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Developing an Input–Output based method to estimate a national-level EROI (energy return on investment)

Lina Brand-Correa, Paul Brockway, Claire Carter, Tim Foxon, Anne Owen and Peter Taylor

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ABSTRACT

Concerns have been raised that declining energy return on energy investment (EROI) from fossil fuels and low levels of EROI for alternative energy sources could constrain the ability of national economies to continue to deliver economic growth and improvements in social wellbeing. However, in order to test these concerns on a national scale, there is a conceptual and methodological gap in relation to calculating a national-level EROI and analysing its policy implications. We address this by developing a novel application of an Input-Output methodology to calculate a national-level indirect energy investment, one of the components needed for calculating a national-level EROI. This is a mixed physical and monetary approach using Multi-Regional Input-Output data and an energy extension. We discuss some conceptual and methodological issues relating to defining EROI for a national economy, and describe in detail the methodology and data requirements for the approach. We obtain initial results for the UK for the period 1997-2012, which show that the country's EROI has been declining since the beginning of the 21st Century. We discuss the policy relevance of measuring national-level EROI, and propose avenues for future research.

KEYWORDS

EROI, Multi-Regional Input-Output, net energy analysis, resource depletion, biophysical economics, energy transition.

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About the Authors

Lina Brand-Correa is a Postgraduate Researcher at the University of Leeds. She focuses on the general topics of energy, society, and economic systems. She is particularly interested in understanding how energy provisioning systems are related to society and the economy, with a special focus on human well-being. For this purpose, she uses concepts such as exergy, useful work, Energy Return on Energy Invested (EROI), energy services on one hand, and economic growth, development, human wellbeing, human needs on the other.

Paul Brockway is a Research Fellow in Phase 3 (2014-2019) of the UK Energy Research Council (UKERC) Theme 4: Energy, Economy and Societal Preferences. His research is focussed on studying macroeconomic energy-economy interactions, through primarily the lens of exergy analysis. Exergy is considered as 'available energy', and enables the study of the energy conversion chain from primary to final to useful stages - where it is lost in exchange for energy services.

Claire Carter is currently undertaking a doctoral research degree at the Science & Policy Research Unit (SPRU), University of Sussex. She is researching global energy return on energy invested (EROI or EROEI) over time from the range of energy supply technologies using a system dynamics modelling approach.

Tim Foxon is Professor of Sustainability Transitions at SPRU, University of Sussex. His research explores the technological and social factors relating to the innovation of new energy technologies, the co-evolution of technologies and institutions for a transition to a sustainable low-carbon economy, and relations and interdependencies between energy use and economic growth. He is co-leader of the CCCEP project on systemic approaches to low-carbon transitions.

Anne Owen is a Research Fellow in Material Flow Accounting and Input-output Analysis at the University of Leeds. She is currently working on developing an input-output database for the UK capable of tracing all the flows of goods and services that result on the UK's final demand for products. When data on the raw materials extracted by sector and the energy used by sector is added to this database, she will be able to calculate the full supply chain impacts of the products we consume. These impacts take into account materials and energy used both in the UK and in the countries we trade with.

Peter Taylor has over twenty years of experience working on a wide range of energy and climate change issues. He is currently Professor of Sustainable Energy Systems in the Centre for Integrated Energy Research, a joint venture between the faculties of Engineering and Environment. He is also a member of the UK Energy Research Centre and the Centre for Climate Change Economics and Policy. Peter's work focuses on interdisciplinary research combining science, technology, economics and policy to enhance the understanding of, and policy responses to, the challenges of accelerating the transition to sustainable low-carbon energy systems.

1. Introduction

The concept of energy return on energy investment (EROI) is part of the field of study of net energy analysis (NEA), and is one way of measuring and comparing the net energy availability to the economy from different energy sources and processes. In broad terms, it can be understood as “the ratio of energy returned from an energy-gathering activity compared to the energy invested in that process” (Hall & Kiltgaard 2012, p.310). Building on a long history of ideas in biophysical economics (see, for example, Cleveland, 1987), this concept has been used by e.g. Hall and Kiltgaard (2012) as a basis for further developing an energy-focused approach to the economy.

This approach is driven by concerns around a decline in the EROI of fossil fuels and low levels of EROI for alternative energy sources. In the case of fossil fuels, it is argued that the depletion of easily recoverable fossil fuel reserves is outpacing technological advancements for the improvement of fossil fuel extraction, leading to decreasing values of EROI for these fossil energy sources (see e.g. Dale et al. 2011; Gagnon et al. 2009; Lambert et al. 2013). Moreover, some authors (Hall et al. 2014; e.g. Dale & Benson 2013) have argued that the EROIs of many renewable energy technologies necessary to decarbonise global energy supply are currently lower than the fossil fuels that they need to replace. However, it should be recognized that the EROI of renewable energy sources varies hugely depending on the technology and location. For instance, Raugei et al. (2012) and Kubiszewski et al. (2010) calculate that, for electricity generation, the latest solar and wind technologies respectively have EROI values comparable to gas -or coal- fired power plants. The future trends in the EROI of renewable energy systems are also very uncertain – being dependant both on the pace of technological innovation (which may increase EROI) and the need for increased back-up generation and storage (which may decrease EROI from a full energy system perspective).

The higher the EROI of an energy supply technology, the more “valuable” it is in terms of producing (economically) useful energy output. In other words, a higher EROI allows for more net energy to be available to the economy, which is valuable in the sense that all economic activity relies on energy use to a greater or lesser extent. Analyses of the EROI of different energy sources and extraction/capture processes using particular technologies are relatively common, e.g. see Cleveland (2005), Brandt (2011), and Hall, Lambert, & Balogh (2014). These are important in terms of presenting a picture of the potential contribution of individual energy sources to the energetic needs of the economy. However, less attention has so far been paid to determining EROI values for national economies, which requires a different methodological approach to traditional EROI analyses due to the mix of particular resource locations, exploitation times and technologies applied to “produce” energy, i.e. to extract fossil fuels and capture flows of renewable energy in a given national territory.

This paper aims to help with the need to develop a method for measuring EROI for national economies, in particular for calculating indirect energy investment, and thus contribute to the growing field or NEA. It does so by proposing a novel application of an Input-Output methodology using Multi-Regional Input-Output data for the UK for the period 1997-2012. This approach is described in detail in section 3, followed by the presentation and discussion of results in section 4, and some conclusions and policy recommendations in section 5. But firstly we explain the importance of a national-level EROI in section 2, describe how it differs from other types of EROI, and discuss some of the methodological issues associated with EROI calculations in general.

2. A national-level EROI: the concept

Our aim in this paper is to develop an Input-Output based methodology, to calculate a national-level EROI ($EROI_{nat}$). We start with a succinct background of the EROI concept and its different types. We then follow by putting forward some arguments on the conceptual relevance of a $EROI_{nat}$ as we have defined here. Finally, this section discusses persistent conceptual issues in the EROI literature and a description of the conceptual choices we made.

2.1. Background

EROI (or EROEI) is a key metric in NEA. The concept of net energy (i.e. amount of usable energy after extraction and processing) dates back from the second half of the 20th Century (e.g. Hall, Lavine, & Sloane, 1979; Hall, 1972; Smith, 1960). The term (EROI) however, was first used by Cleveland et al. (1984). It is a dimensionless number1 that expresses the result of energy returns over energy invested.

Most EROI studies consider an energy supply technology for a particular resource type and in a particular location. Such studies typically have the “mine-mouth” (or “well-head” or “farm-gate”) as the boundary drawn for evaluating the energy return in relation to the energy required to get it, without further transformation processing (Murphy & Hall 2010). These EROI calculations are often referred to as “standard” EROI ($EROI_{stnd}$) (Murphy et al. 2011):

$$EROI_{stnd} = \frac{energy\ output\ from\ extraction}{direct\ and\ indirect\ energy\ inputs} \tag{1}$$

A simple graphical description can be found in Figure 1, showing how $EROI_{stnd}$ for a particular energy resource (oil) compares to other EROI calculations with extended system boundaries. Other, less common, types of EROI calculations for a single energy source vary depending on the chosen system boundary (e.g. $EROI_{pou}$ and $EROI_{ext}$) and thus including more or fewer stages along the energy transformation

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[1] It is worth noting that EROI values in general are often expressed as ratios.

chain. $EROI_{stnd}$ is more commonly used to compare different fuels or energy carriers, or when analysing changes in EROI of a specific fuel over time and the consequences for the wider economy (see for example Hall et al., 2014; Murphy and Hall, 2011).

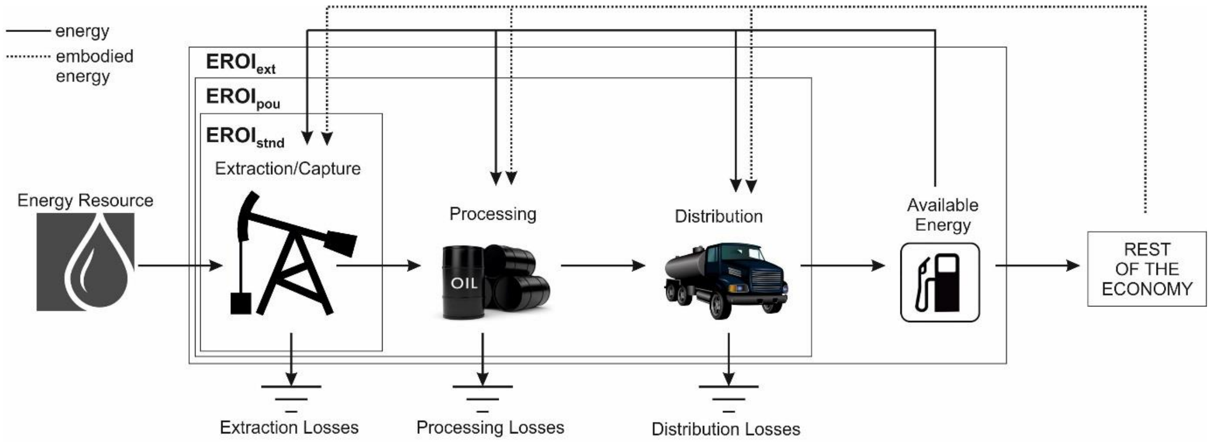

Figure 1. Types of EROI
$EROI_{stnd}$: standard EROI.

$EROI_{pou}$: EROI at the point of use.

$EROI_{ext}$: extended EROI.

When a number of energy resources are examined within certain geographical limits, such as a country, then another type of EROI is needed: a societal or national-level EROI. As far as we are aware, the only attempt to calculate a societal EROI ($EROI_{soc}$) was undertaken by Lambert et al. (2013; 2014). They estimate the average EROI for all energy supply technologies deployed by a nation. $EROI_{soc}$ is calculated by dividing the average energy obtained per dollar of spending (summed over different fuel inputs to the economy) by the primary energy needed to obtain one dollar's worth of economic production. Their results suggest that countries with higher societal EROIs have higher standards of living, as measured by the Human Development Index (HDI). However, their calculations are based on price and energy intensity information. There is a danger that using a price-based approach introduces distortions to the calculated EROI2.

Earlier attempts to calculate the net energy for a country include Leach (1975) and Peet et al. (1987), but they did not include trade in their calculations, a key element in

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[2] Prices represent both physical and non-physical factors at play in the economy and hence do not necessarily reflect resource availability or accessibility. Under the assumption of perfectly competitive markets, prices can be assumed to reflect quality, accessibility and scarcity. However, the underlying assumptions for perfectly competitive markets can be contested. Moreover, scarcity in this context represents economic scarcity (supply relative to demand) at a particular moment in time and does not necessarily reflect absolute resource scarcity (availability).

a globalised world. More recent studies that attempted national-level net energy estimations include the studies by King et al. (2015; 2015), King (2015), Fizaine and Court (2016), and Raugei and Leccisi (2016). However, these studies diverge from our own in that they have either not used an Input-Output framework to account for trade in calculating indirect energy, or they have focused on single energy sources rather than the whole production of energy by a nation. An exception to this is the study undertaken by Herendeen (2015), where an Input-Output framework is used to connect net energy with the price of energy and other goods and services. We will discuss their results in more detail when presenting the results from this first application.

2.2. The benefits of a national-level EROI

There are three key reasons why a national-level EROI is important. Firstly, traditional energy analyses do not usually address directly the issue of resource depletion (or reduced accessibility, i.e. resources that are more difficult to extract/capture)3. Yet, this is important because if a country is understood to require a given level of net energy input to support its economic activity, a declining EROI trend would imply that the total gross energy requirements of the economy could rise, even without economic growth. In this case, a national-level EROI becomes relevant as a key metric in the energy-economy analysis toolbox.

Secondly, when measured over time to take account of dynamic effects, EROI can provide valuable information about the extent of resource depletion and technological change in resource extraction/capture4. Here the system boundary for EROI is established at the resource extraction/capture5 level, rather than including downstream transformation processes. Therefore, a national-level EROI time series can be analysed together with other national-level energy-economic studies. This would provide additional information to improve our understanding as to how the dynamics of resource depletion (or accessibility) and technological change relate to energy quality and the dynamics of conversion efficiencies.

[3] In traditional energy analyses this might be addressed indirectly through prices and price projections, or perhaps through data and projections on reserves. However, we believe that EROI gives a better picture of resource depletion and accessibility, one that is based on energy accounting of extraction/capture processes.

[4] A declining EROI over time indicates that resource depletion is outpacing technological change (Murphy et al. 2011), i.e. the quantity of output of a certain energy resource (or its accessibility) (Dale et al. 2012) is declining faster than the advancements in technology to harvest it more efficiently.

[5] We use both of these terms in order to include both the extraction of energy resource stocks (e.g. coal, oil and gas) and the capture of energy flows through its conversion to electricity (e.g. wind and solar).

Thirdly, EROI has economic relevance since large energy returns in excess of the corresponding energy investments enable diverse economic activities. This is the case as the physical energy cost of energy supply is likely to have a larger economic impact than might be expected from its cost share[6]. This is because if the physical cost of energy production rises then this might severely impact the productive resources available to the rest of the economy (in terms of labour, physical infrastructure and investment capital, for instance). A national-level EROI can help understand the potential for growth or change of a national economy in relation to the physical energy cost of extracting/capturing the energy it requires.

2.3. Conceptual issues and choices

The main persistent[7] conceptual issues in the EROI literature are: how to define the boundary of analysis (as shown in Figure 1), how to account for embodied[8] energy inputs, how to deal with temporality and how to account for energy quality. We will discuss each of them in turn, providing our own conceptual choices for this specific definition of $EROI_{nat}$. Our choices do not necessarily intend, however, to point towards final solutions to these methodological issues, but rather contribute to the discussion of defining EROI at a national level.

2.3.1. Boundary of analysis

There is a consensus around the accounting starting point for EROI in general, regardless of the type. EROI "assumes that the energy in the ground (or coming from the sun) is not to be counted as an input" (Herendeen 2004, p.284). Therefore, EROI accounts for energy inputs once they have been either extracted or harnessed for human purposes, but not the energy content of the resource that is being extracted/harnessed[9].

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[6] The cost share theorem states that changes in energy costs should not affect the macro-economy, since energy costs are a small fraction of total economic activity. However, an ecological economics analysis argues that the cost share theorem breaks down, as energy is a more significant input for economic activity than applied by its cost share (Kümmel 2013; Ayres et al. 2013).
[7] These issues are still being identified in recent EROI publications (Murphy et al. 2011; Brandt & Dale 2011), but are largely the same as those that Leach (1975) identified and were discussed in a NEA workshop held in August 1975 at Stanford, California.
[8] By embodied energy we mean all the energy that went into a process. This is different from embedded energy, which relates to the energy content of specific materials or infrastructures.
[9] Note that this start point of accounting for energy contrasts with the approach of another assessment tool: Life Cycle Analysis (LCA). In LCA the energy that is present in the environment or the energy source is the start point for accounting in measures of, for instance, cumulative energy demand.

However, there are three main considerations when assessing boundaries for EROI. Firstly, how many energy processing and transformation stages to take into account: primary energy, final consumption (of energy carriers) or useful energy10? Secondly, a decision is required as to the inclusion of energy inputs at each of the energy stages under analysis, i.e. should these inputs include embodied energy in capital equipment, operation and maintenance energy, energy consumed by the labour force, etc. Thirdly, a consideration is required as to the range of energy sources that will be analysed, within what geographical limits and in which time frame.

In relation to the first consideration, how far to go along the energy chain in order to include more processing and transformation stages depends on the type of EROI (see Figure 1). Our definition of $EROI_{nat}$ establishes this boundary at the first stage of extraction/capture of energy sources. In terms of most energy reporting (e.g. International Energy Agency –IEA- Energy Balances), this means energy “production”. Energy “production” does not include energy imports but it does include energy exports. In other words, we are assessing the energy extracted/captured in a country (energy returned), regardless of whether or not is then exported and without accounting for energy imports (see Figure 2). This means that a country that imports all of its primary energy will not have an EROI value when using this methodology. Conversely, if a country export all of its primary energy, it will still have an EROI value when using this methodology.

[10] Primary energy generally refers to the energy extracted or captured from the natural environment (e.g. crude oil, coal, hydropower, etc.) (IEA & Eurostat 2005). Final energy (also called secondary energy) generally refers to energy as it is delivered to the final economic consumer, after undergoing transportation and transformation processes (e.g. gasoline, diesel, electricity, etc.) (IEA & Eurostat 2005). At the point of use, final energy undergoes one last transformation process as it passes through an end-use conversion device, for example furnaces, electric appliances or light bulbs. End-use devices transform energy into a form that is useful for human purposes, hence the term “useful energy” as the outcome of this last conversion process.

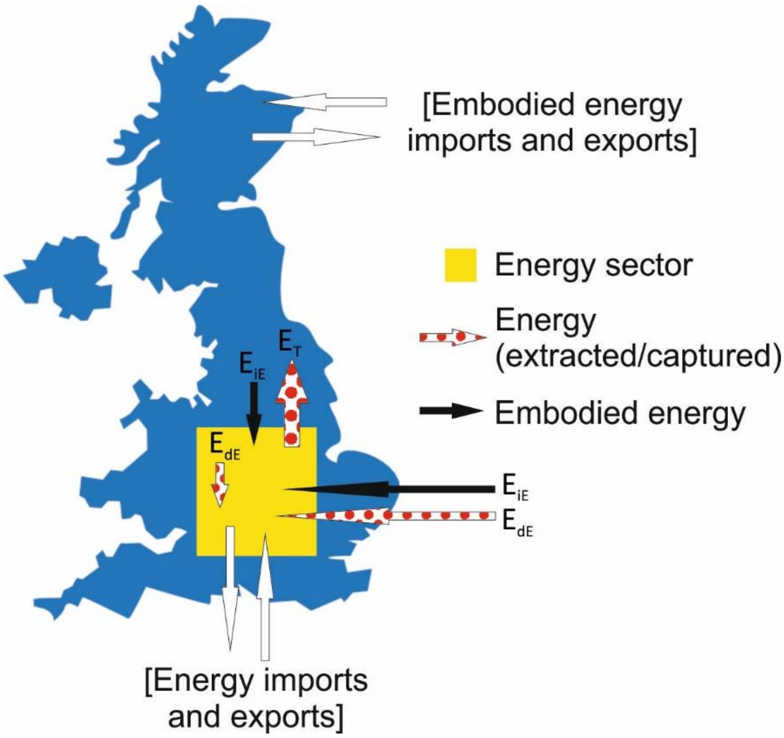

Figure 2. National level EROI – UK case

Notes: Black and dotted arrows represent what we measure, while white arrows represent flows that occur but that are not included in this approach to $EROI_{nat}$ given its boundary of analysis.

In relation to the second consideration, on the extent of energy inputs included at each energy processing and transformation stage, it depends on the specific EROI study. Most EROI studies include the direct energy and material (as embodied energy) inputs as well as the indirect energy and material inputs, i.e. the inputs required to make the initial inputs. We have decided to adopt this commonly used boundary in the calculation of $EROI_{nat}$. Brandt et al. (2013) have developed a framework for tracking direct energy inputs as well as different number of indirect energy inputs. Further expansion of the boundary that determine the energy inputs can be made. For example, indirect labour consumption can be included, as well as the consumption of auxiliary services and the environmental impacts of the production of direct and indirect energy and materials. Hall et al. (2009) calculate $EROI_{ext}$ for US oil using an expanded boundary for the inputs.

Third, there is the consideration of how many energy sources are being analysed, within which geographical limits and in which time frame. Many EROI studies focus on a single energy source in a single location at a certain point in time. Murphy et al. (2011) and Hall et al. (2014) have undertaken detailed reviews of published EROI values for single energy sources and regions. There are very few temporal EROI studies. Two exceptions are Brandt (2011), who conducted an EROI investigation of oil in California over the period 1955 to 2005 and Brandt et al. (2013) investigating EROI for oil sands in Alberta over the period 1970 to 2010. For our case of the $EROI_{nat}$, the geographical limits correspond to a national territory, the number of energy sources analysed correspond to all the energy sources extracted/captured within that territory and the time frame is only constrained by data availability. In summary, our proposed approach attempts to calculate $EROI_{nat}$ from a territorial production perspective (as opposed to a consumption perspective).

2.3.2. Accounting for embodied energy inputs

Depending on the chosen boundaries for the calculation of EROI, and data availability, a particular methodology can be applied for the accounting of embodied energy inputs. The two main methodologies used are process analysis and Input-Output (IO) (Murphy et al. 2011). The former is most commonly used; it is a bottom-up approach most appropriate when assessing a single energy source through clearly defined processing stages (Murphy et al. 2011). As data collection can be problematic and time consuming when using this approach, published LCA data sets are sometimes used (see for example Harmsen et al. (2013)). Also, as Arvesen and Hertwich (2015) note, care is needed to ensure that LCA boundary conditions are consistent with the EROI calculation.

Given the boundary definition of our $EROI_{nat}$, we have chosen to use IO; a top-down approach that is more appropriate when the boundary is expanded to multiple processes (Murphy et al. 2011), e.g. when considering activities at a national level. This is due to it being able to quantify interrelationships across economic sectors (Murphy et al. 2011), and even enable the attribution of embodied energy inputs to traded goods and services. Physical flows are estimated from monetary economic data in this approach.

2.3.3. Temporality

The timing of energy inputs and energy outputs over the functional life of the supply technology is important, since there are typically high energy inputs at the beginning (construction) and at the end (decommissioning) of the life of the energy extraction or capture location (see Figure 3). The issue of temporality does not, however, involve any sort of discounting of time (as it does in other types of metrics such as cost-benefit analysis). This is discussed in detail for the case of photovoltaic panels by Dale (2012) and Dale & Benson (2013), and in King et al. (2015).

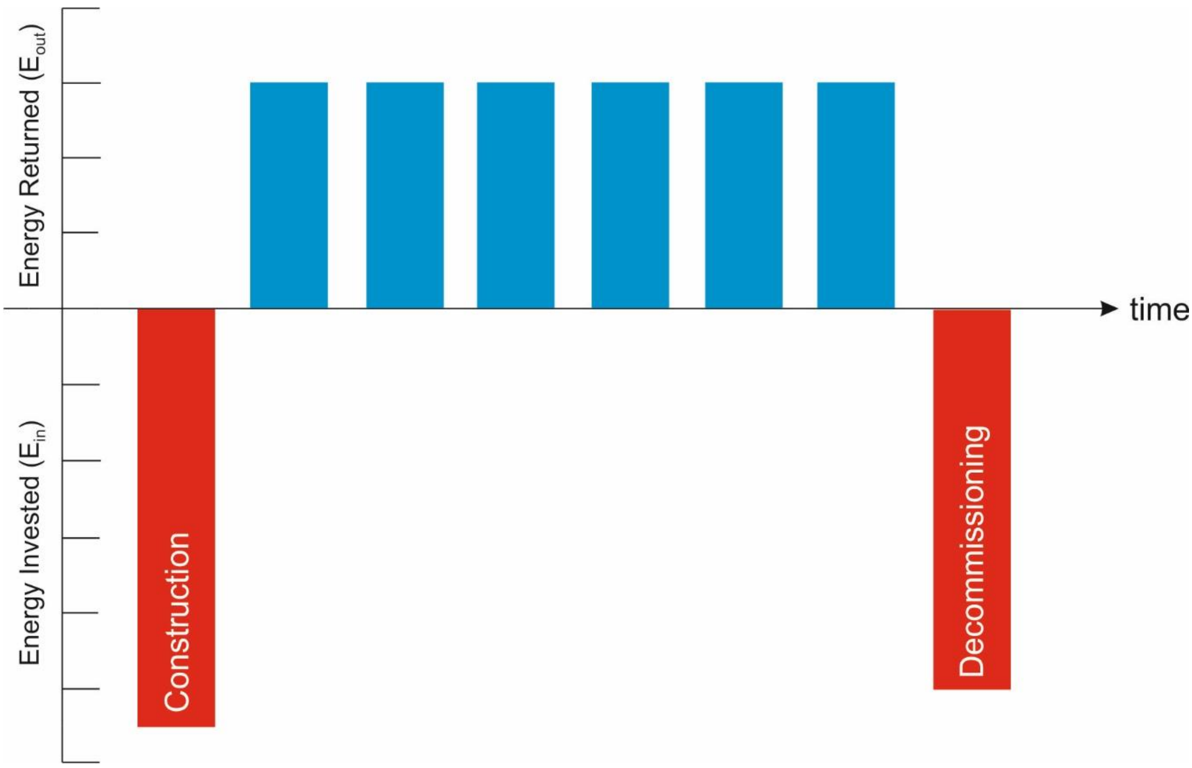

Figure 3. EROI inputs over time

However, when the boundary is expanded over larger geographical spaces and several energy sources, as obtaining such data for all energy sources is impractical, therefore a pragmatic approach is required. For our $EROI_{nat}$ we assume that the temporal patterns of energy inputs will balance out, since not all energy extraction or capture projects will be at the same stage of development. Therefore accounting for $EROI_{nat}$ in any given year broadly reflects the whole country's EROI across all energy sources irrespective of the stage of development of specific energy extraction and capture projects. However, as Murphy et al. (2011, p.1893) point out "this assumption would be accurate only if the system is in 'steady state', i.e., not growing or shrinking". Note that this pragmatic assumption may fail to capture shortfalls in energy available to the economy for an interim period. For example, in the context of rapid mitigation to address climate change, there is a need to invest heavily in the capture or extraction technology for particular energy sources in a short period of time. In these sorts of periods, $EROI_{nat}$values would be very low, and would be followed by periods of higher $EROI_{nat}$ once the technologies are in place (Dale & Benson 2013).

2.3.4. Accounting for energy quality

How to account for the differences in energy quality of the different energy sources has been a persistent methodological issue in energy analysis, and hence also for conducting NEA. It is important to account for energy quality because thermal energy and electricity, for example, are very different in terms of their capacity to do work, but also in their density, cleanliness, ease of storage, safety, flexibility of use, etc. These differences should be accounted for since they are relevant for societies and economies. However, and despite its importance, most EROI studies do not undertake any form of energy quality adjustment.

There are, in general, two approaches for accounting for differences in energy quality: price-based and physical units (Murphy et al. 2011, pp.1896–1899). The price-based approach is used more often when accounting for energy inputs using a top-down approach given the extent of economic data (e.g. Lambert et al. 2014). However, this approach rests on contentious assumptions of competitive markets and lack of accounting for externalities (Cleveland et al. 2000).

The physical units approach on the other hand, should be used more often in process analysis, where detailed physical data are available. Moreover, there is recent work that has been using physical units (particularly exergy11) to account for thermodynamic energy quality at a national-level (Brockway et al. 2014; Warr et al. 2010; Brockway et al. 2015; Williams et al. 2008). Nonetheless, it is important to acknowledge that exergy does not account for certain aspects of energy quality that are important for economic purposes (e.g. capacity for storage, cleanliness, transportability, density, and so on) (Cleveland et al. 2000; Murphy et al. 2011).

The type of quality adjustment we have made in our methodology is closer to the physical units approach. We have relied on the physical content method used by many energy agencies, by which the primary energy equivalent of any renewable energy source is its physical energy content (IEA 2016). Given that our boundary of analysis is taken at the production stage, this correction is less important than if we chose final consumption as the boundary of analysis. Therefore, we consider that further energy quality adjustments are a key part of future research, ideally using useful exergy, particularly considering the social and economic importance of being able to fairly compare different energy sources based on their usefulness.

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[11] Exergy can be defined as "the maximum possible work that may be obtained from a system by bringing it to the equilibrium in a process with reference surroundings" (Kostic 2012, p.816). As Gaggioli & Wepfer (1980, p.823) state, exergy "is synonymous with what the layman calls 'energy'. It is exergy, not energy, that is the resource of value, and it this commodity, that 'fuels' processes, which the layman is willing to pay for". For further details on exergy see Wall (1986; 1977; 2003), Kanoglu et al. (2012), Dincer (2002), Rosen (2006; 2002), Sciubba and Wall (2007).

3. A national-level EROI: the data and the methodology

3.1. Input-Output and Energy

Like many other energy analysis techniques, energy IO analysis was developed in the 1970s driven by the oil price shock of the time (Casler & Wilbur 1984). It has been mainly used to quantify energy flows through the different economic sectors (see for example Bullard & Herendeen, 1975; Bullard, Penner, & Pilati, 1978; Wright, 1974). However, to the best of our knowledge, it has not been used to directly calculate a national-level EROI value. Perhaps the study by Peet et al. (1987) is the closest, but it focused on specific sectors (i.e. oil and electricity) only, in addition to calculating net energy and not EROI specifically. We will now describe the data that we use to calculate $EROI_{nat}$ for the UK ($EROI_{nat(UK)}$) for 1997-2012, followed by a detailed description of the IO methodology.

3.2. $EROI_{nat(UK)}$: Data

We use IEA data (IEA 2015) and a Multi-Regional Input-Output (MRIO) model to construct a Multi-Regional Input-Output model for the UK (UKMRIO), using IO data produced by the UK's Office of National Statistics (ONS 2014). This data is supplemented with additional data on UK trade with other nations and how these other nations trade between themselves from the University of Sydney's Eora MRIO database. The Eora MRIO database (Lenzen et al. 2013) is used to disaggregate the UK's import and export data to further sectors from other world regions. Since Eora contains data from almost 200 countries, we are able to select the most appropriate regional grouping for the trade data. For this study, we construct six regions: the UK, the Rest of Europe, the Middle East (to account for trade with this oil producing region), China, the Rest of the OECD, and the Rest of the World. The UKMRIO is based on 106 sectors, two of which are energy industries/sectors relevant to our boundary definition (i.e. extraction/capture industries). A basic structure of an Input-Output model is shown in Figure 4. Following a standard procedure in IO modelling, an environmental extension for energy use relating to each transaction is added in physical units (MJ), though the main IO table is based on monetary units (Roberts 1978). This could be considered a drawback of this dataset, which uses a direct impact coefficient approach (or energy intensity approach). However, its use is justified by data availability (there are no MRIO energy extended databases that we know of that use a hybrid-unit approach12) and unit consistency.

[12] A single region IO hybrid-unit matrix with an energy extension was constructed by Guevara (2014) for Portugal using IEA (International Energy Agency) data.

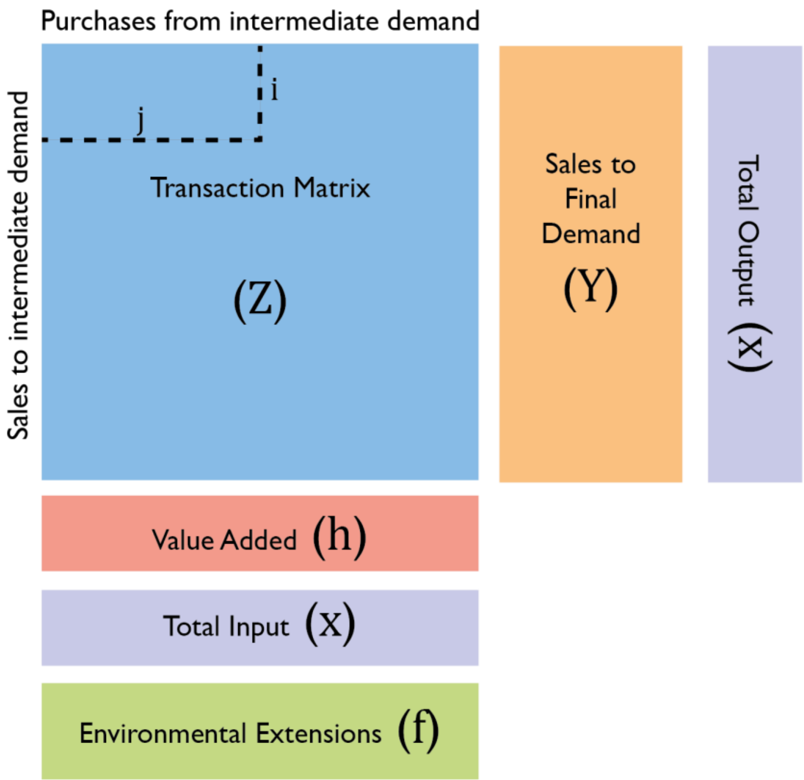

Figure 4. Basic structure of an Input-Output framework with and environmental extension

3.3. $EROI_{nat(UK)}$: Methodology

Our approach aims to track all indirect energy investment requirements of the energy sector. It does so by using a whole economy's transaction matrix to allocate energy sales and purchases to every industry, and then track down the paths that lead to the energy industry itself. In this case, $EROI_{nat(UK)}$ attempts to trace the indirect energy flows used by the UK's own energy sector in order to extract/capture energy (represented by black arrows in Figure 2). By using a MRIO model, we can take into account indirect energy investments that were originated overseas (see Figure 2). We consider it to be a novel application of a well-established methodology in the field of emissions accounting.

As described in section 0, the system boundary is drawn at the extraction/capture stage; therefore equation (2) is consistent with equation (1).

$$EROI_{nat(UK)} = \frac{E_{out}}{E_{in}} \tag{2}$$

Where:

E_{out} = net energy outputs from extraction/capture from the UK's energy sectors (or energy output from extraction in (1))

E_{in} = direct and indirect energy inputs (from the UK and abroad) to the UK's energy sectors (as in (1))

The energy return at a national level, E_{out} is calculated as follows:

$$E_{out} = E_T - E_{dE} \tag{3}$$

Where:

E_T = total primary energy produced in the UK. This is taken from "production" in IEA energy balances.

E_{dE} = total UK energy sector's direct energy use (both from the UK and the other 5 regions) used to extract/capture UK's energy. This is taken from "energy industry own use" in IEA energy balances.

Similarly, the energy invested in producing this, E_{in} is calculated as:

$$E_{in} = E_{dE} + E_{iE} \tag{4}$$

Where:

E_{iE} = total indirect energy use (both from the UK and the other 5 regions) used to extract/capture UK's energy. In other words, this is the embodied energy used by the UK's energy extracting/capture sectors in order to produce energy.

Having constructed the UKMRIO model, E_{iE} can be calculated, following the detailed matrix algebra IO procedure described in Appendix A, together with a simple numerical example.

Finally, the EROI at a national level for the UK is calculated by substituting these expressions into equation (2), as follows:

$$EROI_{nat(UK)} = \frac{E_T - E_{dE}}{E_{dE} + E_{iE}} \tag{5}$$

4. Results and Discussion

Applying the UK IO data, IEA data and MRIO model to equation (5), we calculated $EROI_{nat(UK)}$ for the period 1997-2012. We found that the $EROI_{nat}$ for the UK for the period increased from 5.6 in 1997 to a maximum value of 9.6 in 2000, before gradually falling back to a value of 6.2 in 2012 (Figure 5). This means that for every unit of energy the UK energy extracting/capture sectors have invested, they have obtained an average of 7.9 units of energy during the period 1997-2012. In other words, on average, 12% of the UK's extracted/captured energy does not go into the economy or into society for productive or well-being purposes, but rather needs to be reinvested by the energy sectors to produce more energy.

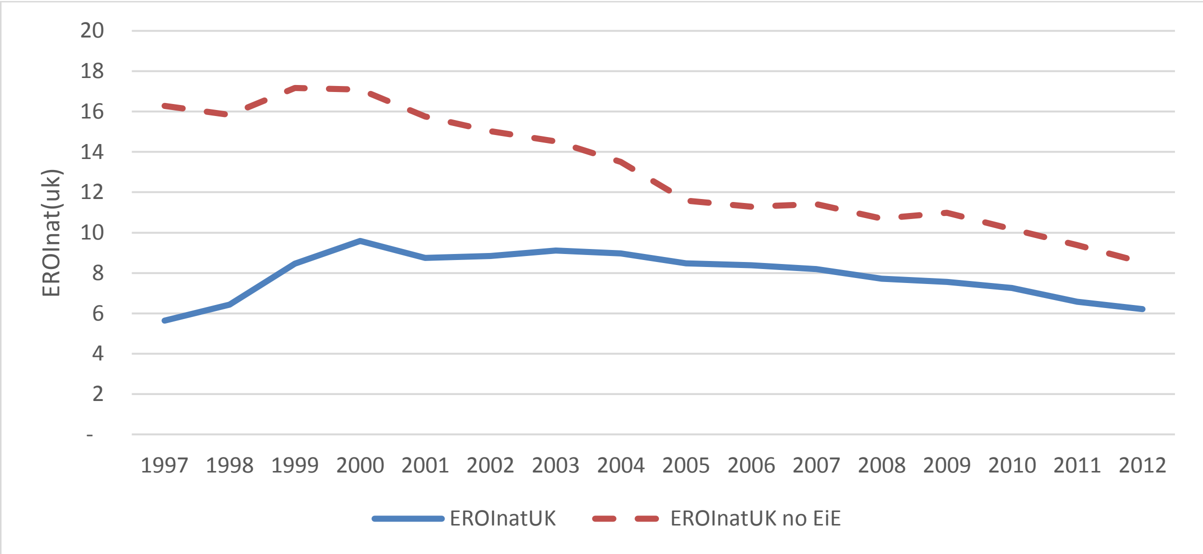

Figure 5. $EROI_{nat(UK)}$ (1997-2012): Comparison of results with and without indirect energy (E_{iE})

This of course has implications for the energy sector, for resource management and technology development, and for the economy, as described in section 0. If Fizaine and Court (2016) are right in their assessment, where a minimum societal EROI of 11 is required for continuous economic growth (assuming the current energy intensity of the US economy), the UK is below that benchmark.

Figure 5 also shows the relevance of including indirect energy (EiE) in the calculation of $EROI_{nat(UK)}$. A $EROI_{nat}$ calculation, using only energy industry's own use as the energy inputs gives higher values because there is an element missing in the denominator. By including indirect energy use (EiE), using the IO methodology described in section 0, we obtain a more complete view of the energy invested into the energy producing sectors. This is the key contribution of the methodology we outline here and a step forwards in the EROI literature. Our calculations for the UK without including indirect energy (EiE) are a same order of magnitude to King et al.'s (2015) calculations of EROI (or net power ratio –NPR as they call it).

The evolution of the energy returned (numerator Eout) and the energy invested (denominator Ein) are shown in Figure 6. Since 1999 the UK's production of energy has been declining steadily (compensated by increased imports). For a national-level EROI from a production perspective, this means that we are extracting/capturing less energy by using a relatively stable stream of energy inputs. Thus the steady decline of $EROI_{nat(UK)}$ from 2003 onwards.

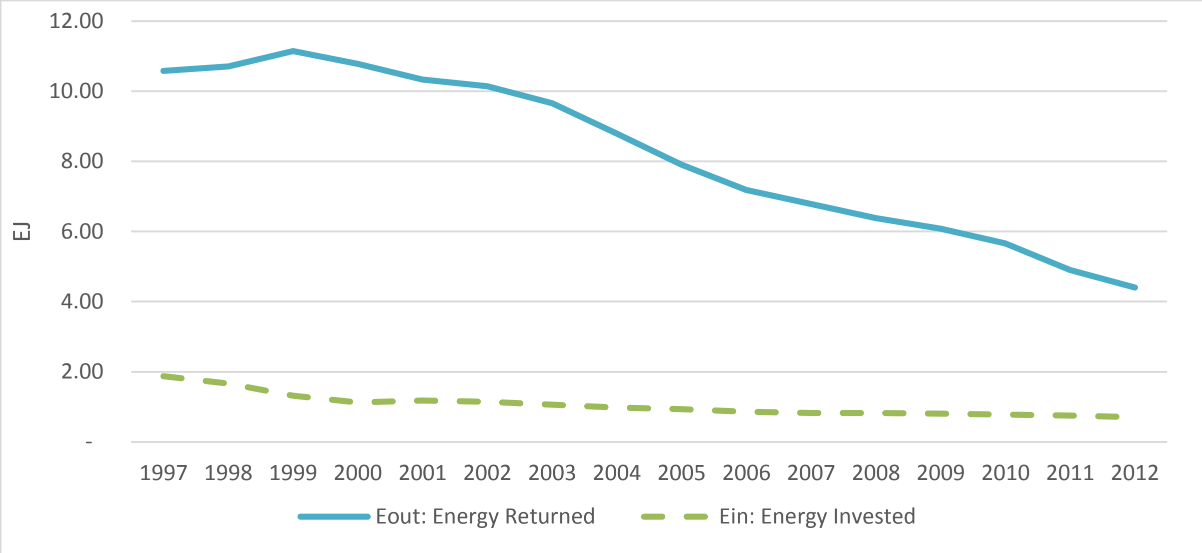

Figure 6. Energy Returned (E_{out}) and Energy Invested (E_{in}) in the UK (1997-2012)

Furthermore, considering that oil and gas dominate the UK's energy production mix (see Figure 7), changes in the EROI values of these particular fuels are likely to dominate the changes in the UK's $EROI_{nat}$. From past literature reviews on the EROI of different energy sources, there seems to be a consensus that coal has the highest EROI, followed by oil and then gas (Dale et al. 2012; Murphy & Hall 2010). Therefore, the steeper decline of $EROI_{nat(UK)}$ from 2010 onwards is explained by a reduction in the proportion of those three fossil fuels in the UK's total production.

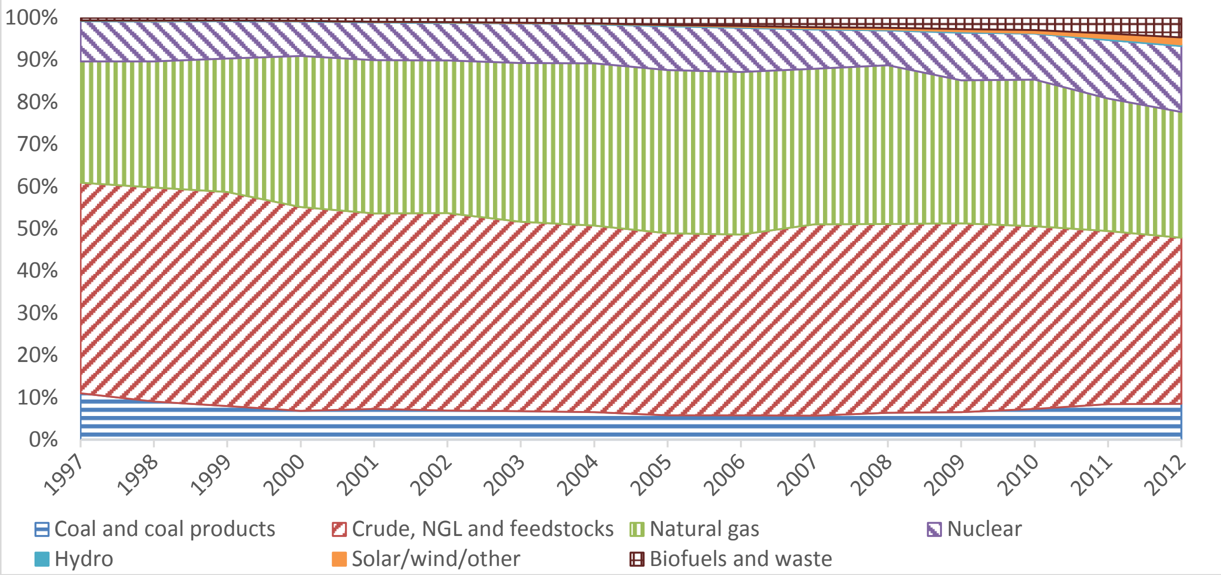

Figure 7. UK energy production: share of energy sources 1997-2012
Data taken from IEA (2015).

Table 1. UK's rate of production of different energy sources (1997-2010 and 2010-2012)

Energy Source	Change in Production (%)	
	1997-2010	2010-2012
Coal and coal products	-0.6	0.0
Crude, NGL and feedstocks	-0.5	-0.1
Natural gas	-0.3	-0.2
Nuclear	-0.4	0.1
Hydro	-0.1	0.4
Solar/wind/other	13.5	14.2
Biofuels and waste	1.6	0.7

Data taken from IEA (2015).

One drawback of our approach to calculating a national-level EROI is that it cannot provide energy source specific information of which moments in time energy investments are made and energy returns are obtained. However, we believe that by providing a time-series, our proposed approach provides an important element of temporal dynamics at a national scale. The greater availability of IO data would allow for time-series to be constructed for other countries, and we suggest this to be undertaken as future research. In this sense, we present our results to the academic community in the hopes of opening a constructive discussion.

5. Conclusions and Policy Implications

This paper developed and applied a new approach to quantify EROI for national economies, particularly when it comes to calculating indirect energy inputs. It contributes to the growing literature on net energy analysis. The approach is based on Input-Output analysis and is, to the best of our knowledge, a novel application of MRIO datasets which has been enabled by the advances in IO data gathering and computing power. Its key contribution is to provide an estimation of indirect energy investments at a national level. Hence, we consider it a step forwards towards the called made by Murphy and Hall (2010, p.115) for improved “quantity and quality on the data on ‘energy costs of energy generating industries’”.

The relevance of a national-level EROI lies in its potential to inform national-level energy policy making. $EROI_{nat(UK)}$ over time provides information on the relative resource depletion and technological change in the UK’s energy sector. We found that the UK as a whole has had a declining EROI in the first decade of the 21st century, going from 9.6 in 2000 to 6.2 in 2012. This information is important, particularly for a country that is aiming to transition to a low-carbon economy, where high values of national-level EROI would contribute to a successful transition. These initial results show that more and more energy is having to be used in the extraction of energy itself rather than by the UK’s economy or society.

Other authors (Herendeen 2015; Carey W King et al. 2015) have attempted to connect EROI values to the price of energy and other services in order to give them more policy relevance. We argue that the methodology described here has the potential to inform national and international energy policy. Once developed further, for more countries and more years, the results can answer important questions such as: Which countries are extracting and capturing energy with a better return to their energy invested? Which countries are doing better in terms of technological development and/or resource conservation? How do $EROI_{nat}$ values for different countries relate to their energy imports and exports? Therefore, we suggest two avenues for future research: first, apply this methodology for more countries and more years; and second, extend the methodology to develop a national-level EROI from a consumption perspective, i.e. expanding the boundary of analysis (an effort that would complement the work of Herendeen (2015)).

As a final thought, in 1974 the US passed a law such that “all prospective energy supply technologies considered for commercial application must be assessed and evaluated in terms of their ‘potential for production of net energy’” (Berndt 1982). This was triggered by the 1973-74 oil crisis. Once oil supply issues had returned to normal the law was abandoned as the additional calculations were regarded as unnecessary. Given the emerging interest in alternative tools for energy analysis and the pressing need of a transition to a low carbon economy, perhaps it is time to reinstate the importance of undertaking such analysis. Even if the EROI values of renewables may increase in future from current relatively low values –there is contrasting evidence on current values (Raugei et al. 2012; Kubiszewski et al. 2010)- we need to better understand what that would imply for our economies and societies. For the guidance of national energy policy, EROI at a national level could help inform policy decisions that aim to manage an energy transition (Carbajales-Dale et al. 2014).

APPENDIX A

A note on notation: A bold lower case letter represents a vector. A bold capital letter represents a matrix. Non-bold lower case and capital letter represent scalars. A vector with a "hat" ($\widehat{}$) represents a diagonal matrix, whose diagonal elements are the elements of the vector. $\mathbf{I}$ is the identity matrix, and is a matrix of zeros whose diagonal is made of ones.

Consider the transaction matrix Z (Figure A 1). In the top left hand corner of Z is the UK data, followed by 5 world regions (the Rest of Europe, the Middle East, China, the Rest of the OECD, and the Rest of the World). Each region contains 106 industry sectors. Z displays sales by each industry in rows and the columns represent purchases by each industry. In other words, reading across a row reveals which other industries a single industry sells to and reading down a column reveals who a single industry buys from in order to make its product output. A single element, z_{ij}, within $\mathbf{Z}$ represents the contributions from the i^{th} supplying sector to the j^{th} producing sector in an economy. The $\mathbf{Z}$ matrix is in monetary units.

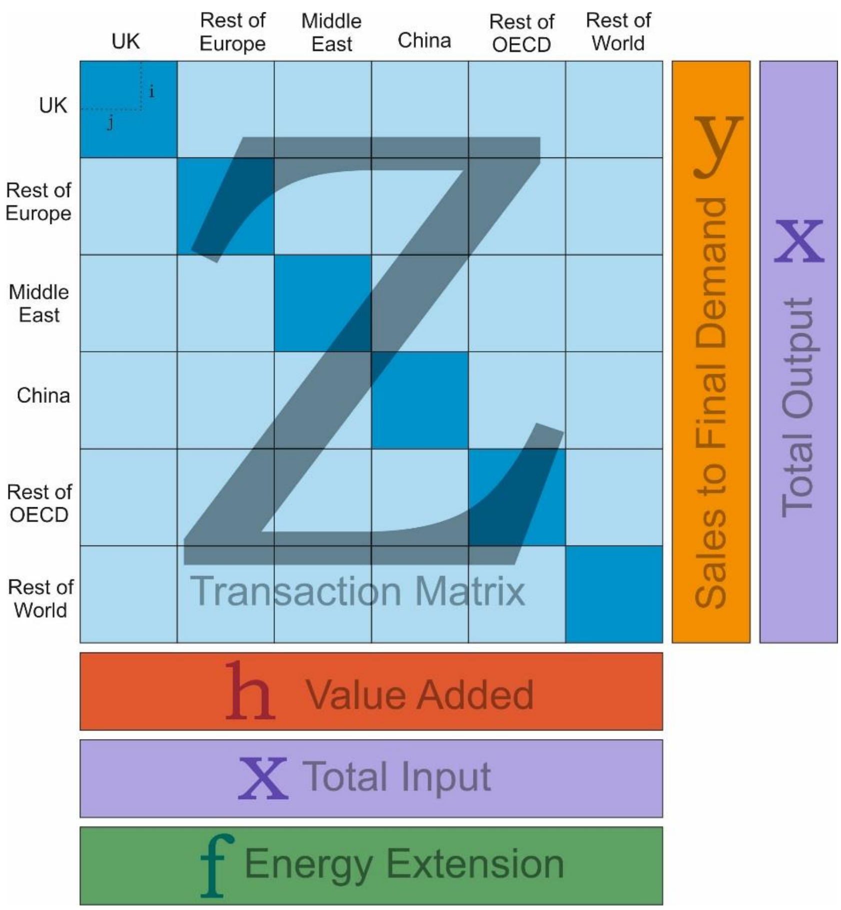

Figure A 1. Basic Structure of the UK MRIO.

Reading across the table, the total output (x_i) of sector i can be expressed as:

$$x_i = z_{i1} + z_{i2} + \cdots + z_{in} + y_i \quad \text{(A 1)}$$

where y_i is the final demand for the product produced by the particular sector. Essentially, the IO framework shows that the total output of a sector can be shown to be the result of its intermediate and final demand. Similarly if a column of the IO table is considered, the total input of a sector is shown to be the result of its intermediate demand and the value added in profits and wages ($\mathbf{h}$). The sum across total output ($\mathbf{x}$) and total input ($\mathbf{x}$) will be equal.

If each element, z_{ij}, along row i is divided by the output x_j, associated with the corresponding column j it is found in, then each element z_{ij} in $\mathbf{Z}$ can be replaced with:

$$a_{ij} = \frac{z_{ij}}{x_j} \quad \text{(A 2)}$$

forming a new matrix $\mathbf{A}$, known as the direct requirements matrix. Element a_{ij} is therefore the input as a proportion of all the inputs in the production recipe of that product.

Equation (A 2) can be re-written as:

$$z_{ij} = a_{ij}x_j \tag{A 3}$$

Substituting for (A 3) in (A 1) forms:

$$x_i = a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n + y_i \tag{A 4}$$

Which, if written in matrix notation is $= \mathbf{Ax} + \mathbf{y}$. Solving for $\mathbf{x}$ gives:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-\mathbf{1}}\mathbf{y} \tag{A 5}$$

(A 5) is known as the Leontief equation and describes output $\mathbf{x}$ as a function of final demand $\mathbf{y}$. $(\mathbf{I} - \mathbf{A})^{-\mathbf{1}}$ is known as the Leontief inverse (denoted hereafter as $\mathbf{L}$). Therefore (A 5) can be re-written as:

$$\mathbf{x} = \mathbf{Ly} \tag{A 6}$$

Consider a row vector $\mathbf{f}$ of annual energy produced required by each industrial sector (an environmental extension in Figure 4). Then it is possible to calculate the energy intensity ($\mathbf{e}$) by dividing the total energy input of each sector by total sector output ($\mathbf{x}$), in terms of joules per pound for example, as follows:

$$\mathbf{e} = \mathbf{f}\hat{\mathbf{x}}^{-\mathbf{1}} \tag{A 7}$$

In other words, $\mathbf{e}$ is the coefficient vector representing energy per unit of output.

Multiplying both sides of (A 6) by $\mathbf{e}$ gives:

$$\mathbf{ex} = \mathbf{eLy} \tag{A 8}$$

and from (A 7) we simplify (A 8) to:

$$\mathrm{f} = \mathbf{eLy} \tag{A 9}$$

However, we need the result $(\mathbf{f})$ as a flow matrix $(\mathbf{F})$, rather than a scalar, and so we use the diagonalised $\hat{\mathbf{e}}$ and $\hat{\mathbf{y}}$:

$$\mathbf{F} = \hat{\mathbf{e}}\mathbf{L}\hat{\mathbf{y}} \tag{A 10}$$

$\mathbf{F}$ is produced energy in matrix form, allowing the UK's use of energy from the full supply chain of extraction/capture to be determined. $\mathbf{F}$ is calculated by pre-multiplying $\mathbf{L}$ by energy per unit of output and post-multiplying by final demand. Energy is reallocated from extraction/capture sectors to the sectors that use this produced energy.

We will use input-output analysis techniques to calculate total indirect energy use (both from the UK and the RoW) used to extract/capture UK's energy. This is E_{iE} in (5) from the main text. To calculate E_{iE} we calculate a new flow matrix $\mathbf{F^0}$ which shows the UK's total use of energy from the full supply chain if there was no flow to the energy sectors. The indirect energy use is therefore the difference between $\mathbf{F}$ and $\mathbf{F^0}$.

To calculate $\mathbf{F^0}$, we generate a new version of the transactions matrix, $\mathbf{Z^0}$, which is exactly the same as $\mathbf{Z}$ apart from the fact that $\mathbf{Z^0}$ has zeros in the cells that represent the UK energy sector's expenditure on all other energy products.

Let $\mathbf{Z^0}$ contain n regions and m sectors. Sectors c to e are the energy sectors and region k is the UK. An element of $\mathbf{Z^0}$ is z_{ij}^{rs0}which represents the monetary flow from sector i in country r to sector j in country s. We know that $z_{ij}^{rs0} = 0$ if i and j belong to the set of energy sectors (c to e) and if region $s = k$ (the UK). In other words:

$$\mathbf{Z^0} = z_{ij}^{rs0} = \begin{Bmatrix} 0\ if\ i,j\ \in \{c, \dots, e\}\ and\ s = k \\ z_{ij}^{rs0} otherwise \end{Bmatrix} \tag{A 11}$$

Then

$$\mathbf{F^0} = \hat{\mathbf{e}}(\mathbf{I} - \mathbf{Z^0}\widehat{\mathbf{x}^{-1}})^{-1}\,\hat{\mathbf{y}} \tag{A 12}$$

and

$$E_{iE} = \sum_{r}^{n} \sum_{j \in \{c,\dots,e\}} \sum_{j \in \{c,\dots,e\}} F_{ij}^{rk} - F_{ij}^{rk0} \tag{A 13}$$

Essentially, $\sum_r^n \sum_{j\in\{c,\ldots,e\}} \sum_{j\in\{c,\ldots,e\}} F_{ij}^{rk}$ is the sum of all the direct and indirect energy that forms energy inputs to make UK energy products.

$\sum_r^n \sum_{j\in\{c,\ldots,e\}} \sum_{j\in\{c,\ldots,e\}} F_{ij}^{rk0}$ is the sum of the direct energy that forms energy inputs to make UK energy products.

And the difference is the sum of the indirect energy that forms energy inputs to make UK energy products.

Finally, we do this for each of the 16 years (1997-2012) we have data for.

We present here a simple numerical example. Let's assume we have a 3 region model (UK, rest of the world 1 - RoW1 and rest of the world 2 - RoW2). Each region has 4 sectors, two of which are energy producing sectors.

Z, y, h, x, f and e are presented in Figure A 2.

		UK				RoW1				RoW2				UK	RoW1	RoW2	
		Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	y	y	y	x
UK	Agri	100	30	5	3	6	10	10	4	3	5	5	2	500	10	5	698
	Manu	20	200	10	6	10	8	6	2	5	4	3	1	300	4	2	581
	Energy1	15	20	100	25	10	2	2	2	5	1	1	1	100	4	2	290
	Energy2	15	15	100	25	2	2	2	0	1	1	1	0	100	2	1	267
RoW1	Agri	10	6	2	1	75	22	4	3	2	4	4	1	8	450	4	596
	Manu	2	15	0	1	15	150	7	5	4	4	3	2	2	250	1	461
	Energy1	2	1	1	2	12	15	75	18	4	1	1	2	2	80	1	217
	Energy2	2	1	2	1	12	12	75	18	1	0	0	1	1	80	1	207
RoW2	Agri	30	20	5	3	60	40	10	6	1000	20	10	5	30	60	600	1899
	Manu	5	50	1	1	10	100	2	2	100	2500	15	15	30	60	400	3291
	Energy1	5	3	2	5	10	6	4	10	100	150	1500	300	6	12	400	2513
	Energy2	2	2	5	3	4	4	10	6	50	150	250	300	6	12	300	1104
	h	490	218	57	191	370	90	10	131	624	451	720	474				
	x	698	581	290	267	596	461	217	207	1899	3291	2513	1104				
	f	10	15	300	100	0	0	1	1	0	0	2	3				
	e	0.01	0.03	1.03	0.37	-	-	0.00	0.00	-	-	0.00	0.00				

Figure A 2. Numerical example: Z, y, h, x, f and e.

After applying equations (A 1) to (A 10) we obtain $\mathbf{F}$, shown in Figure A 3.

		UK				RoW1				RoW2			
		Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2
UK	Agri	8.7	0.4	0.1	0.0	0.2	0.2	0.1	0.0	0.1	0.1	0.1	0.0
	Manu	0.8	12.2	0.3	0.1	0.5	0.4	0.2	0.1	0.2	0.1	0.1	0.0
	Energy1	26.7	31.4	178.2	18.3	18.3	6.6	4.3	2.2	8.3	2.7	1.6	1.4
	Energy2	9.4	9.7	24.7	45.2	3.7	2.1	1.3	0.4	1.7	0.8	0.5	0.3
RoW1	Agri	-	-	-	-	-	-	-	-	-	-	-	-
	Manu	-	-	-	-	-	-	-	-	-	-	-	-
	Energy1	0.0	0.0	0.0	0.0	0.1	0.1	0.6	0.1	0.0	0.0	0.0	0.0
	Energy2	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.5	0.0	0.0	0.0	0.0
RoW2	Agri	-	-	-	-	-	-	-	-	-	-	-	-
	Manu	-	-	-	-	-	-	-	-	-	-	-	-
	Energy1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.2	0.3	0.9	0.3
	Energy2	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.5	0.4	1.3

Figure A 3. Numerical example: F.

In order to calculate E_{iE}, following equations (A 11) and (A 12), we create $\mathbf{F^0}$ from $\mathbf{Z^0}$. The latter is shown in Figure A 4 and the former is shown in Figure A 5.

		UK				RoW1				RoW2				UK	RoW1	RoW2	
		Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	y	y	y	x
UK	Agri	100	30	5	3	6	10	10	4	3	5	5	2	500	10	5	698
	Manu	20	200	10	6	10	8	6	2	5	4	3	1	300	4	2	581
	Energy1	15	20	0	0	10	2	2	2	5	1	1	1	100	4	2	165
	Energy2	15	15	0	0	2	2	2	0	1	1	1	0	100	2	1	142
RoW1	Agri	10	6	2	1	75	22	4	3	2	4	4	1	8	450	4	596
	Manu	2	15	0	1	15	150	7	5	4	4	3	2	2	250	1	461
	Energy1	2	1	0	0	12	15	75	18	4	1	1	2	2	80	1	214
	Energy2	2	1	0	0	12	12	75	18	1	0	0	1	1	80	1	204
RoW2	Agri	30	20	5	3	60	40	10	6	1000	20	10	5	30	60	600	1899
	Manu	5	50	1	1	10	100	2	2	100	2500	15	15	30	60	400	3291
	Energy1	5	3	0	0	10	6	4	10	100	150	1500	300	6	12	400	2506
	Energy2	2	2	0	0	4	4	10	6	50	150	250	300	6	12	300	1096
	h	490	218	267	252	370	90	10	131	624	451	720	474				
	x	698	581	290	267	596	461	217	207	1899	3291	2513	1104				
	f	10	15	300	100	0	0	1	1	0	0	2	3				
	e	0.01	0.03	1.03	0.37	-	-	0.00	0.00	-	-	0.00	0.00				

Figure A 4. Numerical example: $\mathbf{Z^0}$

		UK				RoW1				RoW2			
		Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2	Agri	Manu	Energy1	Energy2
UK	Agri	8.66	0.43	0.04	0.02	0.15	0.20	0.13	0.05	0.08	0.08	0.05	0.03
	Manu	0.74	12.16	0.15	0.10	0.45	0.36	0.20	0.06	0.22	0.15	0.08	0.04
	Energy1	14.96	17.97	109.95	0.19	11.01	3.77	2.49	1.34	4.97	1.53	0.94	0.81
	Energy2	5.20	4.89	0.08	38.63	1.08	1.05	0.64	0.11	0.54	0.42	0.25	0.10
RoW1	Agri	-	-	-	-	-	-	-	-	-	-	-	-
	Manu	-	-	-	-	-	-	-	-	-	-	-	-
	Energy1	0.02	0.02	0.00	0.00	0.10	0.11	0.62	0.06	0.03	0.01	0.01	0.01
	Energy2	0.02	0.01	0.00	0.00	0.10	0.10	0.25	0.46	0.02	0.01	0.00	0.01
RoW2	Agri	-	-	-	-	-	-	-	-	-	-	-	-
	Manu	-	-	-	-	-	-	-	-	-	-	-	-
	Energy1	0.03	0.04	0.00	0.00	0.06	0.08	0.02	0.02	0.25	0.29	0.92	0.27
	Energy2	0.04	0.07	0.00	0.00	0.08	0.13	0.05	0.02	0.32	0.49	0.44	1.32

Figure A 5. Numerical example: $\mathbf{F^0}$

Finally, we apply equation (A 13) and obtain E_{iE} of 117.64.

Assuming we obtain from the IEA for our numerical example $E_T = 425$ and $E_{dE} = 130$, we can insert these components in equation (5) and obtain $EROI_{nat(UK)} = 1.1$

$$EROI_{nat(UK)} = \frac{425 - 130}{130 + 117.64}$$

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