UNIVERSITY OF LEEDS

This is a repository copy of *Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/148748/

Version: Accepted Version

Article:

Brockway, PE orcid.org/0000-0001-6925-8040, Owen, A orcid.org/0000-0002-3872-9900, Brand Correa, LI et al. (1 more author) (2019) Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. Nature Energy, 4 (7). pp. 612-621. ISSN 2058-7546

https://doi.org/10.1038/s41560-019-0425-z

© The Author(s), under exclusive licence to Springer Nature Limited 2019. This is an author produced version of an article published in Nature Energy. Uploaded in accordance with the publisher's self-archiving policy.

Reuse
Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Estimation of global final stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources

Paul E. Brockway [a,*], **Anne Owen**[a], **Lina Brand-Correa**[a], **Lukas Hardt**[a]

[a]*Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK*
* Corresponding author: p.e.brockway@leeds.ac.uk. Tel.: +44-113-343-2846

Fossil fuels under many scenarios remain the dominant energy source to at least 2050. However, harder-to-reach fossil fuels require more energy to extract and hence are coming at an increasing 'energy cost'. Associated declines in fossil fuel energy-return-on-investment ratios at first appear of little concern, given published estimates for oil, coal and gas sources are typically above 25:1. However, such ratios are measured at the primary energy stage, but should be estimated instead at the final energy stage (e.g. electricity, petrol) where energy enters the economy. Here, we calculate global time-series (1995-2011) energy-return-on-investment ratios for fossil fuels at both primary and final energy stages. We concur with common primary-stage estimates (~30:1), but find very low ratios at the final stage: around 6:1, and declining. This implies fossil fuel energy-return-on-investment ratios may be much nearer to those of renewables and could decline precipitously in the near future.

The field of net energy analysis first came to prominence during the 1970s oil crises[1–4] as a means of assessing how much energy is delivered to society. Various metrics have emerged[5] including energy profit ratio, energy gain, energy payback, and the most well-known 'energy-return-on-investment' (EROI). Kunz et al.[6] define EROI in its simplest form as a ratio which "divides the total energy output by the energy input". Several factors have contributed to increasing attention being paid to the EROI research field. First, there are concerns over declining EROI ratios of fossil fuels – which under many scenarios remain the dominant energy source to at least 2050[7] – due to depletion of finite reserves[8,9]. Second, the estimated EROI ratios for renewable energy sources are often contentious, vary greatly depending on adopted methodology, and are commonly estimated as lower than fossil fuels[10]. Concerns follow that the renewables-led energy transition required to meet climate targets[11] may have adverse socio-economic impacts[12]. Third, EROI as a topic has become more accessible through the readily-visualised concepts of a 'net energy cliff'[9] – where available net energy declines precipitously below EROI ratios of 5:1 - and a minimum threshold level of societal-level EROI[13,14].

However, much of the increased attention is confined to academic circles. One reason may be that fossil fuel EROI is commonly estimated at the primary (energy source) stage, where EROI ratios (i.e. for oil, coal and gas) are high, typically over 25:1[8,15]. Such ratios suggest to modellers and policy makers that EROI ratios won't fall below a threshold of concern until well into the renewables transition[12]. However, this is a misleading perception, as instead, fossil fuel EROI should be estimated at the final (energy carrier) stage (e.g. electricity, gas, and petrol), where energy enters the economy. This enables a fairer comparison to renewables-based EROI estimates, and the platform for improved energy and climate policy.

We build on recent EROI research[10,15,16] to provide an estimate of global fossil-fuel based EROI at a final energy stage, which better matches that of renewables-based EROI. We combine national-level International Energy Agency (IEA) energy data with a multi-regional input-output (MRIO) approach to include a wider boundary of direct energy production sectors and associated indirect (supply-chain) energy impacts, including trade. To enable comparison to existing methods and EROI ratios, we estimate global fossil fuel EROI for both primary ($EROI_{PRIM}$) and final ($EROI_{FIN}$) energy stages, and also provide time-series estimates for the 1995-2011 period. Our results indicate that by 2011 global ratios for $EROI_{FIN}$ (~6:1) are much lower than $EROI_{PRIM}$ (~30:1), and both are declining. Two implications follow. First, EROI of fossil fuels may be much nearer to renewables than commonly supposed, meaning a global renewables transition may not be as biophysically troublesome as previously thought. Second, the low and declining $EROI_{FIN}$ ratios for fossil fuels provides an immediate concern, and also implies we are much nearer a 'net energy cliff' than previously thought, where the non-linearity of EROI means low ratios (below 5:1) quickly restrict available net energy to society.

Global fossil fuel EROI based on a final energy stage

Cleveland et al.'s[17] landmark study in the 1980s estimated EROI in the United States for fossil fuels at the 'well head' (oil and gas) and 'mine mouth' (coal). Since then, many fossil fuel EROI studies have been published[15], though largely these remain at the primary energy stage (as coal, oil, gas). The most common exceptions are fossil fuel based EROI estimates of electricity, which are at the final energy stage. However, their methodologies (and hence estimates) vary, with some (e.g. ref.[10,15]) taking primary stage EROI estimates and applying direct (thermal) loss factors in conversion to electricity, while others (e.g. ref.[18]) use LCA-based methods to include both thermal losses and supply-chain energy investment.

At the same time, an increasing number of studies are estimating EROI ratios for modern renewables, particularly electricity generated from photovoltaics (PV) and wind turbines – which are seen as two energy technologies pivotal[11] for reductions in global greenhouse gas emissions.

A summary of the different EROI estimates for these two different energy sources (fossil fuels and renewables) at primary and final energy conversion stages is given in Table 1:

Table 1: Comparison of EROI ratio estimates for different energy sources/carriers and conversion stages

Energy source / carrier	Published estimates of EROI ratios (X:1) at different energy conversion stages		
	Primary energy stage (EROI$_{PRIM}$)	Final energy stage (EROI$_{FIN}$)	Reference
Coal	40 – 55 (mine mouth)		Hall et al.[15]
	80 (mine mouth)		Court and Fizaine[19]
Oil	15 (well head)		Court and Fizaine[19]
	18 (well head)		Gagnon et al.[8]
	20 (well head)		Hall et al.[15]
		4-5 (refined oil fuels)	Brandt[20]
Gas	18 (well head)		Gagnon et al.[8]
	20 (well head)		Hall et al.[15]
	75 (well head)		Court and Fizaine[19]
Electricity (gas)		6^{Δ}	Hall et al.[15]
		8^{Δ}	King and Van Den Bergh[10]
		$11^{o} – 14^{o}$	Raugei and Leccisi[18]
Electricity (coal)		4^{o}	Raugei and Leccisi[18]
		$13^{\Delta} – 18^{\Delta}$	Hall et al.[15]
		17^{Δ}	King and Van Den Bergh[10]
Electricity (PV)	19* – 38*	$6^{o} – 12^{o}$	Raugei et al.[21]
		10^{Δ}	Hall et al.[15]
		4^{o} - 20^{o}	Leccisi et al.[22]
Electricity (Wind)		$14^{o} – 26^{o}$	Kubiszewski et al.[23]
		$15^{o} – 30^{o}$	Raugei and Leccisi[18]

* 'Primary energy equivalent' value by Raugei et al. [21], estimated by dividing EROI$_{FIN}$ value for PV (6-12) by the EU-27 electric grid efficiency η_{grid}= 0.31.

$^{\Delta}$ includes power plant / transformational conversion efficiencies only

^{o} includes power plant / transformational conversion efficiencies AND supply chain energy investments

Table 1 reveals the divergence between the modal EROI estimates: primary-stage fossil fuels are much higher (typically 20:1-80:1) than final-stage renewable electricity (typically 5:1-20:1). This creates a potentially misleading perception to modellers of high fossil fuel EROI and low renewables EROI. Raugei[24] warns such apples-to-oranges comparisons are flawed, as they "compare [energy] carriers that cannot be put to similar end-use". As energy-economy models are now starting to include EROI within their analytical framework, this has the potential to lock-in bias towards fossil fuels. For example, Sers and Victor[12] suggest an 'energy-emissions trap' is approaching, as "Reducing emissions will necessitate the transition from relatively high EROI dispatchable fossil fuels to […] relatively low EROI intermittent renewables".

Sers and Victor's reference to 'intermittent' renewables highlights an important point: estimation of EROI for renewables is a much newer field with a host of interwoven issues ongoing for the mainly life cycle analysis (LCA) based methodology, including capital investment, payback times, and intermittency.

Whilst resolving such renewables-EROI issues are worthy and should continue, we suggest the heavy focus on them has distracted from the equally pressing need to move fossil fuel EROI to the final energy calculation stage. This is important for two key reasons. First, incumbent fossil fuels remain important: the Intergovernmental Panel on Climate Change (IPCC) future scenarios assume they remain as the dominant source of energy to at least 2050[25]. Second, EROI increasingly is being included in energy-economy models as noted earlier, to help study future energy transitions[10,26] and their macroeconomic impacts[12,27,28]. As energy enters the productive economy at the final energy stage, EROI ratios at the same final energy stage are thus also in the correct format for inclusion in energy-economy models.

Matching fossil-fuel EROI estimates to the same (final) energy stage and (economy-wide or global) scale as energy-economy models is therefore important. Currently, economy-wide and global fossil-fuel EROI estimates – excluding electricity as seen in Table 1 – remain at a primary energy stage, using either a site-level or price based approach. Lambert et al.[9] provide an example of the site-level approach, collating sample studies from different countries at the 'mine mouth' and 'well head'. The price-based approach typically involves using energy prices and/or expenditure data to estimate direct and indirect (including capital) energy investment[29]: Gagnon et al.[8], Court and Fizaine[19] and Guilford et al.[30] provide examples. King et al.[31] provide another route, using total energy expenditure to estimate aggregate EROI.

Analytical approach

We build on previous work by Brand-Correa et al.[16], developing an input-output based approach to estimate global fossil fuel EROI at final and primary energy stages for the period 1995-2011. Two key advances underpin the method. First, we use International Energy Agency (IEA) extended energy balances time-series data[32]. This provides us with country-level data for fossil fuel energy produced at both a primary and final energy stage. It also allows access to the direct energy use for energy production sectors at both primary energy (e.g. coal mines) and final energy (e.g. oil refineries, coke production, coal gasification) stages. Second, we use EXIOBASE – a large global multi-regional input-output (MRIO) database[33] - to estimate the indirect 'supply-chain' energy associated with production of fossil fuel energy at both primary and final energy stage, including trade.

We adopt a net EROI ($EROI_{net}$) calculation basis, as given in equation (1), where net energy output is equal to the gross (or total) energy output, minus the energy input. This aligns firstly with other net energy research[6,10,34], which focuses on the energy that enters the productive economy, and secondly with our final energy data which is already in net energy terms. (Note, *net* EROI = *gross* EROI – 1 as shown in Methods. Therefore our results are applicable to both definitions, and we remove the Net suffix hereafter).

$$EROI_{net} = \frac{Net\ energy\ output}{Energy\ input} = \frac{Gross\ energy\ output - energy\ input}{Energy\ input} \qquad (1)$$

Our conceptual boundaries for calculating global $EROI_{PRIM}$ and $EROI_{FIN}$ are set out in Figure 1:

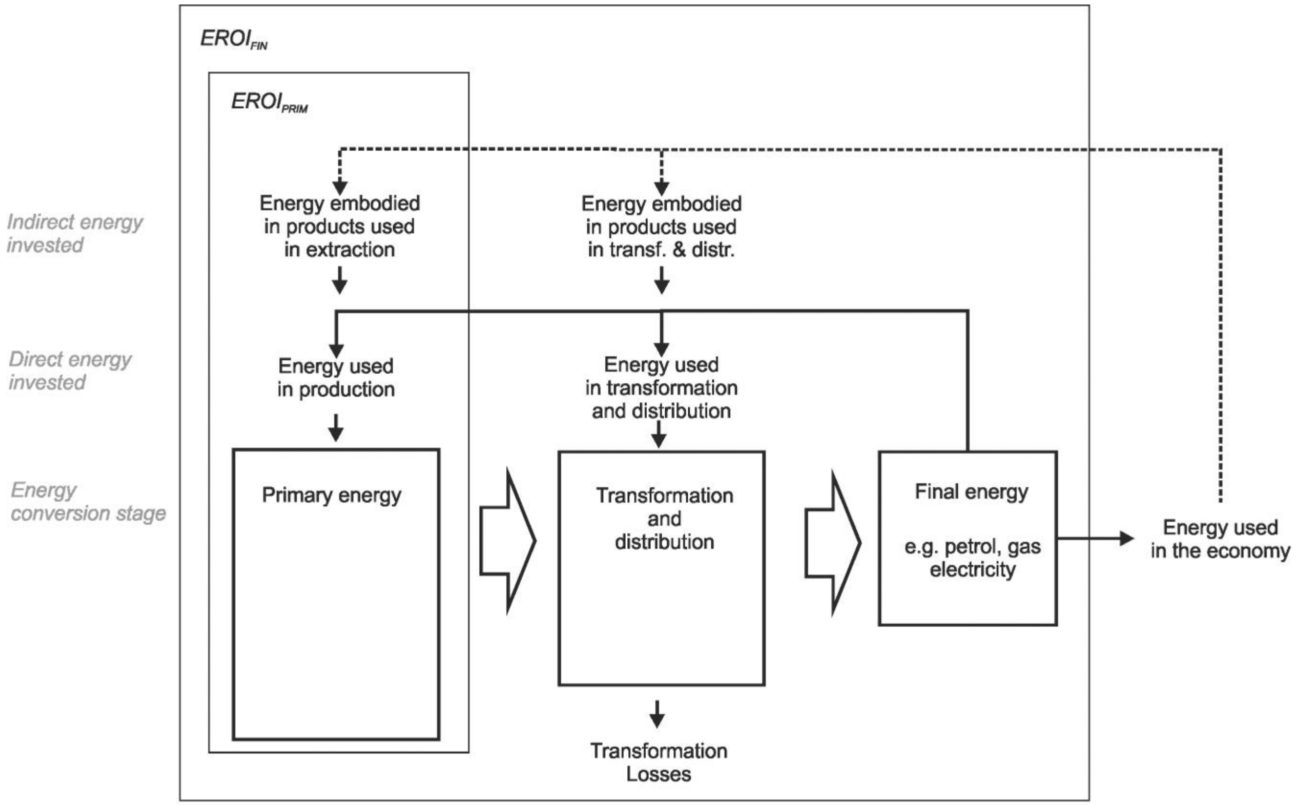

Figure 1: Conceptual framework for global fossil fuels energy-return-on-investment estimation. $EROI_{PRIM}$ is aggregate fossil fuel EROI at the primary energy conversion stage. $EROI_{FIN}$ denotes aggregate fossil fuel EROI at the primary energy conversion stage. Direct energy invested is the energy consumed in production, transformation and distribution of energy. Indirect energy invested is the supply-chain embodied energy in products that are used in production, transformation and distribution of energy.

Referring to Figure 1, we calculate the components of $EROI_{PRIM}$ and $EROI_{FIN}$ via equations (2) and (3), which adapt equation (1) to the primary and final energy stages:

$$EROI_{PRIM} = \frac{Net\ energy\ produced}{Energy\ invested} = \frac{E_{T\_PRIM} - E_{dE\_PRIM}}{E_{dE\_PRIM} + E_{iE\_PRIM}} \tag{2}$$

$$EROI_{FIN} = \frac{Net\ energy\ produced}{Energy\ invested} = \frac{E_{T\_FIN} - E_{dE\_FIN}}{E_{dE\_FIN} + E_{iE\_FIN}} = \frac{Total\ Final\ Consumption\ (TFC)}{E_{dE\_FIN} + E_{iE\_FIN}} \tag{3}$$

The calculations proceed in three steps, in turn calculating net energy produced; and the direct energy (E_{dE}) and indirect energy (E_{iE}) invested in energy production. These are outlined next, with further detail provided in Methods (including modelling limitations).

From equation (2), the net energy produced for $EROI_{PRIM}$ is equal to the total gross production of primary energy (E_{T_PRIM}), minus the direct energy used by the energy extraction industries (E_{dE_PRIM}). We obtain values for E_{T_PRIM} from the 'production' energy data from the IEA extended world energy balances[32]. In IEA terms, this is a sub-category of 'total primary energy supply', and represents the primary energy extracted in each country/region, including exports, but excluding imports. As we use the EXIOBASE MRIO database in our analysis, we do not need to account for imported energy, as these flows will be reflected in the MRIO transaction matrices.

Next, in equation (3), we directly obtain the net energy produced at the final energy stage via the 'Total Final Consumption' (TFC) provided in the IEA extended world energy balances[32]. This is equal to the gross final energy (for fossil fuels) used by each country/region (E_{T_FIN}), minus the direct energy (E_{dE_FIN}) associated with the production of the final energy.

The direct energy component (E_{dE}) in equations (2) and (3) represents the direct energy invested to extract fossil fuels or produce fossil-fuel based final energy. We obtain information for E_{dE} from the 18 'Energy Industry Own Use' (EIOU) sub-categories in the IEA's extended energy balances[32], which follows their accounting conventions for 'Energy industry own use and Losses' – see also the IEA's 'World Energy Balances: Database Documentation[35]. As shown in Table 2, E_{dE_PRIM} includes only two EIOU sub-categories (Coal mines, Oil and gas extraction), whereas E_{dE_FIN} also includes the additional 12 EIOU categories involved in producing final energy (e.g. Own use in electricity, Coal gasification, Coke production).

Table 2: IEA Energy Industry Own Use categories included in Direct Energy *(E_{dE})*. Two IEA categories are included within direct energy included for primary-stage EROI ($EROI_{PRIM}$). Fourteen IEA categories are included within direct energy included for final-stage EROI ($EROI_{FIN}$). Sub-allocations are shown to direct energy for electricity ($EROI_{dE\_FIN\_ELECT}$) and other finished fuels ($EROI_{dE\_FIN\_FUEL}$).

Energy Industry Own Use - IEA categories		**Fossil fuel production**	**Fossil fuel production, refining + transformation into final energy**		
		Included in E_{dE_PRIM}?	**Included in E_{dE_FIN}?**	**Allocation to**	
				$E_{dE\_FIN\_ELECT}$	$E_{dE\_FIN\_FUEL}$
1	Coal mines	Yes	Yes	by coal share for ELECT/FUEL use	
2	Oil and gas extraction	Yes	Yes	by oil & gas share for ELECT/FUEL use	
3	Blast furnaces (EBLASTFUR)	No	Yes	0%	100%
4	Gas works (EGASWKS)	No	Yes	by gas share for ELECT/FUEL use	
5	Gasification plants for biogases	No	No	0%	0%
6	Coke ovens (ECOKEOVS)	No	Yes	0%	100%
7	Patent fuel plants (EPATFUEL)	No	Yes	0%	100%
8	BKB/peat briquette plants (EBKB)	No	Yes	0%	100%
9	Oil refineries (EREFINER)	No	Yes	0%	100%
10	Coal liquefaction plants (ECOALLIQ)	No	Yes	0%	100%
11	Liquefaction (LNG) / regasification plants	No	Yes	by gas share for ELECT/FUEL end use	
12	Gas-to-liquids (GTL) plants (EGTL)	No	Yes	0%	100%
13	Own use in electricity, CHP and heat plants	No	Yes	100%	0%
14	Pumped storage plants	No	No	0%	0%
15	Nuclear industry	No	No	0%	0%
16	Charcoal production plants (ECHARCOAL)	No	No	0%	0%
17	Non-specified (energy)	No	Yes	by ELECT / FUEL split of cat. 1-16 sum	
18	Losses	No	Yes	• Coal/oil/gas products: by ELECT / FUEL end use split. • Electricity: by FF share to ELECT. • Heat: by FF share to FUEL	

Our method for calculating E_{iE} uses Input-Output analysis to obtain the 'indirect' or 'supply chain' energy used by the EIOU sub-categories involved in fossil fuel extraction and production at primary and final energy stages. We build on the work of Brand-Correa et al.[16], who developed the IO-based methodology we use to estimate indirect energy for EROI calculations. Their work was applied to a single country (UK) study. For our global study, we make significant modifications and improvements, including the use of EXIOBASE[33], and calculate E_{iE} at both primary and final energy stages. To estimate indirect energy, either life cycle analysis (LCA) or IO-based analysis can be used. More commonly, LCA analysis is used for site-level (mainly fossil fuels) or device-level (mainly renewables) EROI estimates, due to better availability of granular data – see Murphy et al.[36]. At an economy-wide and global level, IO analysis is more often used as LCA data becomes very complex at scale, and has been used for EROI estimates by Brand-Correa et al.[16] and Palmer[37]. However, we also note studies suggest that IO-derived EROI is typically lower than a process-based LCA study for exactly the same data[38].

The MRIO-based method for calculating E_{iE} follows the conventional approach used in consumption-based emissions[39] and energy accounting[40]. The accounting matrices are used to determine the how global industrial outputs respond to a unit change in final demand. An environmental extension vector of either energy extracted or fuel used per unit of industrial output can be combined with the accounting matrices to measure the full supply chain energy required to meet final demand. We use the numerator in equation (2) ($E_{T\_PRIM} - E_{dE\_PRIM}$) and equation (3) (TFC) to construct different 'net energy' extension vectors for both primary and final energy stages, by allocating net energy at primary and final energy stages to EXIOBASE industries. An overview of the IO framework is given in Figure 2. EXIOBASE energy industries at primary and final energy stages are given in Table 3:

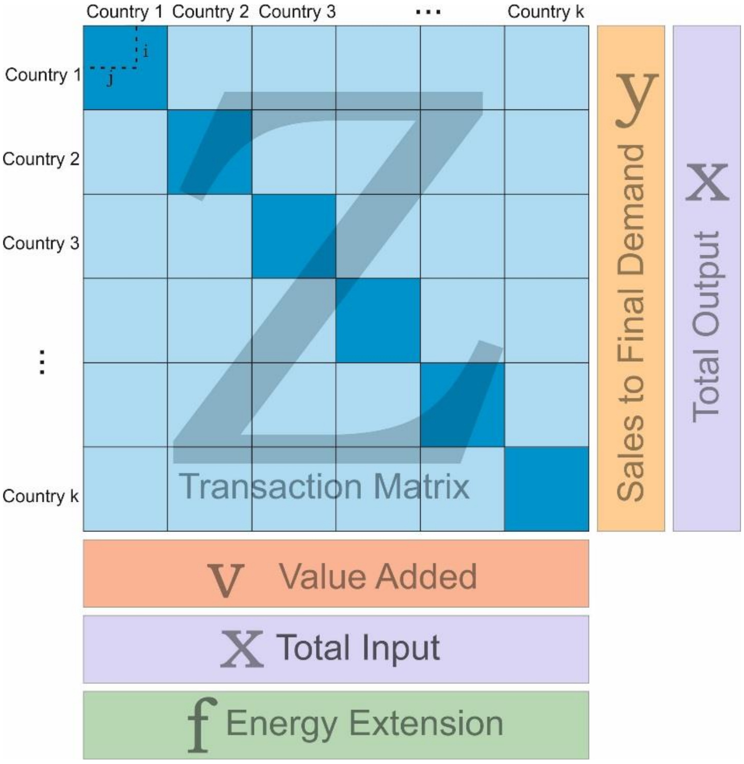

Figure 2: Basic multi-regional input-output structure with energy extensions vector (adapted from [16]). The $\boldsymbol{Z}$ matrix contains all inter-sector transactions. Vector $\boldsymbol{v}$ denotes value-added data, while vector $\boldsymbol{x}$ represents the total economic output, and vector $\boldsymbol{y}$ is sales to households (final demand). $\boldsymbol{Z}$, $\boldsymbol{v}$, $\boldsymbol{x}$ and $\boldsymbol{y}$ are in financial units. Vector $\boldsymbol{f}$ is the energy extension, which is in energy units.

Table 3. EXIOBASE fossil fuel energy sectors. Nine EXIOBASE sectors concern energy extraction and/or finished fuels production. These are mapped to primary and final energy stages, which then form the energy extension vectors for the input-output based calculation of indirect energy (E_{iE}) for primary and final stage EROI.

EXIOBASE energy sectors	**Used in EROI calculations?**	
	Primary energy stage	**Final energy stage**
Sector 20: Mining of coal and lignite; extraction of peat	Yes	Yes
Sector 21: Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	Yes	Yes
Sector 22: Extraction of natural gas and services related to natural gas extraction, excluding surveying	Yes	Yes
Sector 23: Extraction, liquefaction, and regasification of other petroleum and gaseous materials	Yes	Yes
Sector 56: Manufacture of coke oven products	No	Yes
Sector 57: Petroleum Refinery	No	Yes
Combined sector 96, 97 & 101: Production of electricity by coal, gas and petroleum	No	Yes

The calculated $EROI_{FIN}$ ratio is an aggregate metric which combines all fossil fuel based refined fuels and electricity outputs. To provide more detail, we split $EROI_{FIN}$ into refined fuels ($EROI_{FIN\_FUEL}$) and electricity ($EROI_{FIN\_ELECT}$) as shown in equations (4) and (5). Refer to Methods for more detail.

$$EROI_{FIN\_ELECT} = \frac{Total\ Final\ Consumption\ (TFC\_ELECT)}{E_{dE\_FIN\_ELECT}+E_{iE\_FIN\_ELECT}} \tag{4}$$

$$EROI_{FIN\_FUEL} = \frac{Total\ Final\ Consumption\ (TFC\_FUEL)}{E_{dE\_FIN\_FUEL}+E_{iE\_FIN\_FUEL}} \tag{5}$$

Global fossil fuel energy-return-on-investment results

Figure 3 presents our results for global $EROI_{PRIM}$ and $EROI_{FIN}$. We estimate that the average $EROI_{PRIM}$ for all fossil fuels has declined by around 23% in the 16 year period considered (37:1 to 29:1). These are similar magnitudes (see Table 1) and rates of decline to other published estimates[8,15,19]. The aggregate results for all fossil fuels represent a combination of different trends for different kinds of fuel. All types of fossil fuels show a declining trend. The EROI for coal starts at the highest value (50:1) in 1995 but declines sharply, by 42% to reach ratios similar to the other fossil fuels in 2011 (about 29:1). This strong decline is largely driven by increasing use of indirect energy in Chinese coal production. EROI ratios for oil and gas are much lower but also decline less strongly. EROI for oil production declines by 19% from 35:1 to 28:1. EROI for gas production declines by 10% from 32:1 to 29:1.

Our calculated value for global $EROI_{FIN}$ is much smaller than $EROI_{PRIM}$, and declines by 11% from 6.8 (1995) to 6.1 (2011).

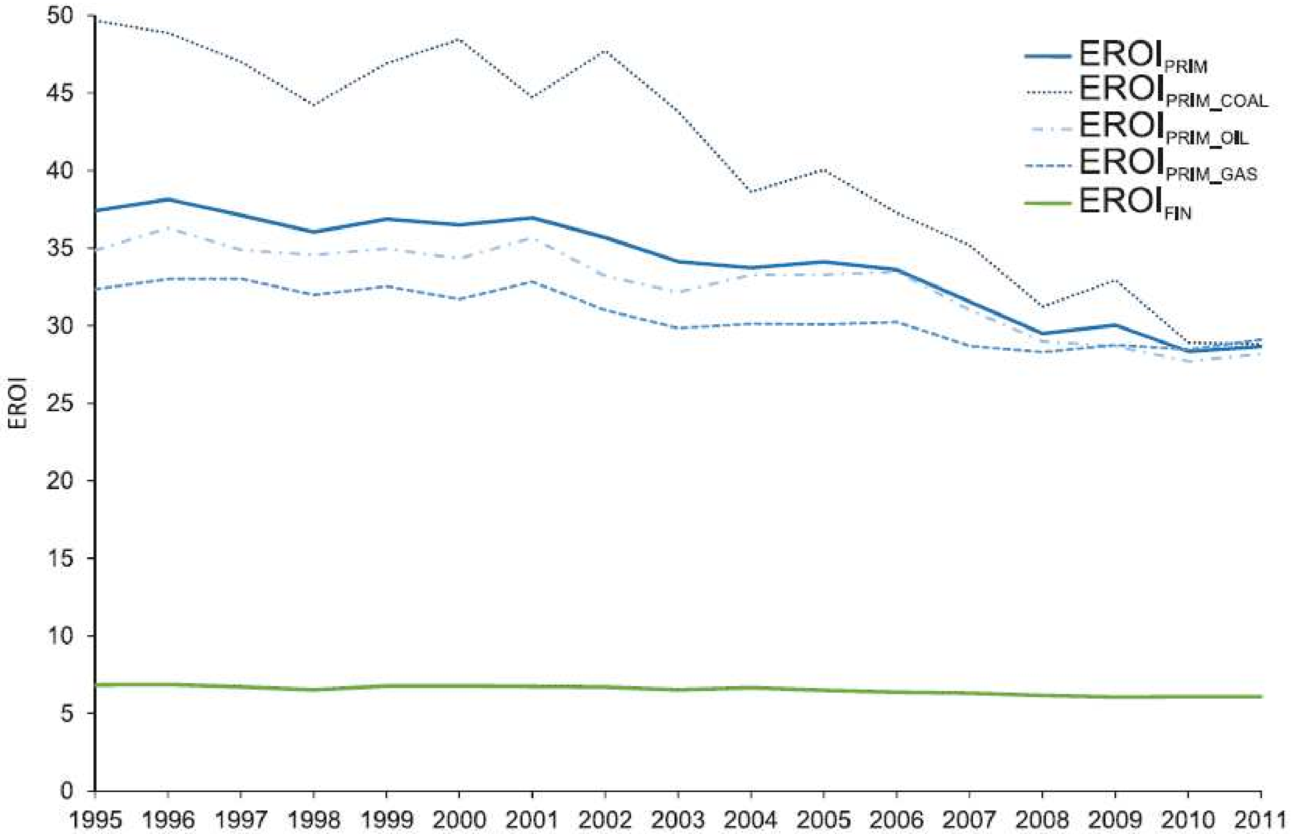

Figure 3: Global primary stage fossil fuel energy-return-on-investment ratios from 1995 to 2011. $EROI_{PRIM}$ is aggregate fossil fuel primary-stage EROI, with associated primary-stage EROI ratios for coal, oil and gas denoted by $EROI_{PRIM\_COAL}$, $EROI_{PRIM\_OIL}$ and $EROI_{PRIM\_GAS}$ respectively. $EROI_{FIN}$ denotes aggregate final-stage fossil fuel EROI.

Figure 4 splits $EROI_{FIN}$ into two important sub-components, with EROI of fossil fuel based electricity $(EROI_{FIN\_ELECT})$ around 3:1, versus other refined fuels $(EROI_{FIN_{FUEL}})$ ~ 8:1. The growth in world electricity consumption as a fraction of total final energy consumption (TFC) may therefore be one factor in the decrease of $EROI_{FIN}$. The value of $EROI_{FIN\_ELECT}$ (~ 3:1) is at the lower end of the range estimated via LCA analysis by Raugei and Leccisi[18] given in Table 1 (4:1 for coal-based electricity and 11:1 for gas-based electricity), but is comparable given the majority of fossil fuel based electricity uses coal, and the inclusion of electricity distribution losses in our $EROI_{FIN\_ELECT}$ ratio.

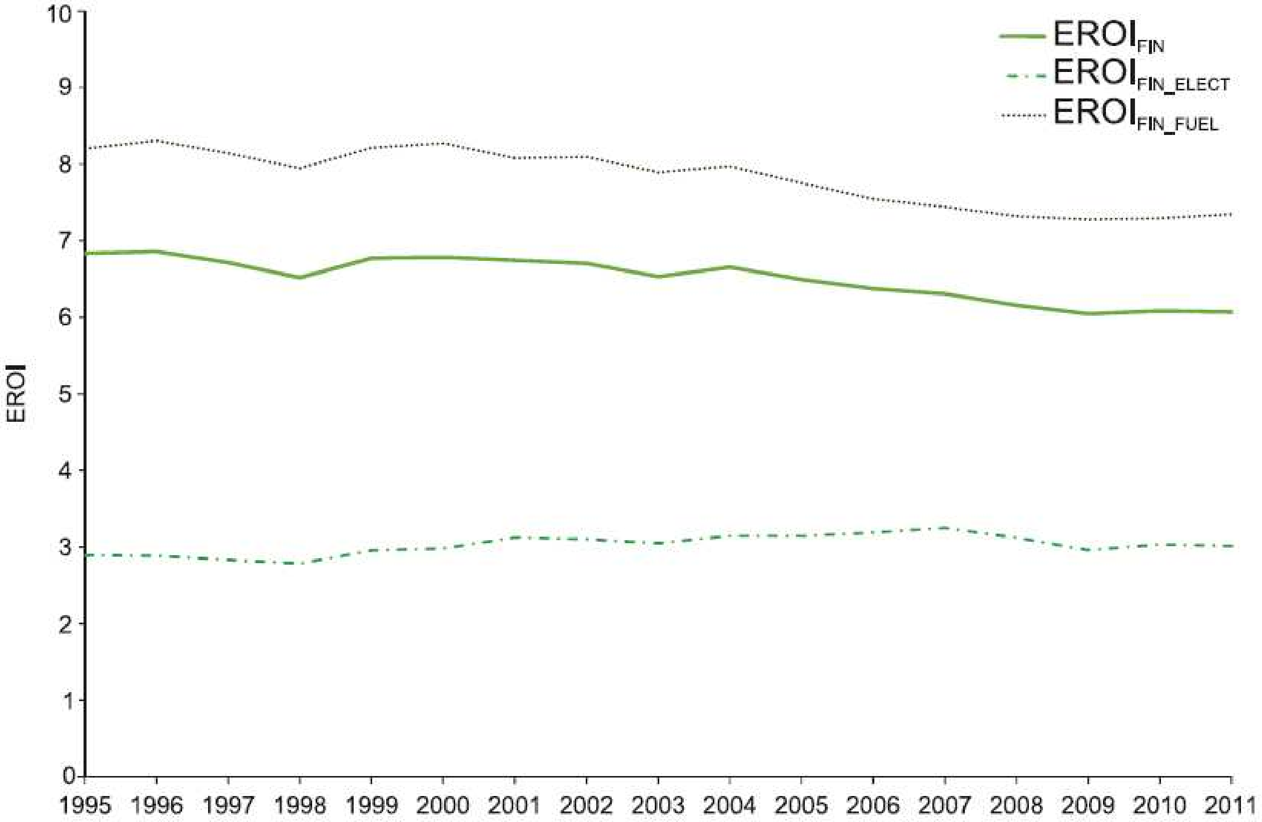

Figure 4: Global final stage fossil fuel energy-return-on-investment ratios from 1995 to 2011. $\mathrm{EROI_{FIN}}$ denotes aggregate final-stage fossil fuel EROI. $\mathrm{EROI_{FIN\_ELECT}}$ and $\mathrm{EROI_{FIN\_FUEL}}$ denote final-stage EROI for fossil fuel based electricity and other refined fossil fuels respectively

Further insights can be gained by studying the EROI component terms in equations (2) and (3) given in Figure 5. First, regarding their magnitudes, we find that $EROI_{FIN}$ is significantly lower than $EROI_{PRIM}$ mainly because the EROI denominator (E_{dE}+E_{iE}) is 4-5 times larger at the final energy stage than primary energy stage. This is mainly caused by a larger contribution from direct energy (E_{dE}), as the number of EIOU energy production sectors has broadened from 2 to 14. In addition, the numerator (E_T-E_{dE}) is around a third smaller at the final energy stage, which further reduces $EROI_{FIN}$. Second, the declining time-series trends exhibited by both $EROI_{FIN}$ and $EROI_{PRIM}$ are because the denominator (E_{dE}+E_{iE}) increases at a faster rate than the numerator (E_T-E_{dE}).

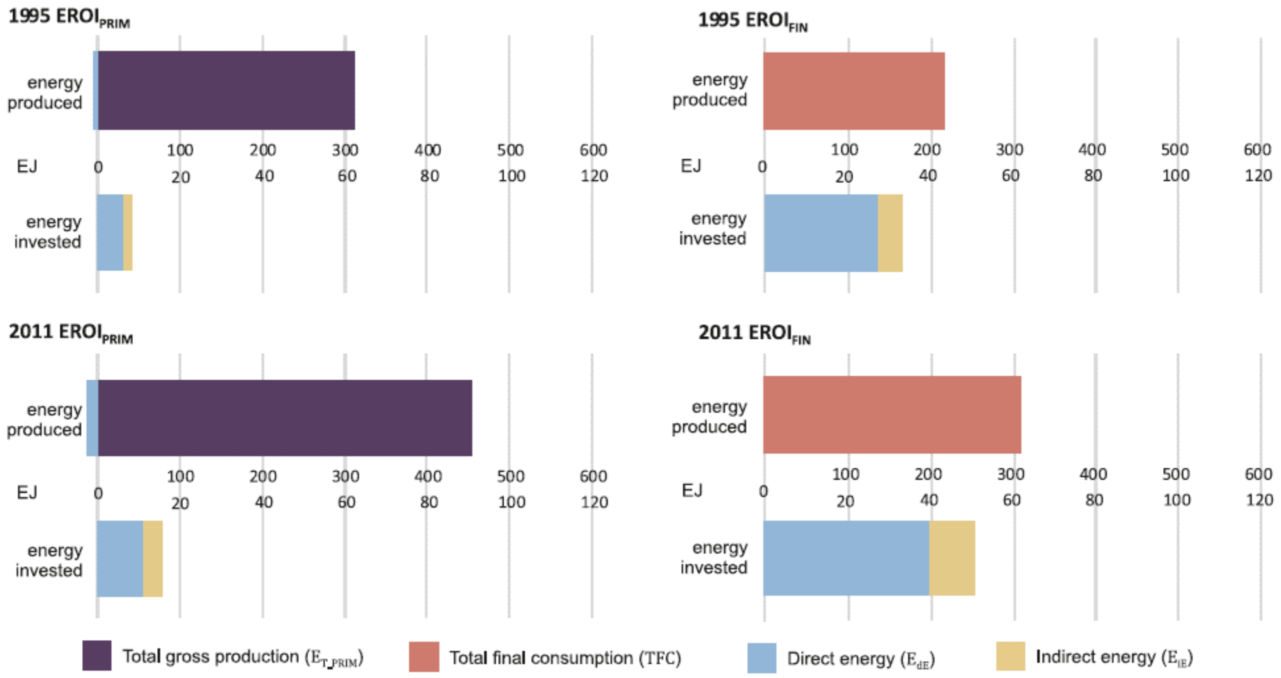

Figure 5: Components of the energy-return-on-investment calculations. EROI component terms in equations (2) and (3) shown for both primary and final energy stages for the start year of 1995 and end year of 2011. The elements contributing to the numerator and denominator are shown above and below the scale bar, respectively. Please note that the scale of the denominator differs to the numerator scale.

A more complete view of fossil fuel EROI

The results of our analysis provide key insights for the global transition to a climate-compatible energy system.

Firstly, renewable-based electricity might not be as disadvantaged compared to fossil fuels - in EROI terms - as is often suggested in the literature[12]. Our global fossil fuel EROI analysis suggests $EROI_{FIN\_ELECT}$ (~3:1) may be below the EROI ratios estimated for modern renewables (e.g. PV and wind) when measured at the same final energy stage (see Table 1). These ratios are much lower than conventional, primary energy stage $EROI_{PRIM}$ (~30:1), supporting the driving concern and the rationale behind the paper. In addition, our estimates for $EROI_{PRIM}$ may actually be conservatively high, as the MRIO-based method does not include all aspects of fossil fuel industry capital investment and decommissioning. Our findings suggest a large-scale transition to renewable energy sources does not necessarily imply a significant reduction in economy-wide EROI. On the contrary, such low and declining $EROI_{FIN}$ ratios would mean the renewables transition may actually halt – or reverse - the decline in global EROI at the final energy stage.

Secondly, the low ratios (~6:1) of fossil fuel EROI at the final energy stage, and their declining nature (10% decrease 1995-2011) gives reason for concern. Figure 6 shows fossil-fuel EROI at the final energy stage is nearer the ‘net energy cliff’ than has been supposed at a primary energy stage[6]. This matters, as the net energy cliff is highly non-linear: the reduction in net energy availability by moving from an EROI ratio of 10:1 to 5:1 (-10%) is much greater than 40:1 to 20:1 (-2.5%). Our results suggest we may already have entered this zone of highly non-linear change, where further modest declines in $EROI_{FIN}$ ratios lead to increasingly rapid reductions in the available net energy to society.

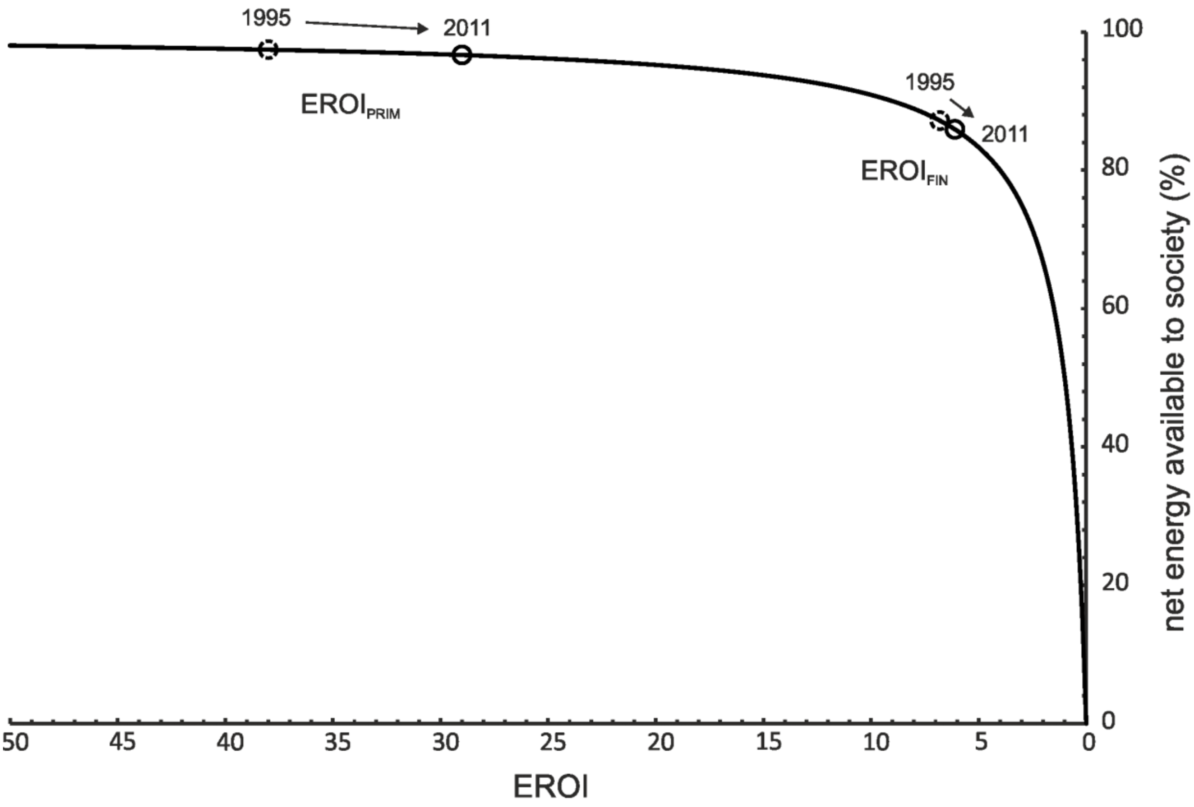

Figure 6: Analysis results superimposed on the 'net energy cliff'. X-axis denotes energy-return-on-investment (EROI) ratios between 0-50. Y-axis denotes the net energy available to society, calculated from the EROI ratios. For example, an EROI ratio of 10:1 means 90% of the energy obtained is available to society. Declining EROI ratios below 5:1 have rapidly reducing available net energy, hence the 'net energy cliff' term. The analysis results for 1995 and 2011 are then superimposed on the EROI – available net energy curve. $EROI_{PRIM}$ is aggregate fossil fuel EROI at the primary energy conversion stage. $EROI_{FIN}$ denotes aggregate fossil fuel EROI at the primary energy conversion stage **(adapted from Mearns[41])**.

Thirdly, given the low and declining final energy stage $EROI_{FIN}$ ratios and proximity to the net energy cliff, we should more seriously and urgently consider the potential societal impacts and response to reductions in the net energy available to society. These effects could be significant: reductions in energy supply and/or significant increases in energy prices in the past have often been associated with economic crises[42–44]. It is very unclear how these non-linear impacts of declining EROI on the availability of net energy will impact society and economy. However, it is likely that any impacts would unfold in a similarly non-linear fashion. The investigation of such net energy constraints on the socio-economy starts at a very low base. On the one hand, aspects of EROI (i.e. the relationship between gross energy, net energy and economic impacts) are generally not included in many of the energy-economy models[45,46] that are used to investigate possible pathways to a low-carbon future[47]. On the other hand, when EROI is included, such models do not include low (enough) EROI ratios for fossil fuels[10,12]. As a result, socio-economic impacts are limited in the model (since high EROI ratios are included) and reinforces the perception that a transition to renewables will lower overall EROI.

One logical response to declining net energy availability of fossil fuels at an economy-wide level would be to increase total production of fossil fuels (E_{T_FIN}), to compensate for significant rises in direct energy associated with their production (E_{dE_FIN}), to maintain absolute net energy levels (E_T-E_{dE}) to the remaining productive part of the economy. This is the trap set by the net energy cliff, would be disastrous from the perspective of climate change, as higher overall levels of fossil fuel combustion will increase associated greenhouse gas emissions. That said, such increases in fossil fuel production may not be readily feasible, given the decreasing availability of large and easy-to-extract fossil energy reserves[48].

Two other responses could alternatively be employed, preferably together as they acts as complements. Firstly, the scale and speed of the renewables transition could be increased. If renewables-based EROI is higher than fossil fuels, this provides added impetus for this option. However, fossil fuels still provide the large majority of the global energy consumed and are likely to do so for the foreseeable future. Therefore, a rapid transition to renewable energy sources will still require significant energy subsidies from fossil fuels, as renewables have a significant temporal lag before they achieve net energy payback[49,50]. Any transition period featuring a large build-rate of new renewable capacity would therefore be characterised by incumbent fossil fuels and their low EROI ratios. Secondly, following Cullen and others[51], increasing attention is placed on how we can become more efficient in utilising constrained (final) energy to deliver increased end energy services.

Conclusions

Conceptually, the estimation of fossil fuel EROI at the final energy stage is much more relevant to society and the economy than at the primary energy stage, because final energy is much closer to end energy services. It also enables a fairer comparison, between fossil fuels and renewables, and is at the same stage of energy conversion that is used by aggregate energy-economy models, which are increasingly including net energy and EROI. However, most current methods for calculating global fossil fuel EROI (except electricity) remain at a primary energy stage, and do not provide the required, equivalent basis for comparison. To address this, we include all fossil fuel based IEA energy production sectors, which increases direct energy, and estimate indirect supply-chain energy from energy production via MRIO analysis.

Empirically, the effect is to reduce EROI ratios for fossil fuels from ~30:1 (at primary energy stage) to 6:1 (at final energy stage). The low and declining EROI ratios we obtain by including a more complete spectrum of direct and indirect energy use demonstrates the importance moving the calculation of EROI from primary to final energy stage. These results confirm that we have been overlooking potential energetic constraints to our economies from fossil fuel use, whilst being too focussed on the impacts of renewables transition. We find it credible that declining EROI ratios of fossil fuels will lead to constraints on the energy available to society in the not-so-distant future, and that these constraints might unfold in rapid and unexpected ways.

Our results challenge established conventions: renewables-based EROI may be higher than fossil fuel EROI, when measured at the same final energy stage. This translates to an urgent need to include fossil fuel EROI at the final energy stage in energy-economy models, to study possible socio-economic impacts and responses. These insights are urgently required, as future policy and energy infrastructure investment decisions are being made now to meet climate change mitigation commitments.

Methods

Data. Our analysis draws on two key data sources. The first source is the extended world energy balances provided by the IEA for 142 countries and two rest-of-world regions[32]. All the energy data used in our study is based on IEA data. The second source is the EXIOBASE MRIO database V3.4[33]. EXIOBASE V3.4 provides global input-output transaction matrices describing trade flows between 163 industries in 44 countries and 5 rest-of-world regions as well as details on final demand expenditure on each industry in each country/region. All data is selected on an annual basis covering the years 1995 to 2011. The EXIOBASE data forms the basis of the input-output analysis that we perform to determine the indirect energy used in the fossil fuel producing industries. EXIOBASE V3.4 contains energy extension vectors but these vectors are not consistent with the data we used for the net energy and direct energy components of equations (2) and (3). Therefore, for consistency and to suit our purposes, we constructed energy extension vectors based on the IEA extended energy balances, one for each EROI stage (primary and final energy).

From IEA energy balances to EXIOBASE vectors. We use data from the IEA extended energy balances in all three steps of our analysis. The relevant categories from IEA's extended energy balances are allocated to the 49 countries/regions in EXIOBASE using a concordance matrix A in the data repository[52].

At the primary energy stage we obtain the gross production of energy, E_{T_PRIM}, using IEA's 'production' category (a sub-category of "total primary energy supply"). As the scope of our analysis is restricted to fossil fuels, only fossil fuel production is considered (14 IEA energy products, see primary energy stage concordance matrix B in the data repository[52]. We obtain the direct energy used by the fossil fuel extracting industries, E_{dE_PRIM}, from IEA's 'energy industry own use' categories. Only those categories directly relating to the extractive energy industries are considered (Table 2). We subtract the energy industry's own use of energy from the figures for gross production to avoid double-counting of the direct energy use of the energy industry in our EROI calculations. Finally, we construct the extension vector required for the input-output analysis by allocating the gross production of energy from the IEA data to the four relevant energy-producing industries in EXIOBASE for each country/region.

At the final energy stage we use IEA's 'Total Final Consumption' (TFC) to calculate the numerator of the EROI in equation (3). As the scope of our analysis is restricted to fossil fuels, we include only the consumption of energy carriers derived from fossil fuels (29 IEA energy products, see final energy concordance matrix C in the data repository[52]. We then obtain the direct energy used by the fossil fuel extraction and energy production industries, E_{dE_FIN}, from IEA's 'energy industry own use' categories, as shown in Table 2. Finally, we create the extension vector for the MRIO analysis by allocating IEA's total final consumption by products (29 fossil fuel derived final consumption products) to (seven) EXIOBASE industries. Note that we do not allocate IEA's total final consumption by the categories in which energy is used, but rather by the products (or energy sources) that are used at that stage.

For splitting $EROI_{FIN}$ into $EROI_{FIN\_ELECT}$ and $EROI_{FIN\_FUEL}$ as given in equations (4) and (5), we require estimates of the three components. First, TFC is split into electricity (TFC_{ELECT}) refined fuels (TFC_{FUEL}) directly from the IEA data. Second, E_{dE_FIN} is split into $E_{dE\_FIN\_ELECT}$ and $E_{dE\_FIN\_FUEL}$ parts via the allocation shown in Table 2. Third, as calculating components of indirect energy ($E_{iE\_FIN\_ELECT}$ and $E_{iE\_FIN\_FUEL}$) is not possible directly due to the lack of required EXIOBASE sector granularity (e.g. oil refineries would need to be split between ELECT and FUEL use). Therefore, we estimate $E_{iE\_FIN_{ELECT}}$ and $E_{iE\_FIN\_FUEL}$ by assuming the same indirect-to-direct energy ratio (E_{iE_FIN} / E_{dE_FIN}) applies to the sub-components. As $E_{iE_FIN}$is around 20-25% of E_{dE_FIN}this assumption will not affect the end EROI ratios greatly.

Input-output analysis. The indirect energy used by fossil fuel industries is calculated using input-output analysis – a macroeconomic technique most commonly used for consumption-based accounting[53]. The method builds on previous work by Brand-Correa et al.[16]. Referring to the IO framework in Figure 2, taking the EXIOBASE 4.3 MRIO database, we first express total economic output $\mathbf{x}$ as a function of final demand $\mathbf{y}$. This process will demonstrate how every global industry contributes to the supply chain of a single final demand product and can consequently be used to understand the supply chain energy used by the fossil fuel sector.

Alongside $\mathbf{y}$ and $\mathbf{x}$, EXIOBASE also contains the transaction matrix $\mathbf{Z}$ and value-added data $\mathbf{v}$ (refer to Figure 2). Sales by each industry, to both other industries and final demand, are recorded along the rows. The columns show expenditure by each industry on both intermediate goods, and taxes and wages (found in value added). For the purpose of this initial explanation, $\mathbf{y}$ takes the form of a single column of total global final demand.

Reading across the full database, the total output (x_i) of sector i can be expressed as equation (6):

$$x_i = z_{i1} + z_{i2} + \cdots + z_{in} + y_i \tag{6}$$

where z_{ij} is the contribution from the ith supplying sector to the jth producing sector in an economy and y_i is the final demand for the product produced by the particular sector. If each element z_{ij} is divided by the output x_j associated with the corresponding column j, then each element z_{ij} in $\mathbf{Z}$ can be replaced with:

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{7}$$

forming a new matrix $\mathbf{A}$, known as the direct requirements matrix. Element $a_{ij}$is the proportion of all the inputs in the production recipe of that product. Equation (6) can therefore be re-written as:

$$x_i = a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n + y_i \tag{8}$$

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

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{9}$$

Equation (9) is known as the Leontief equation and describes output $\mathbf{x}$ as a function of final demand. $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse (denoted hereafter as $\mathbf{L}$). Now consider a row vector $\mathbf{f}$ of energy assigned to industrial sectors. In this analysis, $\mathbf{f}$ is the fossil fuel net energy either at the primary energy stage (the numerator in (2)) or at the final energy stage (numerator in (3)). Energy intensity $\mathbf{e}$ is calculated by dividing $\mathbf{f}$ by the total sector economic output $\mathbf{x}$, as given in equation (10):

$$\mathbf{e} = \mathbf{f}\hat{\mathbf{x}}^{-1} \tag{10}$$

A vector with a "hat" ($\widehat{\ }$) represents a diagonal matrix, whose diagonal elements are the elements of the vector. Multiplying both sides of the Leontief equation (9) by $\mathbf{e}$ gives equation (11):

$$\mathbf{ex} = \mathbf{eLy} \tag{11}$$

which simplifies to the energy extension vector (seen in Figure 2) given by equation (12):

$$\mathbf{f} = \mathbf{eLy} \tag{12}$$

Diagonalising both $\mathbf{e}$ and $\mathbf{y}$ means that the result $\mathbf{F} = \hat{\mathbf{e}}\mathbf{L}\hat{\mathbf{y}}$ is an energy flow matrix of the same dimensions as $\mathbf{Z}$ showing the energy inputs by sector and region into any product. If rather than representing global final demand, $\mathbf{y}$ is the final demand of a particular country, k, $\mathbf{F}$ is now the total energy required to meet consumption in country k. Hereafter we use individual country vectors for $\mathbf{y}$ and results are calculated separately for each country in the database, before being summed to calculate a total global figure.

An individual element in the $\mathbf{Z}$ matrix z_{ij}^{rs} describes the flow from sector i in country r to sector j in country s. Input-output tables usually contain some monetary flow in the cell $z_{i=j}^{r=s}$. This could represent, for example, Chinese Coal inputs to the Chinese Coal producing sector. Since this should be captured by E_{dE} (either at the primary energy or the final energy stage), we need to adjust the original EXIOBASE $\mathbf{Z}$ matrix to remove these particular flows. We remove these flows (found on the diagonal) by setting the cell value to zero and recalculating the associated total output vector $\mathbf{x}$. This means that when energy consumption-based accounts are calculated, the direct energy is redistributed such that the result matrix $\mathbf{F}$ is the true result of indirect energy flows. Continuing with the example above, any energy found in cell $f_{i=j}^{r=s}$ will be an indirect flow of Chinese Coal which involves a supply chain which passes the coal via some other sector before it is used again in the production of Chinese Coal products.

Next, let the fossil fuel energy sectors in Table 3 be the set e to g. In the adapted matrix $\mathbf{Z}$ for any country r in the set of all countries, if a sector i belongs to the set of fossil fuel energy sectors, $z_{i=j}^{r=s} = 0$, we obtain in equation (13):

$$\mathbf{Z} = z_{i=j}^{r=s} = \begin{Bmatrix} 0 \text{ if } i \in \{e, \dots, g\} \\ z_{i=j}^{r=s} \text{ otherwise} \end{Bmatrix} \tag{13}$$

Hereafter, in this section, $\mathbf{Z}$ represents this adapted matrix with the modifications on the diagonal to avoid double counting direct energy (E_{dE}). The same adapted matrix is used in the calculations for each country described below.

To calculate the *indirect fossil fuel energy* (E_{iE}) used at primary and final energy conversion stages, we calculate a new flow matrix $\mathbf{F^0}$ which shows the energy used from the full supply chain *if there were no fossil fuel energy flows to that particular fossil fuel energy sector.* The indirect energy used by fossil fuel industries is therefore the difference between $\mathbf{F}$ and $\mathbf{F^0}$.

To calculate $\mathbf{F^0}$, we need to generate a new version of the transactions matrix $\mathbf{Z}$ for each country in the database. This matrix is exactly the same as the adapted $\mathbf{Z}$ but replaces monetary flows with zeros for any columns associated with that country's fossil fuel energy products. We will call $\mathbf{Z^0}$ this further modified country-specific transaction matrix. This means that energy flows that interact with any part of the supply chain of a fossil fuel energy product are removed from $\mathbf{F^0}$. $\mathbf{F^0}$ will not only register zero energy in the production recipe (column) of a fossil fuel product, but the energy flows throughout the rest of the matrix will not contain energy that interacted with the fossil fuel product supply chain. Consequently, when finding $E_{iE} = \sum \mathbf{F} - \mathbf{F^0}$, we are identifying any energy that interacted with any part of the fossil fuel product supply chain regardless of the final product made.

For example, for Chinese fossil fuel products (either at the primary or the final energy stage), $\mathbf{F^0}$ will not register any fossil fuel energy flows used in any part of the supply chain involved in the making of such products. More specifically, for instance $\mathbf{F^0}$ will not register Chinese Coal used in the US steel industry, then used in the Chinese oil industry. Therefore, the difference between $\mathbf{F}$ and $\mathbf{F^0}$ will provide all these types of flows, which constitute indirect energy (E_{iE}).

To make country k's $\mathbf{Z^0}$ matrix we make a mask matrix $\mathbf{M^k}$ which contains ones for all columns except the columns corresponding to that country's set of fossil fuel energy sectors e to g (from Table 3). For any sector j in the specific country k, these destination columns are zero if j is in the set of e to g, as given in equation (14):

$$\mathbf{M^k} = m_{ij}^{rk} = \begin{Bmatrix} 0 \text{ if } j \in \{e, \dots, g\} \\ 1 \text{ otherwise} \end{Bmatrix} \tag{14}$$

$\mathbf{F^0}$ for country k is calculated by equation (15):

$$\mathbf{F^0} = \hat{\mathbf{e}}(\mathbf{I} - \mathbf{M^k} \otimes \mathbf{Z^0}\widehat{\mathbf{x^{-1}}})^{-1}\,\hat{\mathbf{y}} \tag{15}$$

Where ⊗ denotes element-by-element multiplication. If $\mathbf{F}$ and $\mathbf{F^0}$ contain m sectors and n regions, the E_{iE} for country k is calculated by summing every element in the row i corresponding to every source nation if i belongs to the set of e to g as shown in equation (16):

$$EiE = \sum_{r,s}^{n} \sum_{i \in \{e,\ldots,g\},j}^{m} f_{ij}^{rs} - f_{ij}^{rs0} \tag{16}$$

Finally, we calculate E_{iE} for each of the 49 regions and for each of the 17 years (1995–2011) we have data for and sum the data annually to generate a global E_{iE} value.

$EROI_{gross}$ vs $EROI_{net}$. We note that EROI ratios can (correctly) be measured on either a net ($EROI_{net}$) or gross ($EROI_{gross}$) basis[54], and by dividing the terms in equation (1) by the energy input we find in equation (17) that $EROI_{net}$ = $EROI_{gross}$ – 1. Hence, whilst all our results are described in net terms, an EROI value of 10:1 on a net basis becomes 11:1 on a gross basis, and so on. Therefore, the gist of the arguments made in our paper are however not affected by the adoption of 'net' (versus 'gross') definition of EROI.

$$EROI_{net} = \frac{\frac{Gross\ energy\ output}{energy\ input} - 1}{1} = EROI_{gross} - 1 \tag{17}$$

EROI Boundaries. The calculation of EROI ratios always requires the setting of boundaries around the scope of energy that is considered to be 'energy invested'. The choices made with regard to this boundary have an important influence on the EROI results calculated. Where to best set these boundaries is debated in the literature[55]. There is no agreed set of rules and the potential choices depend on the method used[36]. In our analysis the boundaries of 'energy invested' are largely defined by the characteristics of the data and methods that we employ.

The first component of energy invested in our analysis is drawn from the 'Energy Industry Own Use' flows from the IEA energy balances. The IEA's Database documentation[35] notes these flows cover "the amount of fuels used by the energy producing industries (e.g. for heating, lighting and operation of all equipment used in the extraction process, for traction and for distribution)" in each year . The IEA energy balances break down these flows into different categories. We included different categories of these flows for the primary and final EROI calculations (see Table 2).

In addition to the direct energy used in the energy industries, we also consider it important to include energy that is invested indirectly, via the embodied energy in goods and services that are used by the energy industries to produce energy. We estimate this indirect energy using an input-output approach that is commonly used for energy footprinting. Such an approach implies some clear boundaries on the embodied energy included. Most importantly, the input-output approach we employ only includes embodied energy associated with intermediate inputs in the supply chain. These intermediate inputs represent inputs into the production process that are "turned over at least annually"[56]. Any energy that is embodied in the fixed capital goods, goods that are used in production over several years, is not included. This is a common limitation of global input-output models as there is a lack of detailed data on the amount and composition of capital expenditure at the industry level[57].

Therefore our EROI estimates do not include any energy invested in the production of energy which is associated with the fixed capital equipment employed in the energy producing industries. As capital expenditure is not considered, the estimates for indirect energy use presented in this study are very likely to be underestimated and should be considered as lower-bound values. Especially for renewable energy sources the proportion of indirect energy embodied in capital is likely to be high, which presents another reason why our method is not yet suitable for analysing renewable energy. Södersten et al.[57] present recent progress on endogenising capital expenditure in global MRIO models. Such methods could be used to expand the boundaries of input-output analysis used for the calculation of EROI ratios in future work.

Validation. Important checks were performed on the components of the EROI calculations. First, for total energy (E_T) and TFC, we checked that the sum of country-level data (extracted from the IEA extended energy database and then mapped to EXIOBASE country structures) matched the World totals. Second, for direct energy use (E_{iE}) for EROI_PRIM and EROI_FIN, we performed a similar check that World total matched the EXIOBASE country summation. Third, for indirect energy (E_{iE}), the Matlab code included checks that the code was working correctly, whilst the fraction of indirect (i.e. supply-chain) energy versus direct energy (around 25-30%) accords with Chen and Wu's study of energy embodied in world trade[58]. Last, our calculated primary-stage fossil fuel EROI values (~30:1) were found to be in broad agreement with other published estimates (refer also to Table 1).

Limitations. In addition to the limits that our data and methods pose regarding EROI boundaries discussed earlier, two other limitations need to be taken into account when interpreting our results. Firstly, our analysis is based on annual energy (IEA) and economic (EXIOBASE - MRIO) data. Additional temporal components of indirect energy for our fossil fuel analysis would include both capital investment and decommissioning phases. This is more commonly included in renewables-based EROI and energy payback time (EPBT) studies[38,50]. Secondly, we are confident in the accuracy of our results at a global level, where long term trends prevail over yearly outliers. However, at a country level, we are less confident of our results, since uncertainties associated with individual cells in EXIOBASE's transaction matrix can produce significant distortions. Last, we have been able to provide EROI for coal, oil and gas at the primary energy stage, but not at the final energy stage. This would require more detailed energy data at the final energy level.

Data Statement. The extended energy input datasets were obtained under licence from the International Energy Agency (IEA). The IEA World Energy Statistics and Balances can be downloaded with institutional or other user licence from https://doi.org/10.1787/enestats-data-en. The EXIOBASE 3.4 database is available at (http://exiobase.eu/index.php/data-download/exiobase3mon). The concordance matrices used in the EXIOBASE-based calculations are available in a University of Leeds data repository[52]. The aggregate EROI results datasets generated are available from the corresponding author, upon reasonable request.

Code Availability. The Matlab code written for generating the indirect energy (E_{iE}) in the EROI calculations is available at GitHub at the following link: https://github.com/earao/EROI

Competing Interests

The authors declare no financial and non-financial competing interests.

Acknowledgements

This research was primarily funded by the UK Energy Research Centre, supported by the UK Research Councils under EPSRC award EP/L024756/1. We also acknowledge the support for P.E.B. under EPSRC Fellowship award EP/R024251/1. A.O.'s contributions were also supported by the Centre for Industrial Energy, Materials and Products [EPSRC award EP/N022645/1], and under EPSRC Fellowship award EP/R005052/1. L.I.B-C. was supported by the Living Well Within Limits (LiLi) project funded by the Leverhulme Trust.

Author Contributions

P.E.B., L.I.B-C., A.O. and L.H. jointly designed the study and wrote the paper. P.E.B. and L.H. sourced International Energy Agency data and undertook calculations to calculate total energy produced and direct energy consumed. L.I.B-C. and A.O. performed the multi-regional input-output calculations to obtain indirect energy estimates.

References

1. Gilliland, M. W. Energy Analysis and Public Policy. *Science (80-.).* **189**, 1051–1056 (1975).
2. Odum, H. T. Energy, Ecology, and Economics. *Ambio* **2**, 220–227 (1973).
3. United States Congress. Federal Nonnuclear Energy Research and Development Act of 1974. 1–18 (1974).
4. Bullard, C. W., Penner, P. S. & Pilati, D. A. Net Energy Analysis: Handbook for Combining Process and Input-Output Analysis. *Resour. Energy* **1**, 267–313 (1978).
5. Mulder, K. & Hagens, N. J. Energy Return on Investment: Toward a Consistent Framework. *AMBIO A J. Hum. Environ.* **37**, 74–79 (2008).
6. Kunz, H., Hagens, N. J. & Balogh, S. B. The Influence of Output Variability from Renewable Electricity Generation on Net Energy Calculations. *Energies* **7**, 150–172 (2014).
7. The Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (2014). doi:10.1017/CBO9781107415416
8. Gagnon, N., Hall, C. A. S. & Brinker, L. A Preliminary Investigation of Energy Return on Energy Investment for Global Oil and Gas Production. *Energies* **2**, 490–503 (2009).
9. Lambert, J. G. *et al. EROI of Global Energy Resources. Status, Trends and Social Implications. Report prepared for the United Kingdom Department for International Development*. (2013).
10. King, L. C. & Van Den Bergh, J. C. J. M. Implications of net energy-return-on-investment for a low-carbon energy transition. *Nat. Energy* **3**, 334–340 (2018).
11. International Energy Agency (IEA). *World Energy Outlook 2017*. (2017). doi:10.1016/0301-4215(73)90024-4
12. Sers, M. R. & Victor, P. A. The Energy-missions Trap. *Ecol. Econ.* **151**, 10–21 (2018).
13. Hall, C. A. S., Balogh, S. & Murphy, D. J. R. What is the Minimum EROI that a Sustainable Society Must Have? *Energies* **2**, 25–47 (2009).
14. Fizaine, F. & Court, V. Energy expenditure , economic growth, and the minimum EROI of society. *Energy Policy* **95**, 172–186 (2016).
15. Hall, C. A. S., Lambert, J. G. & Balogh, S. B. EROI of different fuels and the implications for society. *Energy Policy* **64**, 141–152 (2014).
16. Brand-Correa, L. I. *et al.* Developing an Input-Output Based Method to Estimate a National-Level Energy Return on Investment (EROI). *Energies* **10**, **534**, 21 (2017).
17. Cleveland, C. J., Costanza, R., Hall, C. A. S. & Kaufmann, R. Energy use and the US Economy: a Biophysical Perspective. *Science (80-.).* **225**, 890–897 (1983).
18. Raugei, M. & Leccisi, E. A comprehensive assessment of the energy performance of the full range of electricity generation technologies deployed in the United Kingdom. *Energy Policy* **90**, 46–59 (2016).
19. Court, V. & Fizaine, F. Long-Term Estimates of the Energy-Return-on-Investment (EROI) of Coal, Oil, and Gas Global Productions. *Ecol. Econ.* **138**, 145–159 (2017).
20. Brandt, A. R. Oil depletion and the energy efficiency of oil production: The case of California. *Sustainability* **3**, 1833–1854 (2011).
21. Raugei, M., Fullana-i-Palmer, P. & Fthenakis, V. The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles. *Energy Policy* **45**, 576–582 (2012).
22. Leccisi, E., Raugei, M. & Fthenakis, V. The Energy and Environmental Performance of Ground-Mounted Photovoltaic Systems—A Timely Update. *Energies* **9**, 622 (2016).
23. Kubiszewski, I., Cleveland, C. J. & Endres, P. K. Meta-analysis of net energy return for wind power

systems. *Renew. Energy* **35**, 218–225 (2010).

24. Raugei, M. Net energy analysis must not compare apples and oranges. *Nat. Energy* **4**, 86–88 (2019).

25. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014. Summary for Policy Makers. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (2014). doi:10.1017/CBO9781107415324

26. Capellán-Pérez, I. *et al.* Global Model: MEDEAS- World Model and IOA implementation at global geographical level (No. D4.1 (D13)). Barcelona, Spain. (2017). Available at: http://www.medeas.eu/deliverables.

27. Dale, M., Krumdieck, S. & Bodger, P. Global energy modelling — A biophysical approach (GEMBA) part 1: An overview of biophysical economics. *Ecol. Econ.* **73**, 152–157 (2012).

28. Fagnart, J. F. & Germain, M. Net energy ratio, EROEI and the macroeconomy. *Struct. Chang. Econ. Dyn.* **37**, 121–126 (2016).

29. King, C. W. & Hall, C. A. S. Relating financial and energy return on investment. *Sustainability* **3**, 1810–1832 (2011).

30. Guilford, M. C., Hall, C. A. S., Connor, P. O. & Cleveland, C. J. A New Long Term Assessment of Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production. *Sustainability* **3**, 1866–1887 (2011).

31. King, C. W., Maxwell, J. P. & Donovan, A. Comparing World Economic and Net Energy Metrics, Part 2: Total Economy Expenditure Perspective. *Energies* **8**, 12975–12996 (2015).

32. IEA. 'Extended world energy balances', IEA World Energy Statistics and Balances (database),. (2017). doi:10.1787/data-00513-en

33. Stadler, K. *et al.* EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *J. Ind. Ecol.* (2018). doi:10.1111/jiec.12715

34. Brandt, A. R., Dale, M. & Barnhart, C. J. Calculating systems-scale energy efficiency and net energy returns: A bottom-up matrix-based approach. *Energy* **62**, 235–247 (2013).

35. International Energy Agency (IEA). *World Energy Balances: Database Documentation (2018 edition).* (2018). doi:10.2785/020714

36. Murphy, D. J., Carbajales-Dale, M. & Moeller, D. Comparing apples to apples: Why the net energy analysis community needs to adopt the life-cycle analysis framework. *Energies* **9**, 1–15 (2016).

37. Palmer, G. An input-output based net-energy assessment of an electricity supply industry. *Energy* **141**, 1504–1516 (2017).

38. Palmer, G. & Floyd, J. An Exploration of Divergence in EPBT and EROI for Solar Photovoltaics. *Biophys. Econ. Resour. Qual.* **2**, 15 (2017).

39. Barrett, J. *et al.* Consumption-based GHG emission accounting: a UK case study. *Clim. Policy* **13**, 451–470 (2013).

40. Owen, A. *et al.* Energy consumption-based accounts: A comparison of results using different energy extension vectors. *Appl. Energy* **190**, 464–473 (2017).

41. Mearns, E. The global energy crisis and its role in the pending collapse of the global economy. Presentation to the Royal Society of Chemists, Aberdeen, Scotland, 29 October 2008. (2008).

42. Bashmakov, I. Three laws of energy transitions. *Energy Policy* **35**, 3583–3594 (2007).

43. Kilian, L. The Economic Effects of Energy Price Shocks. *J. Econ. Lit.* **46**, 871–909 (2008).

44. Aucott, M. & Hall, C. Does a Change in Price of Fuel Affect GDP Growth? An Examination of the U.S. Data from 1950–2013. *Energies* **7**, 6558–6570 (2014).

45. Bauer, N., Baumstark, L. & Leimbach, M. The REMIND-R model: The role of renewables in the low-

carbon transformation-first-best vs. second-best worlds. *Clim. Change* **114**, 145–168 (2012).

46. Bernard, A. & Vielle, M. GEMINI-E3, a general equilibrium model of international-national interactions between economy, energy and the environment. *Comput. Manag. Sci.* **5**, 173–206 (2008).

47. Clarke, L. *et al.* Assessing Transformation Pathways. in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Edenhofer, O. et al.) 413–510 (Cambridge University Press, 2014).

48. Capellán-Pérez, I., Mediavilla, M., de Castro, C., Carpintero, Ó. & Miguel, L. J. Fossil fuel depletion and socio-economic scenarios: An integrated approach. *Energy* **77**, 641–666 (2014).

49. Bhandari, K. P., Collier, J. M., Ellingson, R. J. & Apul, D. S. Energy payback time (EPBT) and energy return on energy invested (EROI) of perovskite tandem photovoltaic solar cells. *Renew. Sustain. Energy Rev.* **47**, 133–141 (2015).

50. Dale, M. & Benson, S. The energy balance of the photovoltaic (PV) industry — is the PV industry a net energy provider? *Global Climate and Energy Project (GCEP) Symposium 2012* (2012). Available at: http://gcep.stanford.edu/pdfs/symposium2012/MikDale_Symp2012_web.pdf.

51. Cullen, J. M. & Allwood, J. M. Theoretical efficiency limits for energy conversion devices. *Energy* **35**, 2059–2069 (2010).

52. Brockway, P. E., Owen, A., Brand-Correa, L. I. & Hardt, L. Datasets for Nature Energy article “Estimation of global final stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources” (University of Leeds Data Repository, 2019). (2019). Available at: doi:linkTBC.

53. Miller, R. E. & Blair, P. D. *Input-output analysis: foundations and extensions*. (Cambridge University Press, 2009).

54. Brandt, A. R. & Dale, M. A General Mathematical Framework for Calculating Systems-Scale Efficiency of Energy Extraction and Conversion: Energy Return on Investment (EROI) and Other Energy Return Ratios. *Energies* **4**, 1211–1245 (2011).

55. Moeller, D. & Murphy, D. Net Energy Analysis of Gas Production from the Marcellus Shale. *Biophys. Econ. Resour. Qual.* **1**, 5 (2016).

56. Lenzen, M. & Treloar, G. J. Endogenising Capital: A comparison of Two Methods. *J. Appl. Input-Output Anal.* **10**, 1–11 (2004).

57. Södersten, C. J. H., Wood, R. & Hertwich, E. G. Endogenizing Capital in MRIO Models: The Implications for Consumption-Based Accounting. *Environ. Sci. Technol.* **52**, 13250–13259 (2018).

58. Chen, G. Q. & Wu, X. F. Energy overview for globalized world economy: Source, supply chain and sink. *Renew. Sustain. Energy Rev.* **69**, 735–749 (2017).