 Net Energy – NER of the economy

While the EIR_p metric is useful for characterizing systems and supply chains that produce individual commodities, it does not characterize an entire country. The NER for an entire country is approximated as the inverse of the fraction of GDP spent on energy, $f_{e,GDP}$, in that country (see Equation 2). In taking a long-term view of 'energy' consumption, we must consider that food and fodder were the main energy supplies of the preindustrial world. Thus, ***it is important to think about NER from both the 'energy only' and the 'energy + food' system boundaries***. In this paper, I consider both cases using data from multiple sources as described in the results.

$$NER^{-1}_{country} = f_{e,GDP} = \frac{\text{energy (and food) expenditures}}{\text{GDP}} \qquad (2)$$

It is important to note that the NER of a country is equal the average of all $EIR_{p,n}$ when the $EIR_{p,n}$ are weighted by the expenditures on each commodity *n*. For this paper, I calculate the $f_{e,GDP}$ and $NER_{country}$ (energy only) of the US and UK based upon more than one data set to compare boundary definitions and data sources. One calculation is based upon the IEA data set for coal consumption (for electricity generation, industry, and residential), natural gas consumption (for electricity generation, industry, and residential), an approximation for non-fossil electricity consumption (for residential and assuming all other consumption is industrial), and crude oil and refining feedstocks. The calculation in Equation 3, specific to using the IEA price and consumption data, is the sum of energy expenditures over all energy commodities with energy expenditures equal to price multiplied by consumption where p_n, and c_n are the price and consumption quantity, respectively, of energy commodity *n*. I do not yet account for net imports of refined oil products that can increase or decrease 'primary' energy consumption from crude oil. The non-fossil electricity consumption is assumed as a fraction of total electricity consumption that is equal to the fraction of total electricity generation that comes from sources other than coal, natural gas, and petroleum products (I use data from the US EIA for this electricity fraction).

$$NER^{-1}_{country} = f_{e,GDP} = \frac{\text{energy only from IEA data}}{\text{GDP}} = \frac{\sum_n p_n c_n}{\text{GDP}} \qquad (3)$$

In later sections, I also calculate a debt-adjusted GDP and corresponding debt-adjusted NER values to explore how net energy metrics do or do not correlate better to these metrics as an explanation of post-2000 economic trends.

3 Results

3.1 Time series of metrics of net energy, economic growth, and debt

3.1.1 EIR_p of US and UK energy commodities (time series)

Figure 1 and Figure 2 shows the EIRp calculations for the US and UK (England pre-1700, Great Britain 1700-1869, and UK after 1870) over time. All data in both figures are the same and are repeated for different time intervals to show detail for the later time periods.

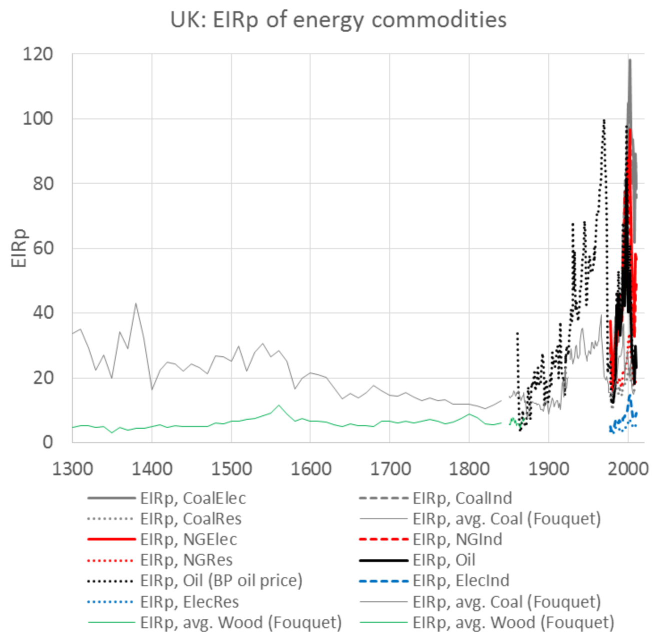
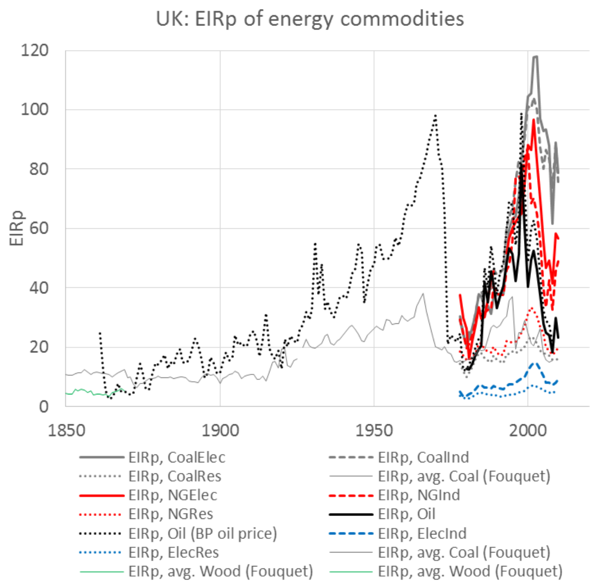


Figure 1. The long-term EIR_p of wood, coal, oil, natural gas, and electricity in England, Great Britain, and the United Kingdom. CoalElec/NGElec = coal/natural gas for electricity generation; CoalInd/NGInd/ElecInd = coal/natural gas/electricity for industrial consumption; CoalRes/NGRes/ElecRes = coal/natural gas/electricity for residential consumption.

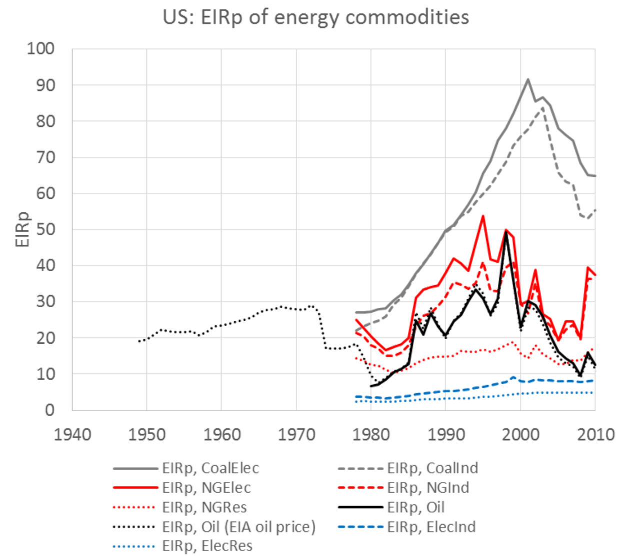
The $EIR_{p,coal}$ had a slow decline for approximately five centuries from 1300 to 1800 before increasing again in the 1800s, likely because of the introduction of steam engines to assist in dewatering of coal mines to increase the rate of coal production. The $EIR_{p,wood}$ remained less than 10 for all time except for the estimate for the decade of the 1560s.

This time series of Figure 1 indicates that coal has always had a higher EIR_p than wood. Of course the decision to use coal or wood was based on many factors related to quality (e.g., pollution) and the technology availability to use each fuel (e.g., furnaces and hearths), not only its cost (or net energy) (Fouquet, 2008).

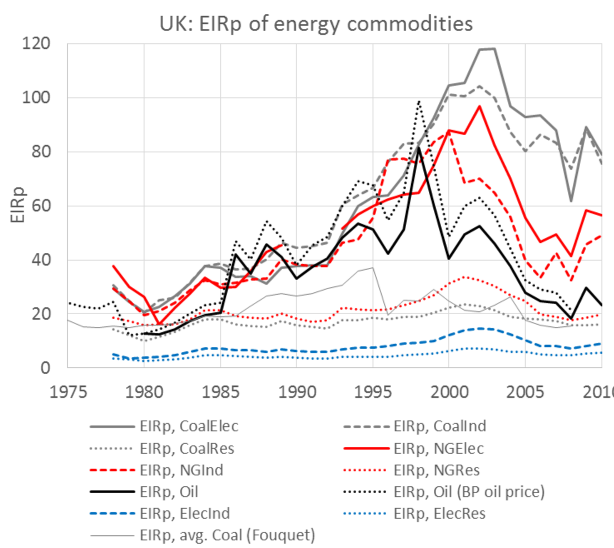
The general trend of Figure 1 and Figure 2, more prevalent from when considering the longer UK data series, is that the high EIR_p (> 40) of primary energy supplies during much of the 20th Century is a relative anomaly in history. However, there is likely some calibration needed between Fouquet's average coal price and the coal prices reported to the IEA from which the 1980-2010 EIR_p values are calculated. This calibration might cause the estimate $EIR_{p,coal}$ from Fouquet's data set to be larger for the entire time series. The differences might lie in the definition of TPES (as in Equation 1), and this calibration (or comparison) is left for future work.



(a)



(b)



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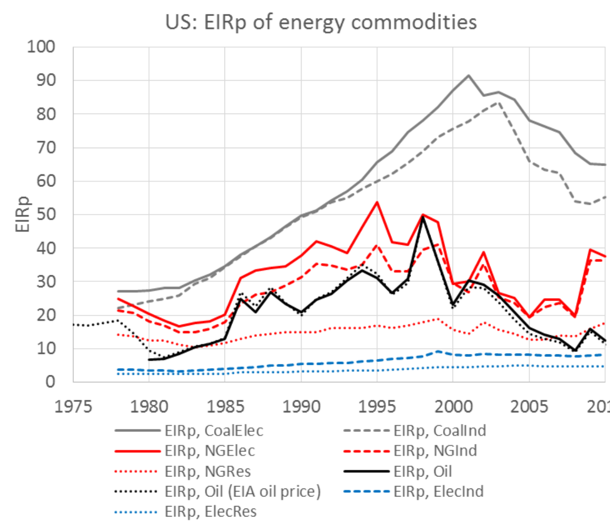
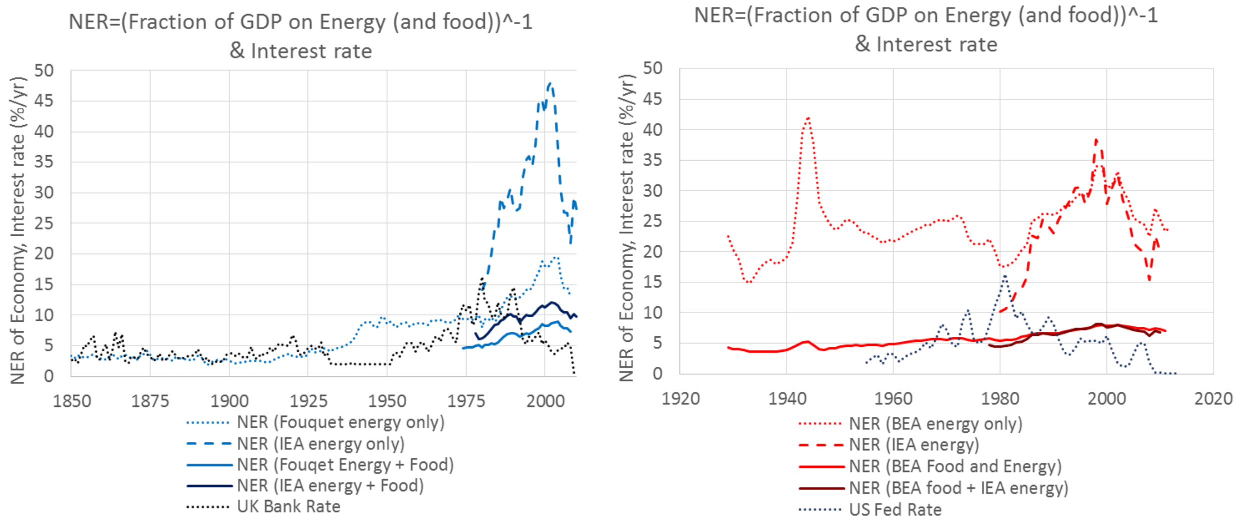


(d)

Figure 2. Following the 1973 Arab Oil Embargo, the EIR_p of all energy commodities rose from near 1980 to the late 1990s before falling until 2008. The $EIR_{p,oil}$ uses IEA first import prices into the US and UK. For the UK, I also calculate $EIR_{p,oil}$ to a longer-term time series of the world crude oil price as reported in the BP Statistical Review of World Energy ("BP oil price). For the US, I calculate an additional $EIR_{p,oil}$ using the EIA US average first purchase price. The EIR_p of all other energy commodities use prices and energy intensity (EI_{US} and EI_{UK}) from the IEA. CoalElec/NGElec = coal/natural gas for electricity generation; CoalInd/NGInd/ElecInd = coal/natural gas/electricity for industrial consumption; CoalRes/NGRes/ElecRes = coal/natural gas/electricity for residential consumption.

3.1.2 Net Energy Ratio (NER) US and UK economies (time series)

Figure 3 shows the time series of the NER of both the US and UK economies over time for the available data. There are ***two system boundaries for the NER calculation***: *energy only* as well as *energy and food*. For both boundaries, both the US and UK have a peak in NER in the late 1990s to mid-2000s. It is the purpose of this paper to place these net energy trends into the context of the present high debt levels (equal to or greater than the highest historical debt levels) and low interest rates.



(a) **(b)**

Figure 3. Different measures of the NER of the overall (a) UK and (b) US economies show that the peak was in the late 1990s to early 2000s when considering a boundary of energy only or when considering energy and food expenditures together.

The data series for expenditures of energy in the UK originate from the expenditures for energy used to provide the energy services of heat, power, transportation, and light (Fouquet, 2010, Fouquet, 2014, forthcoming). The price of energy in the Fouquet data series do not account for the cost of labor (e.g., human capital) but do account for the cost of "agricultural products" for food and fodder that provided the energy to humans and animals for farm work in pre-industrial UK and England. For most of history (before 1930) Figure 3a indicates that the NER of the UK economy was less than 10. I do not show values from 1300-1850, but the NER is between 2.3 and 4.6 for all decades within that span except for the 1340s when NER was below 2 following the Black Death in 1348-1349 that killed approximately one-half of England's population.

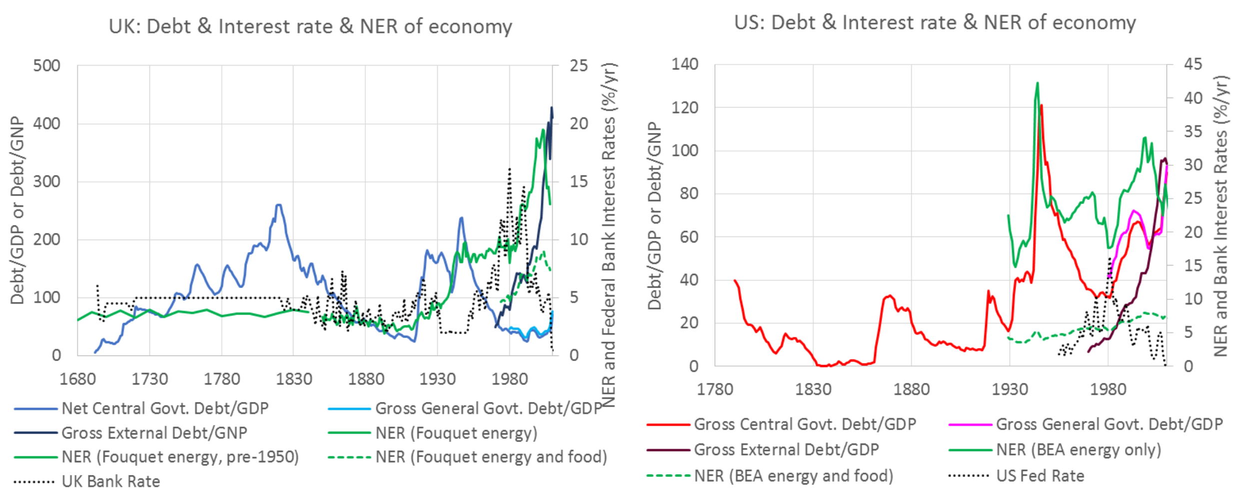
After 1930 the benefits of fossil-fuelled industrialization seem to kick in pushing the NER near 10 (based on the Fouquet energy series). As the UK transformed into an industrial economy, less food and fodder was associated with "energy" for animate power (its traditional use), such that today food is no longer generally considered part of the total primary energy supply. Thus, the NER using the Fouquet energy time series lies in between the NER of the energy-only series using the IEA data and above the NERs when we add the UK Food Survey expenditures to both the IEA and Fouquet data series. If we had the data to extend the "energy and food" NER calculations backwards from the 1970s to the 1920s, we might expect it to align relatively well, or be slightly below, the NER shown for "Fouquet energy only".

Even though the US BEA data include final consumer purchase prices including taxes, the NER of the energy-only calculations using both BEA and IEA data are relatively consistent. Here the main difference is that the IEA data do not include consumer expenditures on taxed refined petroleum products (e.g., gasoline, diesel) so one should expect the NER using the IEA data to be higher (have lower expenditures) than using the BEA data for ‘energy goods and services’. On the other hand, since the BEA data are derived from “personal consumption expenditures” they do not include industrial consumption of energy, and that would tend to make the NER from the IEA data lower (higher expenditures) than that from the BEA.

When considering ‘food and energy’, the trends for the US are similar to that of the UK. Both countries spend a relatively low percentage of GDP (or income) on food. The data estimate the UK minimum food expenditures in 2007 at 5.8% of GDP and the US minimum food expenditures in 2006 at 9.3% of GDP. These correspond to peaks in NER for ‘energy and food’ for the UK at 9.0 (2004, ‘Fouquet energy + food’) and 12.1 (2002, ‘IEA energy + food’) and for the US at 8.0 (2002, ‘BEA energy + food’), 8.2 (1998, ‘BEA food + IEA energy’).

3.1.3 Debt and NER over time

Figure 4 plots the time series of the NER of Figure 3 while comparing to the Reinhart and Rogoff time series for debt levels as a ratio of GDP or GNP. US and UK federal bank annual interest rates are also plotted for reference. Given the greater than 300-year time series for UK bank rates, one can see that interest rates greater than 5%/yr are anomalous. UK bank rates > 5%/yr have only persisted from 1956-2007. Perhaps interest rates > 5% for the UK and US will have only happened for a short time in history in post-World War II.



(a) **(b)**

Figure 4. (a) UK and (b) US debt and NER over time. The UK Bank of England Bank Rate and US Federal Interest rate are also shown.

The purpose of Figure 4 is to explore if there are any relationships between debt accumulation and low net energy (low NER) for the economy. I do not attempt to explain all important factors related to historical debt accumulation in the US and UK. At first glance there appears to be no distinguishable correlation between NER and debt levels. Given the limited scope the comparison of net energy to debt might not be the most appropriate. Debt is a stock (or an accumulation) and NER is more equivalent to describing the profitability of flows related to GDP (a flow). I compare NER to the *rate of accumulation* of debt in a subsequent section.

3.1.3.1 United Kingdom

For the UK, one notable trend is the long-term debt accumulation from the beginning of the data series in 1692 until 1819 at a ratio of 260 net public debt relative to GDP. This occurred during a time of relatively constant NER between 3 and 4 and interest rates at 5%/yr.

After the 1820s coal production started to pick up substantially, possibly enabling or being driven by, the lowering of interest rates. The lower interest rates would encourage investment, and the increased consumption of high EIR_p coal in new industrial machinery increased productivity greatly. Non-ferrous industrial coal consumption increased from approximately 1.2 million tonnes of oil equivalent (Mtoe) in 1750 to 3.2 Mtoe in 1800 (Figure 4.2, (Fouquet, 2008)). Also domestic "effective heating" using coal increased from 0.5 Mtoe in 1800 to 1.2 Mtoe by 1850. From Fouquet's data, I also estimate a significant decrease in the percent of GDP for "power" services in the early 1800s (1810s: 18.1%, 1820s: 15.0%, 1830s: 12.5%, and 1840s: 14.2%) where before the 1810s this percentage was greater than 17% (using data from (Fouquet, 2014, forthcoming)). It was also relatively warm in 1820s-1840 in the UK following a cold snap in the 1810s (Figure 4.7, (Fouquet, 2008)). Thus, the demand for heating was relatively lower in the few decades after 1810 compared to the previous few decades. Agriculture would have also benefitted during this warmer time.

After 1900, the three time periods of rapid debt accumulation are associated with World War I and II (for public debt) and post 1970 for total public and private debt that increased at an average rate of 6%/yr. Further, the increases in debt from 2005-2010 are significant – almost doubling for public debt relative to GDP and 27% higher for total debt relative to GNP. The NER of both 'energy only' and 'energy and food' increase from 1980 to their peaks in the 2000s.

3.1.3.2 United States

Similar to the UK, sharp increases in US public debt/GDP are associated with warfare: early 1860s (US Civil War), late 1910s (World War I), and early 1940s (World War II). Debt accumulation after the onset of the Great Depression (1929) is more pronounced for the US than the UK, perhaps because the UK was already in a higher debt regime.

The NER (using BEA energy only data) appears slightly correlated with net public debt/GDP (correlation coefficient, r = 0.56), but this is only a curious finding at this point. It implies that historically energy became cheaper as debt was accumulated by the government, perhaps via tax breaks, government loans, or other means. This is an area for future investigation because the 1970s were a time of intense change and investment in energy efficiency, energy policy, and environmental regulation whereas the US and UK political movements shifted in the 1980s to reduce regulation. In particular, in the US there were significant energy cost-reducing impacts from vehicle fuel efficiency standards (e.g. Corporate Average Fuel Economy) and a shift to more coal-fired electricity, largely powered by cheap Powder River Basin coal.

The reduction of debt, and ability to forgive European debt after World War II could have been enabled by the large quantity of cheap US energy production. After the East Texas oil fields were discovered, the oil was so prolific that the Texas Railroad Commission was forced to regulate the oil price by prorationing Texas oil production (to prevent a price collapse) (Mitchell, 2013, Yergin, 1991). The high estimate for the EROI of US oil and gas at the well is 24 in 1954, and the $EIR_{p,oil}$ reported in this paper is

25 in 1954 increasing until 1972 to 29 (see Figure 2). Undoubtedly, US oil production costs were low (EROI and $EIR_{p,oil}$ were high) through 1970 at the time of the (as of now) peak US oil production rate.

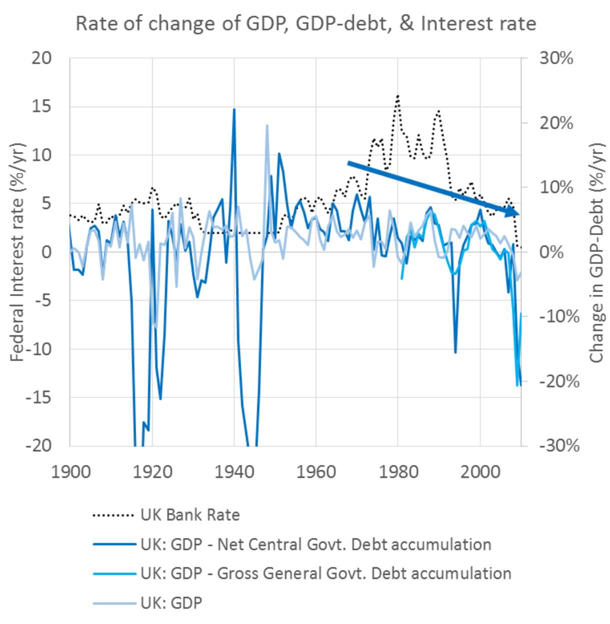
Just as in the case of the UK, the US NER of both 'energy only' and 'energy and food' increase from 1980 to their peaks in the late 1990s/early 2000s alongside a deregulatory energy political environment.

3.1.4 Change in GDP and debt-adjusted GDP

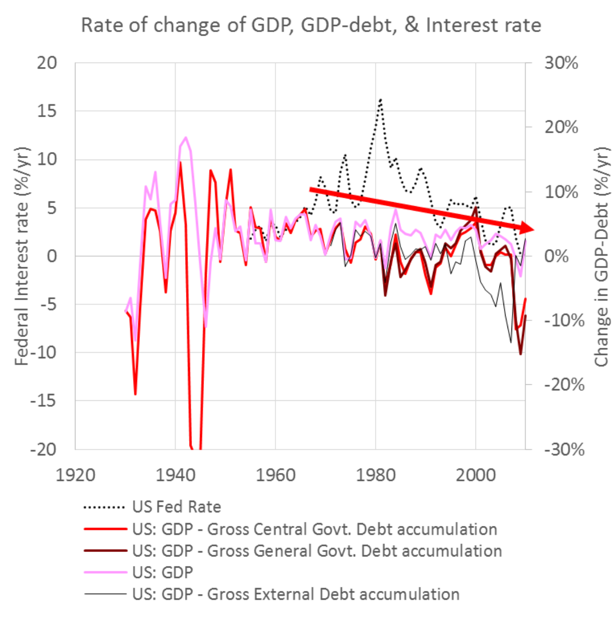
In this section I describe the time series for annual changes in GDP and debt-adjusted GDP (see Figure 5). The reason for using debt-adjusted GDP is to account for GDP growth in year *t*, accompanied by increases in debt (spending) in year *t* while consuming energy in year *t*, but for which the debt is theoretically to be repaid in future years *t +1*, *t+2*, … . I define debt-adjusted GDP in Equation 4 and the annual change, Δ, in debt-adjusted GDP in Equation 5. The annual change in GDP is $\Delta GDP_t = (GDP_t - GDP_{t-1})/GDP_{t-1}$.

$$\text{debt-adjusted GDP}_t = \text{GDP}_t - \text{debt}_t \qquad \textbf{(4)}$$

$$\Delta(\text{debt-adjusted GDP})_t = \frac{(\text{GDP}_t - \text{GDP}_{t-1}) - (\text{debt}_t - \text{debt}_{t-1})}{\text{GDP}_{t-1} - (\text{debt}_t - \text{debt}_{t-1})} \qquad \textbf{(5)}$$



(a)



(b)

Figure 5. The annual change in GDP and debt-adjusted GDP for various debt measures shows a marked declining trend after World War II for both the (a) UK (1900-2010) and (b) US (1929-2010).

Perhaps the most striking notes of the trends in Figure 5 are that:

1) changes in debt-adjusted GDP (and GNP) are more highly variable than changes in GDP,
2) annual changes in GDP post-World War II are generally > 0,
3) annual changes in debt-adjusted GDP are often < 0 after 1980, and

4) annual changes in debt-adjusted GDP are significantly < 0 for end of the time series (for UK 2008-2010; for US 2001-2010) and comparable only to the time periods of World War I, the Great Depression, and World War II.

For the time period 1949-2010, the UK trend in ΔGDP has been slightly downward (linear trend down 0.05%/yr, and low correlation r^2 = 0.09) but Δ(net central govt. debt-adjusted GDP) has trended significantly more downward (linear trend down 0.18%/yr, and higher correlation r^2 = 0.33). For the US the trend in ΔGDP has been slightly downward (linear trend down 0.04%/yr, and low correlation r^2 = 0.07) but Δ(gross central govt. debt-adjusted GDP) has trended significantly more downward (linear trend down 0.13%/yr, and higher correlation r^2 = 0.34).

One can ask the question of what is fundamentally the same and different between the four time periods mentioned in item 4) above. Arguably the US has been engaged in a war effort since the September 11, 2001 terrorist attacks. This war effort has been ramping down since 2009, but more significantly so after 2010. Clearly deficit spending occurs during major war efforts of the UK and US, but perhaps the 21st Century is the first major war spending ending at a time of foreseeable high oil prices ***and*** when the NER for energy and food has been decreasing for a decade (i.e., energy and food expenditures as a fraction of GDP have increased over the last decade). *This combination is unprecedented since the Great Depression*. During World War II the US was benefitting from extremely cheap oil production that was increasing in supply largely from oil fields in East Texas, and this likely played a large role in not only repaying US debt, but in enabling the forgiveness of debt to many European allies.

3.2 Plotting metrics of net energy versus those of economic growth and debt

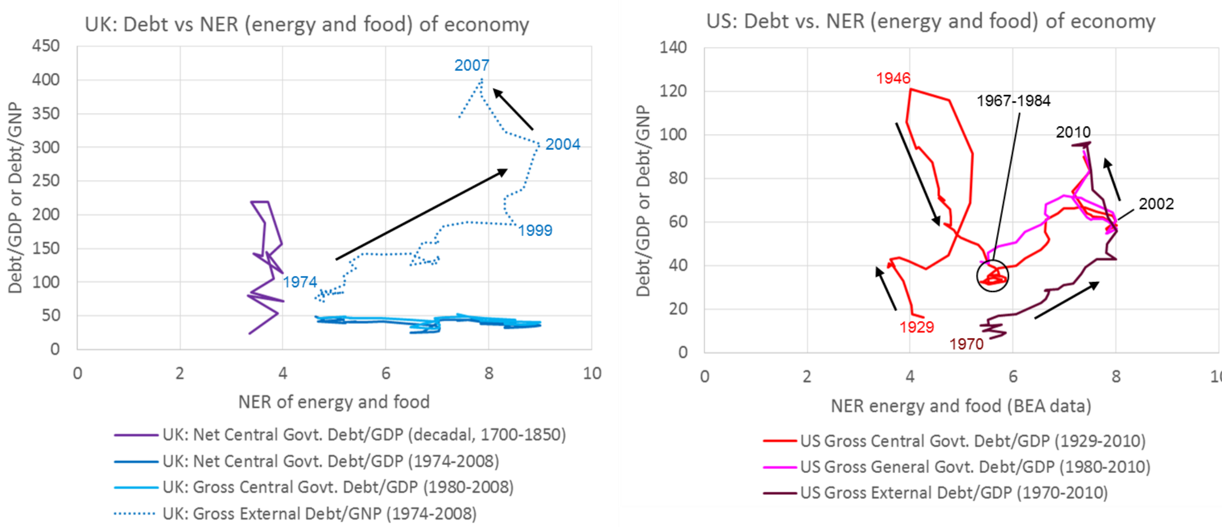
In this section I plot the metrics from the time series of the previous five figures against themselves to look for significant outlying positions in the 'phase space' of economic growth and/or debt accumulation versus net energy. This is one way of looking for economy-wide evidence of Tainter's 'energy complexity spiral' with debt functioning as one metric of the ability of an economy to deal with increasing complexity.

3.2.1 NER vs. Debt/GDP and Debt/GNP

In this section I plot debt/GDP and debt/GNP (US only) versus the NER of the economy considering both energy and food expenditures (see Figure 6) and when considering only energy expenditures (see Figure 7). This plot is somewhat by definition forcing one to cross disciplinary boundaries to simultaneously consider macroeconomic factors (e.g., debt) with ecological systems, or life cycle, metrics of the energy flows within the economy via the NER of the economy.

Trends to the right indicate declining expenditures for energy and/or food relative to the size of the economy. ***Trends upward*** indicate increasing debt accumulation and inability for current economic activity to afford its complexity. Thus, ***trends down and to the right*** indicate the most economically-beneficial scenario that energy and food are becoming cheaper and debts are being repaid. ***Trends up and to the right*** can seem sustainable in that increasing NER implies that the accumulating debt can eventually be repaid as the basic necessities are becoming cheaper.

If NER suddenly decreases (energy expenditures rise) due to a political event or biophysical constraint in extracting and converting energy, then debt is likely to continue to accumulate until realization sets in that the energy and food constraint is not temporary. If debt continues to accumulate relative to GDP *and* the NER of the economy decreases, ***trends up and to the left are unsustainable*** because the basic needs of life are getting too expensive to sustain the current consumption levels. If there are trends "up and to the left" on these figures, then the economy might be considered too complex for the existing energy supply to sustain. If this is the case, then we might expect trends "up and to the left" to last only very short time spans (< decade?) before debt must be decreased by some means. ***Trends down and the left*** (decreasing debt and NER) might indicate that for one or many reasons, the economy is restructuring to overcome debt obligations in spite of the fact that energy and food are becoming more expensive relative to the economic flows estimated by GDP.



(a) **(b)**

Figure 6. The debt/GDP and debt/GNP ratios of the (a) UK and (b) US versus the NER economy metric when considering both "energy and food" expenditures as the boundary of interest.

3.2.1.1 Figure 6 observations

Within the short time series shown in Figure 6 (NER considering energy and food) a trend of "up and to the left" is only observed for the latter part of the last decade: 2002-2010 for the US, 2004-2007 for the UK. I expect US data points for 2011-2013 to reside in a similar region of Figure 6b with respect to the last data point in 2010 with slightly higher debt ratios to just over 100. The BEA data indicate NER = 7.1 for 2011 and 7.2 for 2012. I also expect UK data points for 2009-2013 to reside in a similar portion of Figure 6a, with perhaps slightly lower NER due to continued high oil and natural gas prices in the UK (whereas the US has had relatively low NG prices since 2009).

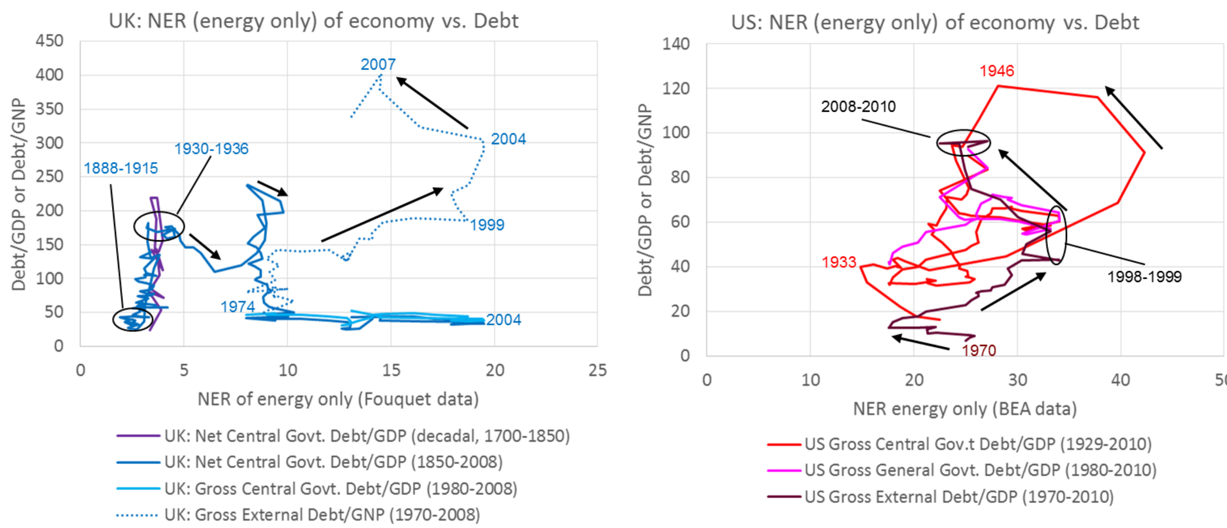
The striking difference between the UK and the US is the level of gross external debt/GNP (or /GDP) is much higher for the UK at similar NER levels for the economy. Other reports seem to indicate US domestic private + public debt as near 300% of GDP after the 2008 financial crisis, and investigation of those data is left for future work (Roxburgh et al., 2010).

3.2.1.2 Figure 7 observations

Data in Figure 7 differ from Figure 6 in that the plotted NER values are calculated at boundary of *energy only*. Hidden within the seemingly more complicated trends for the US are some of the same trends when considering energy and food expenditures. Also, the long-term times series for the UK energy expenditures provides some sharp distinguishing features among time periods before 1930, from 1930-1980s, and after the 1980s.

"Unsustainable" trends "up and to the left" in Figure 7 have been observed in the past data record for the US during the Great Depression (1929-1933), in 1944-1946 associated with World War II, and the decade of the 2000s, and for the UK during the early 1920s (not after the Great Depression) and mid-to-latter part of the decade of the 2000s (2004-2007). From 1946-1960 there was a 15-year trend of decreasing NER and decreasing debt in the US.

For the US data in Figure 7b, perhaps the most clear patterns occur with external debt in three phases: (1) from 1970-1982 "up and to the left" during the time span of the Arab Oil embargo throughout the aftermath of the Iranian revolution and 2nd "oil crisis", (2) from 1982-1998 both NER and debt increased, and (3) then from 1998-2008 NER again decreased as external debt increased. *The two time periods of high and/or increasing energy expenditures (1973-1981 and 1998-2008) clearly stand out in the view of US external debt.*



(a) **(b)**

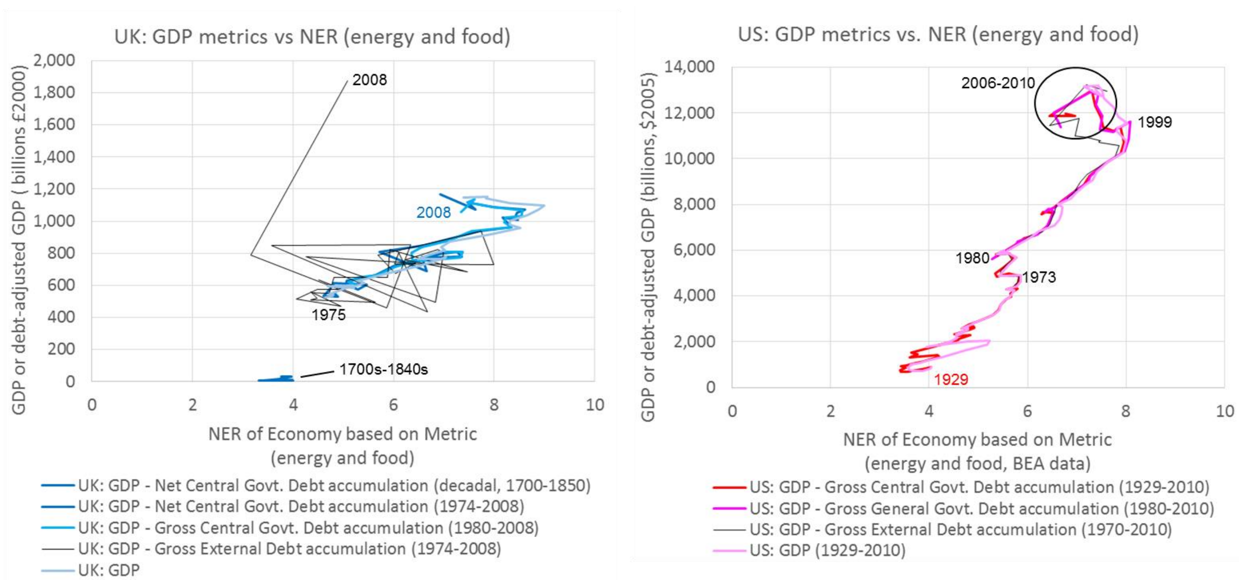
Figure 7. The debt/GDP and debt/GNP ratios of the (a) UK and (b) US versus the NER economy metric when considering *only energy* expenditures as the boundary of interest.

Due to Fouquet's longer data set associated with the UK energy expenditures, we see that energy-only NER (Figure 7a) became greater than five only after 1936. However, recall that this 'energy-only' expenditures includes food and fodder for animate power in preindustrial years. From 1700-1936, the UK central government debt fluctuated from 30% to 200% of GDP. Focusing only on the data 1850-1930, there is a general trend of higher debt levels associated with higher NER (near 5) and lower debt levels associated with lower NER (near 3). Only after the 1930s did the UK economy energy-only NER increase beyond five (likely due to increased use of petroleum). Energy-only NER has been greater than 10 (< 10% of GDP spent on energy) since the late 1970s, and government debt has been less than 50% of GDP since 1973.

Perhaps the most striking feature of Figure 7a is the UK's quickly increasing gross external debt/GNP from 1970-2008 at the same time the central government debt/GDP stays below 50% of GDP until crossing that mark only in 2009. *Similar to the US, the UK external debt from 1999-2008 increases significantly while the energy-only NER decreases significantly ("up and to the left" of Figure 7a).*

3.2.2 NER vs. annual change in GDP and debt-adjusted GDP

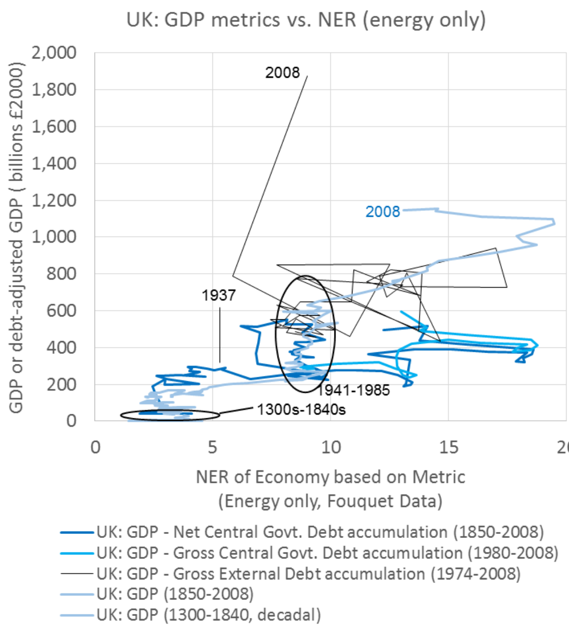
NER is perhaps more applicable to compare to GDP and debt-adjusted GDP rather than to debt only. The reason is because NER is a measure of the rate of energy (and food) production, and GDP is also a measure of the rate of flow of economic activity rather than a measure of accumulated wealth (or debt). In this section I plot GDP and debt-adjusted GDP versus NER based on that same metric of the fraction of GDP or debt-adjusted GDP spent on energy (and food). Thus the y-axis and x-axis for each figure, Figure 8 - Figure 11, are based on the same metric (hence the x-axis labels as "NER of Economy based on Metric." Recall that NER is the inverse of the fraction of the growth metric (e.g. GDP) spent on energy and food, or energy only. Thus, I substitute debt-adjusted GDP for GDP when calculating the NER of these debt-adjusted GDP growth metrics.



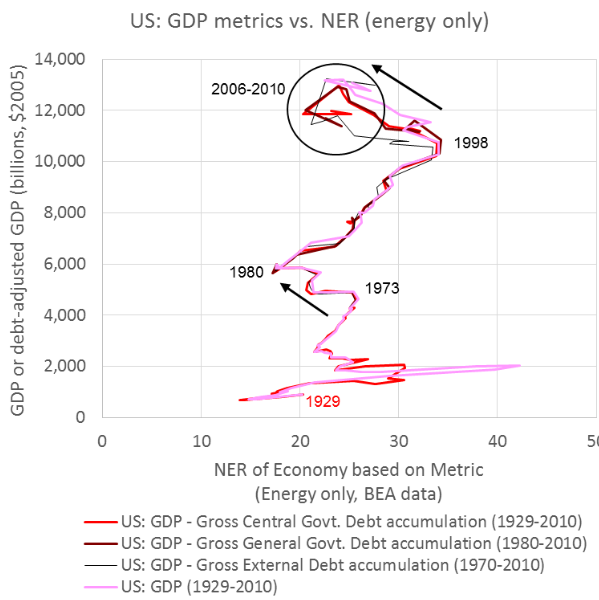
(a) **(b)**

Figure 8. (a) The UK data series used for food expenditures is generally too short to derive much of a trend between NER and GDP and/or debt-adjusted GDP. (b) In the post-World War II era the US has generally seen increasing NER and increasing GDP (and debt-adjusted GDP). Only after 1999 do the debt-adjusted trends significantly differ from that of GDP alone.

Figure 8 and Figure 9 plot GDP and debt-adjusted GDP versus the NER for 'energy and food' and 'energy only', respectively. The UK data series in Figure 8a used for food expenditures is generally too short to derive much of a trend between NER and GDP and/or debt-adjusted GDP. The US data series in Figure 8b has a general trend of increasing NER (for 'energy and food') along with increasing GDP and debt-adjusted GDP. The two time periods when this trend did not hold was the 1970s (related to higher oil and natural gas prices from the Arab Oil Embargo and Iranian Revolution) and the decade of the 2000s leading up to the high oil prices post-2006 and Great Recession of 2007-2009. All four US metrics in Figure 8b are very similar except for the post 2000 time period, and this is perhaps one distinguishing feature of the post-2000 time period where growth has been more debt-induced than the past due to increasing energy and food costs (or decreasing NER).



(a)

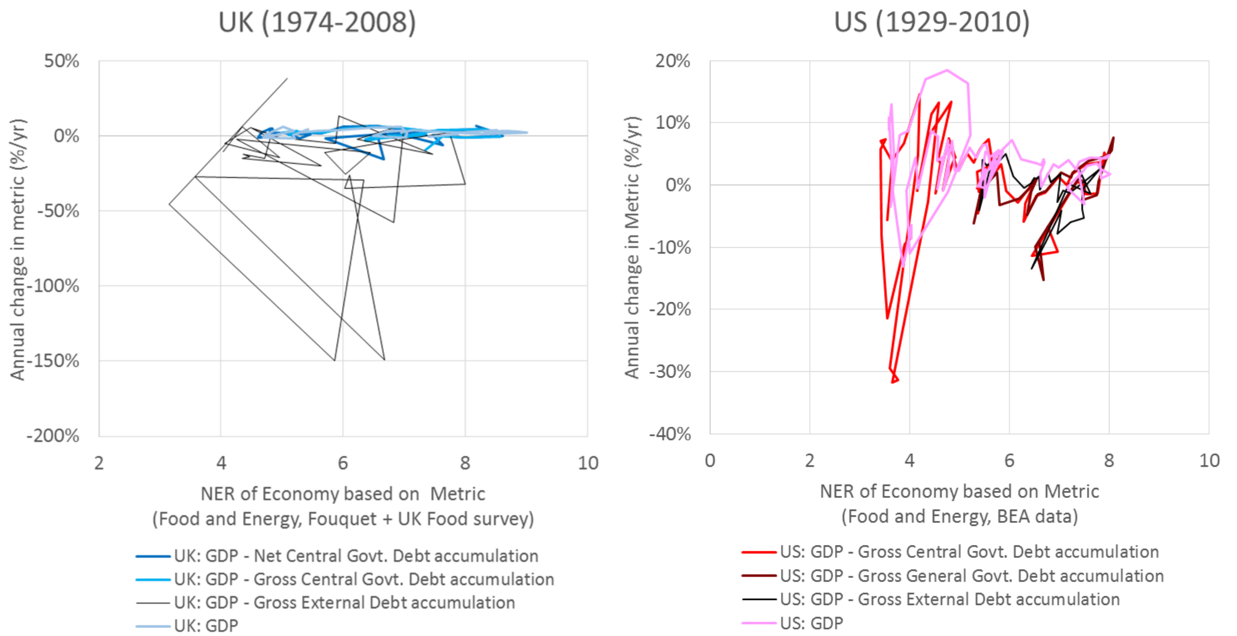


(b)

Figure 9. (a) For the UK, it took until 1936 with NER < 5 for all previous UK history to obtain a real GDP of 200 billion £(2000). This NER < 5 is for energy only, but that includes much food and biomass for power in pre-industrial years. (b) The US GDP and debt-adjusted GDP trends are all similar versus their respective energy-only NER during this time series from 1929-2010, except for some divergence after 1998. Only the decades of increasing energy costs (1970s and 2000s) show an "up and to the left" trend of increasing growth metrics and decreasing NER.

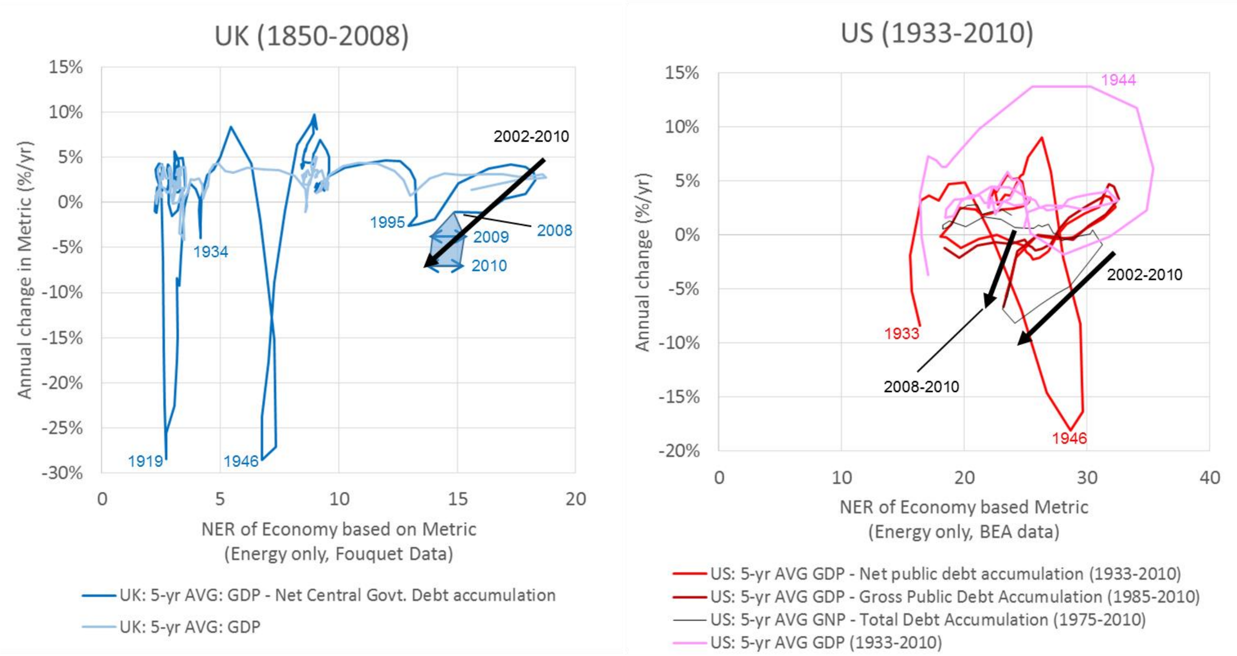
The long-term time series of the UK shows that the energy-only NER (that does include much food and fodder before industrialization) and growth metrics have perhaps three characteristic regions in Figure 9a. The first is the time period before 1937 when NER was always less than 5 (for over 6 centuries). The second time period is 1941-1985 beginning with World War I and perhaps ending at a time when adjustments to new energy production resources (oil and natural gas) and efficiency had eventually mitigated some economic impacts from the 1970s oil crises. *The third time period from 1985 to the present is characterized by a marked difference in the relationship between NER and GDP as compared to NER and the debt-adjusted GDP measures*. GDP continued to grow along with increasing NER (until peaking in 2003 at NER (energy-only) = 19.5) whereas debt-adjusted GDP remained relatively flat after the 1980s. It is possible there is some explanation via the rise of more globalized production and trade, increased monetary relevance of the financial sector, and measures of inequality (e.g., fraction of income going to top 1%). The data show that after the 1980s, the UK government debt ratios stopped decreasing and that of private debt (part of external debt in Figure 4a) increased rapidly.

The interesting trends in the US growth measures versus the energy-only NER (Figure 9b) are largely the same as that for the 'energy and food' NER shown in Figure 8b.



(a) **(b)**

Figure 10. (a) The UK and (b) US annual change in different growth metrics (as indicated by the legend) as related to the NER for energy and food expenditures.



(a) **(b)**

Figure 11. (a) The UK ***five-year average*** **and (b) US** ***five-year average*** **annual change in different growth metrics (as indicated by the legend) as related to the NER for energy-only expenditures. My data set for the UK includes data for the annual change in debt-adjusted GDP (y-axis values) for 2009 and 2010 but not NER (x-axis values). I hypothesize a likely range where NER should be similar for 2009 and 2010.**

There is one distinguishing feature of Figure 10a showing the rate of change of UK growth metrics versus the country level NER considering both energy and food expenditures. The debt-adjusted GDP using gross external debt has both high magnitude negative growth rates (that correspond to the large increase in external debt accumulation) and lower NER than the other metrics.

The US data in Figure 10b imply that there have been time periods (e.g., Great Depression, World War II, and 2008-2010) when a negative change in the metric of GDP or debt-adjusted GDP is approximately linearly related to a change in NER considering energy and food. In 'normal' times when GDP growth is slightly positive, this linear relation does not appear. Only in times of decreasing growth and/or increasing food and energy expenditures does this relation appear. As one moves to the right of Figure 10b, the linear slope of these trends decreases (e.g. the slope becomes flatter), and this is most likely an artifact of the NER being an inverse ratio of the fraction of expenditures for food and energy relative to a growth metric. If I were to plot these same data as the growth metric (not shown) versus these fractions, and not its inverse, the slopes (now negative) are much more similar for each of the three time periods mentioned at the beginning of this paragraph.

In comparing rates of change in the growth metrics to energy-only NER of the UK (see Figure 11a), there are five time periods from 1850-2010 with negative rates of change in debt-adjusted GDP but *only one time period is also associated with declining NER (energy only)*: 2002-2010. Two of the time periods with negative rates of change in debt-adjusted GDP are major wars (World Wars I and II), and two are associated with world recession (Great Depression - 1934 and financial crisis/high energy prices - 2008). It is possible that the high NER (energy-only) in the time period of 1997-2007 will not be witnessed again.

In comparing rates of change in the growth metrics to energy-only NER of the US (see Figure 11b), there are two time periods of both continually declining rates of debt-adjusted GDP growth and decreasing NER: 1951-1986 and 2002-2010. The difference between these two time periods is that the more recent period is marked by *negative* rates in the debt-adjusted GDP growth rates whereas the former time period has primarily *positive* rates of change in debt-adjusted GDP. Thus, the recent time period of 2002-2010 is an outlier with regard to the historical data set of increasing debt and decreasing NER for energy only and NER considering 'energy and food'.

4 Conclusions

Starting several years *before* the onset of the Great Recession (late 2007 through late 2008/early 2009), there had begun a trend of diminishing returns on expenditures for 'food and energy', as measured by NER, for both the US and UK economies. The fundamental long-term trend of *decreasing relative expenditures* for 'food and energy' has reversed for approximately the last 10-15 years. The data estimate the UK minimum food expenditures in 2007 at 5.8% of GDP and the US minimum food expenditures in 2006 at 9.3% of GDP. These correspond to peaks in NER for 'energy and food' for the UK at 9.0 (2004, 'Fouquet energy + food') and 12.1 (2002, 'IEA energy + food') and for the US at 8.0 (2002, 'BEA energy + food'), 8.2 (1998, 'BEA food + IEA energy').

A similar hiatus in the long-term trend of decreasing 'energy and food' NER, but only temporarily, occurred in the 1970s and early 1980s. We might ask if the energy-economic situation of 2007-2010 is fundamentally different from that of 1973-1983. Both time periods involved oil price rises faster than economic adjustments and investments could mitigate. *The two time periods of high and/or increasing energy expenditures (1973-1981 and 1998-2008) clearly stand out in the view of increasing debt.* However, the last decade is unique within the history of the time period of central banking, going back

300 years for the UK, in that this high debt and high energy expenditures situation also occurs at a time of near zero interest rates.

Due to the costs of foreseeable future marginal energy supplies, country debt levels, and low interest rates, this current time period appears more intractable in terms of lowering energy and food expenditures (relative to GDP) further than the minimum (to date) that occurred near the end of the 20th Century. This suggests that the few years surrounding the year 2000 might mark a fundamental turning point in this history of the US and UK (or the world) that is characterized by the passing of the year of the cheapest energy and or 'energy and food' in the history of mankind. If increased energy consumption is required to solve new problems and add complexity, and if increased energy consumption has been associated with decreasing costs, this poses the question of whether our modern economies will be able to increase their complexity to solve future challenges.

It is tantamount that we understand our ability to pay off existing debts if energy and food expenditures will no longer decrease relative to GDP. Some historical debts were paid off by increasing energy consumption or defaulting to some degree. UK and US debt repayment from the 1970s was enabled by reducing interest rates from historical highs, accessing new energy supplies (e.g. Alaska, Gulf of Mexico, and North Sea) that were relatively cheap, and the start of energy efficiency programs for the first time. While investments in energy efficiency can still occur and provide benefits of reduced energy expenditures, today all of the previous options are not available at the same scale and magnitude.

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