



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:

<https://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 orcid.org/0000-0003-3142-8766 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.



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

1 Estimation of global final stage energy-return-on-investment for fossil fuels with 2 comparison to renewable energy sources

3 Paul E. Brockway^{a,*}, Anne Owen^a, Lina Brand-Correa^a, Lukas Hardt^a

4 ^aSustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

5 * Corresponding author: p.e.brockway@leeds.ac.uk. Tel.: +44-113-343-2846

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

16
17 The field of net energy analysis first came to prominence during the 1970s oil crises¹⁻⁴ as a means of assessing
18 how much energy is delivered to society. Various metrics have emerged⁵ including energy profit ratio, energy
19 gain, energy payback, and the most well-known ‘energy-return-on-investment’ (EROI). Kunz et al.⁶ define EROI
20 in its simplest form as a ratio which “divides the total energy output by the energy input”. Several factors have
21 contributed to increasing attention being paid to the EROI research field. First, there are concerns over
22 declining EROI ratios of fossil fuels – which under many scenarios remain the dominant energy source to at
23 least 2050⁷ – due to depletion of finite reserves^{8,9}. Second, the estimated EROI ratios for renewable energy
24 sources are often contentious, vary greatly depending on adopted methodology, and are commonly estimated
25 as lower than fossil fuels¹⁰. Concerns follow that the renewables-led energy transition required to meet climate
26 targets¹¹ may have adverse socio-economic impacts¹². Third, EROI as a topic has become more accessible
27 through the readily-visualised concepts of a ‘net energy cliff’⁹ – where available net energy declines
28 precipitously below EROI ratios of 5:1 - and a minimum threshold level of societal-level EROI^{13,14}.

29 However, much of the increased attention is confined to academic circles. One reason may be that fossil fuel
30 EROI is commonly estimated at the primary (energy source) stage, where EROI ratios (i.e. for oil, coal and gas)
31 are high, typically over 25:1^{3,15}. Such ratios suggest to modellers and policy makers that EROI ratios won’t fall
32 below a threshold of concern until well into the renewables transition¹². However, this is a misleading
33 perception, as instead, fossil fuel EROI should be estimated at the final (energy carrier) stage (e.g. electricity,
34 gas, and petrol), where energy enters the economy. This enables a fairer comparison to renewables-based
35 EROI estimates, and the platform for improved energy and climate policy.

36 We build on recent EROI research^{10,15,16} to provide an estimate of global fossil-fuel based EROI at a final energy
37 stage, which better matches that of renewables-based EROI. We combine national-level International Energy
38 Agency (IEA) energy data with a multi-regional input-output (MRIO) approach to include a wider boundary of
39 direct energy production sectors and associated indirect (supply-chain) energy impacts, including trade. To
40 enable comparison to existing methods and EROI ratios, we estimate global fossil fuel EROI for both primary
41 ($EROI_{PRIM}$) and final ($EROI_{FIN}$) energy stages, and also provide time-series estimates for the 1995-2011
42 period. Our results indicate that by 2011 global ratios for $EROI_{FIN}$ (~6:1) are much lower than $EROI_{PRIM}$
43 (~30:1), and both are declining. Two implications follow. First, EROI of fossil fuels may be much nearer to
44 renewables than commonly supposed, meaning a global renewables transition may not be as biophysically
45 troublesome as previously thought. Second, the low and declining $EROI_{FIN}$ ratios for fossil fuels provides an
46 immediate concern, and also implies we are much nearer a ‘net energy cliff’ than previously thought, where
47 the non-linearity of EROI means low ratios (below 5:1) quickly restrict available net energy to society.

48 **Global fossil fuel EROI based on a final energy stage**

49 Cleveland et al.'s¹⁷ landmark study in the 1980s estimated EROI in the United States for fossil fuels at the 'well
 50 head' (oil and gas) and 'mine mouth' (coal). Since then, many fossil fuel EROI studies have been published¹⁵,
 51 though largely these remain at the primary energy stage (as coal, oil, gas). The most common exceptions are
 52 fossil fuel based EROI estimates of electricity, which are at the final energy stage. However, their
 53 methodologies (and hence estimates) vary, with some (e.g. ref.^{10,15}) taking primary stage EROI estimates and
 54 applying direct (thermal) loss factors in conversion to electricity, while others (e.g. ref.¹⁸) use LCA-based
 55 methods to include both thermal losses and supply-chain energy investment.

56 At the same time, an increasing number of studies are estimating EROI ratios for modern renewables,
 57 particularly electricity generated from photovoltaics (PV) and wind turbines – which are seen as two energy
 58 technologies pivotal¹¹ for reductions in global greenhouse gas emissions.

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

61 **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) 80 (mine mouth)		Hall et al. ¹⁵ Court and Fizaine ¹⁹
Oil	15 (well head) 18 (well head) 20 (well head)	4-5 (refined oil fuels)	Court and Fizaine ¹⁹ Gagnon et al. ⁸ Hall et al. ¹⁵ Brandt ²⁰
Gas	18 (well head) 20 (well head) 75 (well head)		Gagnon et al. ⁸ Hall et al. ¹⁵ Court and Fizaine ¹⁹
Electricity (gas)		6 ^Δ 8 ^Δ 11 [◊] – 14 [◊]	Hall et al. ¹⁵ King and Van Den Bergh ¹⁰ Raugei and Leccisi ¹⁸
Electricity (coal)		4 [◊] 13 ^Δ – 18 ^Δ 17 ^Δ	Raugei and Leccisi ¹⁸ Hall et al. ¹⁵ King and Van Den Bergh ¹⁰
Electricity (PV)	19* – 38*	6 [◊] – 12 [◊] 10 ^Δ 4 [◊] - 20 [◊]	Raugei et al. ²¹ Hall et al. ¹⁵ Leccisi et al. ²²
Electricity (Wind)		14 [◊] – 26 [◊] 15 [◊] – 30 [◊]	Kubiszewski et al. ²³ Raugei and Leccisi ¹⁸

62 * 'Primary energy equivalent' value by Raugei et al.²¹, estimated by dividing EROI_{FIN} value for PV (6-12) by the EU-27
 63 electric grid efficiency $\eta_{grid} = 0.31$.

64 ^Δ includes power plant / transformational conversion efficiencies only

65 [◊] includes power plant / transformational conversion efficiencies AND supply chain energy investments

66
 67 Table 1 reveals the divergence between the modal EROI estimates: primary-stage fossil fuels are much higher
 68 (typically 20:1-80:1) than final-stage renewable electricity (typically 5:1-20:1). This creates a potentially
 69 misleading perception to modellers of high fossil fuel EROI and low renewables EROI. Raugei²⁴ warns such
 70 apples-to-oranges comparisons are flawed, as they “compare [energy] carriers that cannot be put to similar
 71 end-use”. As energy-economy models are now starting to include EROI within their analytical framework, this
 72 has the potential to lock-in bias towards fossil fuels. For example, Sers and Victor¹² suggest an 'energy-
 73 emissions trap' is approaching, as “Reducing emissions will necessitate the transition from relatively high EROI
 74 dispatchable fossil fuels to [...] relatively low EROI intermittent renewables”.

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

78 Whilst resolving such renewables-EROI issues are worthy and should continue, we suggest the heavy focus on
79 them has distracted from the equally pressing need to move fossil fuel EROI to the final energy calculation
80 stage. This is important for two key reasons. First, incumbent fossil fuels remain important: the
81 Intergovernmental Panel on Climate Change (IPCC) future scenarios assume they remain as the dominant
82 source of energy to at least 2050²⁵. Second, EROI increasingly is being included in energy-economy models as
83 noted earlier, to help study future energy transitions^{10,26} and their macroeconomic impacts^{12,27,28}. As energy
84 enters the productive economy at the final energy stage, EROI ratios at the same final energy stage are thus
85 also in the correct format for inclusion in energy-economy models.

86 Matching fossil-fuel EROI estimates to the same (final) energy stage and (economy-wide or global) scale as
87 energy-economy models is therefore important. Currently, economy-wide and global fossil-fuel EROI
88 estimates – excluding electricity as seen in Table 1 – remain at a primary energy stage, using either a site-level
89 or price based approach. Lambert et al.⁹ provide an example of the site-level approach, collating sample
90 studies from different countries at the ‘mine mouth’ and ‘well head’. The price-based approach typically
91 involves using energy prices and/or expenditure data to estimate direct and indirect (including capital) energy
92 investment²⁹: Gagnon et al.⁸, Court and Fizaine¹⁹ and Guilford et al.³⁰ provide examples. King et al.³¹ provide
93 another route, using total energy expenditure to estimate aggregate EROI.

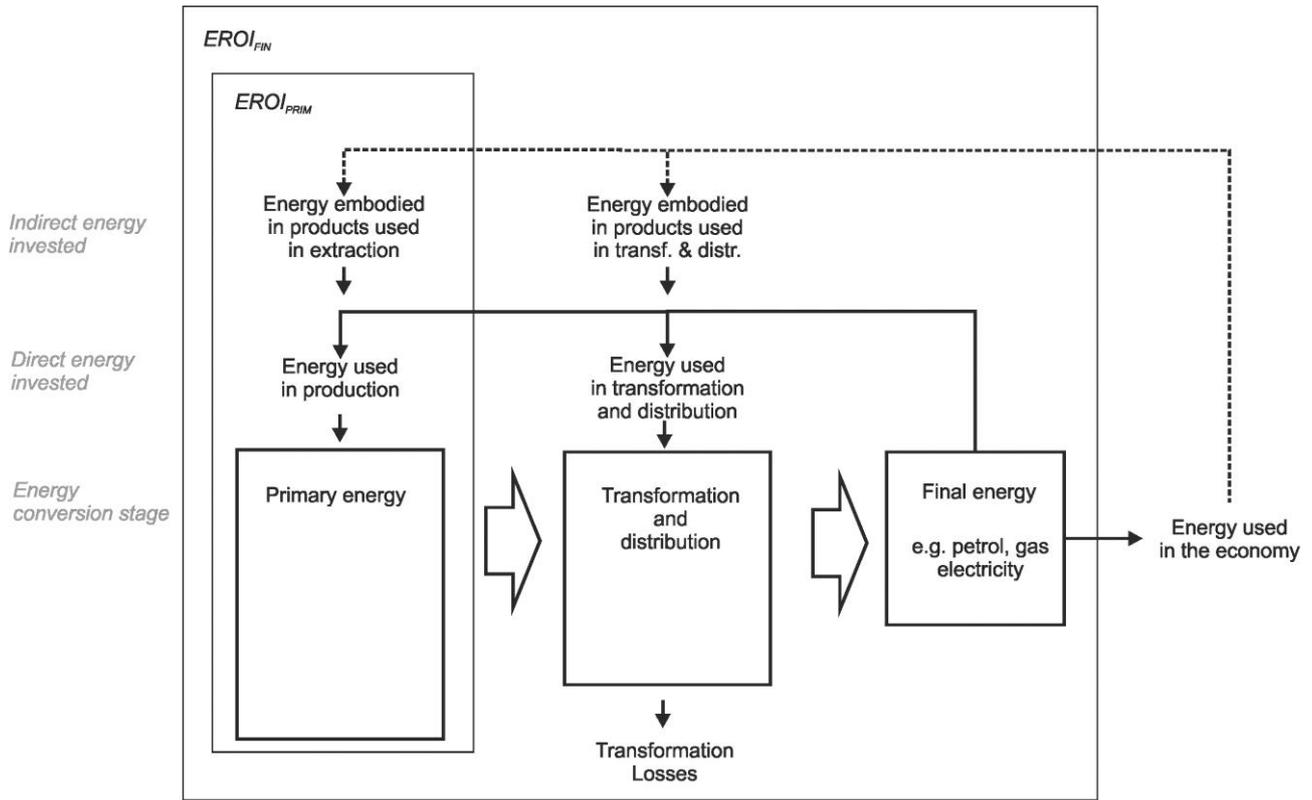
94 **Analytical approach**

95 We build on previous work by Brand-Correa et al.¹⁶, developing an input-output based approach to estimate
96 global fossil fuel EROI at final and primary energy stages for the period 1995-2011. Two key advances underpin
97 the method. First, we use International Energy Agency (IEA) extended energy balances time-series data³². This
98 provides us with country-level data for fossil fuel energy produced at both a primary and final energy stage. It
99 also allows access to the direct energy use for energy production sectors at both primary energy (e.g. coal
100 mines) and final energy (e.g. oil refineries, coke production, coal gasification) stages. Second, we use EXIOBASE
101 – a large global multi-regional input-output (MRIO) database³³ - to estimate the indirect ‘supply-chain’ energy
102 associated with production of fossil fuel energy at both primary and final energy stage, including trade.

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

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

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



109

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

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

$$EROI_{PRIM} = \frac{\text{Net energy produced}}{\text{Energy invested}} = \frac{E_{T_PRIM} - E_{dE_PRIM}}{E_{dE_PRIM} + E_{iE_PRIM}} \quad (2)$$

$$EROI_{FIN} = \frac{\text{Net energy produced}}{\text{Energy invested}} = \frac{E_{T_FIN} - E_{dE_FIN}}{E_{dE_FIN} + E_{iE_FIN}} = \frac{\text{Total Final Consumption (TFC)}}{E_{dE_FIN} + E_{iE_FIN}} \quad (3)$$

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

120 From equation (2), the net energy produced for $EROI_{PRIM}$ is equal to the total gross production of primary
 121 energy (E_{T_PRIM}), minus the direct energy used by the energy extraction industries (E_{dE_PRIM}). We obtain
 122 values for E_{T_PRIM} from the ‘production’ energy data from the IEA extended world energy balances³². In IEA
 123 terms, this is a sub-category of ‘total primary energy supply’, and represents the primary energy extracted in
 124 each country/region, including exports, but excluding imports. As we use the EXIOBASE MRIO database in our
 125 analysis, we do not need to account for imported energy, as these flows will be reflected in the MRIO
 126 transaction matrices.

127 Next, in equation (3), we directly obtain the net energy produced at the final energy stage via the ‘Total Final
 128 Consumption’ (TFC) provided in the IEA extended world energy balances³². This is equal to the gross final
 129 energy (for fossil fuels) used by each country/region (E_{T_FIN}), minus the direct energy (E_{dE_FIN}) associated
 130 with the production of the final energy.

131 The direct energy component (E_{dE}) in equations (2) and (3) represents the direct energy invested to extract
 132 fossil fuels or produce fossil-fuel based final energy. We obtain information for E_{dE} from the 18 ‘Energy
 133 Industry Own Use’ (EIOU) sub-categories in the IEA’s extended energy balances³², which follows their
 134 accounting conventions for ‘Energy industry own use and Losses’ – see also the IEA’s ‘World Energy Balances:
 135 Database Documentation’³⁵. As shown in Table 2, E_{dE_PRIM} includes only two EIOU sub-categories (Coal mines,
 136 Oil and gas extraction), whereas E_{dE_FIN} also includes the additional 12 EIOU categories involved in producing
 137 final energy (e.g. Own use in electricity, Coal gasification, Coke production).

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

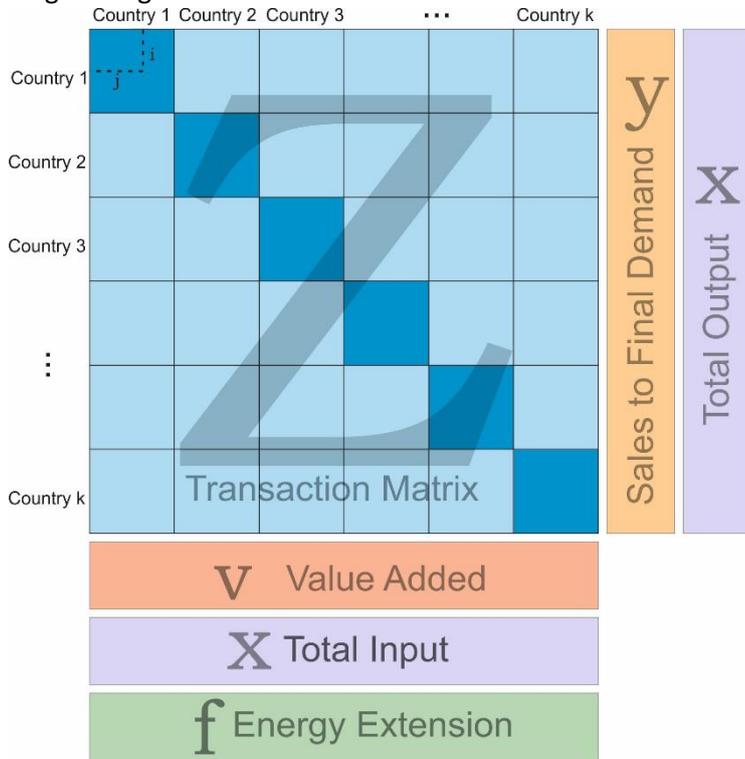
Energy Industry Own Use - IEA categories		Fossil fuel production	Fossil fuel production, refining + transformation into final energy			
			Included in E_{dE_PRIM} ?	Included in E_{dE_FIN} ?	Allocation to	
					$E_{dE_FIN_ELECT}$	$E_{dE_FIN_FUEL}$
1	Coal mines	Yes	Yes	by coal share for ELECT/FUEL use		
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	<ul style="list-style-type: none"> • Coal/oil/gas products: by ELECT / FUEL end use split. • Electricity: by FF share to ELECT. • Heat: by FF share to FUEL 		

142

143 Our method for calculating E_{iE} uses Input-Output analysis to obtain the ‘indirect’ or ‘supply chain’ energy used
 144 by the EIOU sub-categories involved in fossil fuel extraction and production at primary and final energy stages.
 145 We build on the work of Brand-Correa et al.¹⁶, who developed the IO-based methodology we use to estimate
 146 indirect energy for EROI calculations. Their work was applied to a single country (UK) study. For our global
 147 study, we make significant modifications and improvements, including the use of EXIOBASE³³, and calculate
 148 E_{iE} at both primary and final energy stages. To estimate indirect energy, either life cycle analysis (LCA) or IO-
 149 based analysis can be used. More commonly, LCA analysis is used for site-level (mainly fossil fuels) or device-
 150 level (mainly renewables) EROI estimates, due to better availability of granular data – see Murphy et al.³⁶. At
 151 an economy-wide and global level, IO analysis is more often used as LCA data becomes very complex at scale,
 152 and has been used for EROI estimates by Brand-Correa et al.¹⁶ and Palmer³⁷. However, we also note studies
 153 suggest that IO-derived EROI is typically lower than a process-based LCA study for exactly the same data³⁸.

154 The MRIO-based method for calculating E_{iE} follows the conventional approach used in consumption-based
 155 emissions³⁹ and energy accounting⁴⁰. The accounting matrices are used to determine the how global industrial
 156 outputs respond to a unit change in final demand. An environmental extension vector of either energy

157 extracted or fuel used per unit of industrial output can be combined with the accounting matrices to measure
 158 the full supply chain energy required to meet final demand. We use the numerator in equation (2) ($E_{T_PRIM} -$
 159 E_{dE_PRIM}) and equation (3) (TFC) to construct different 'net energy' extension vectors for both primary and
 160 final energy stages, by allocating net energy at primary and final energy stages to EXIOBASE industries. An
 161 overview of the IO framework is given in Figure 2. EXIOBASE energy industries at primary and final energy
 162 stages are given in Table 3:



163
 164 **Figure 2: Basic multi-regional input-output structure with energy extensions vector** (adapted from ¹⁶). The Z matrix
 165 contains all inter-sector transactions. Vector v denotes value-added data, while vector x represents the total economic
 166 output, and vector y is sales to households (final demand). Z , v , x and y are in financial units. Vector f is the energy
 167 extension, which is in energy units.

168
 169 **Table 3. EXIOBASE fossil fuel energy sectors.** Nine EXIOBASE sectors concern energy extraction and/or finished fuels
 170 production. These are mapped to primary and final energy stages, which then form the energy extension vectors for the
 171 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

172 The calculated $EROI_{FIN}$ ratio is an aggregate metric which combines all fossil fuel based refined fuels and
 173 electricity outputs. To provide more detail, we split $EROI_{FIN}$ into refined fuels ($EROI_{FIN_FUEL}$) and electricity
 174 ($EROI_{FIN_ELECT}$) as shown in equations (4) and (5). Refer to Methods for more detail.
 175

$$EROI_{FIN_ELECT} = \frac{\text{Total Final Consumption (TFC_ELECT)}}{E_{dE_FIN_ELECT} + E_{iE_FIN_ELECT}} \quad (4)$$

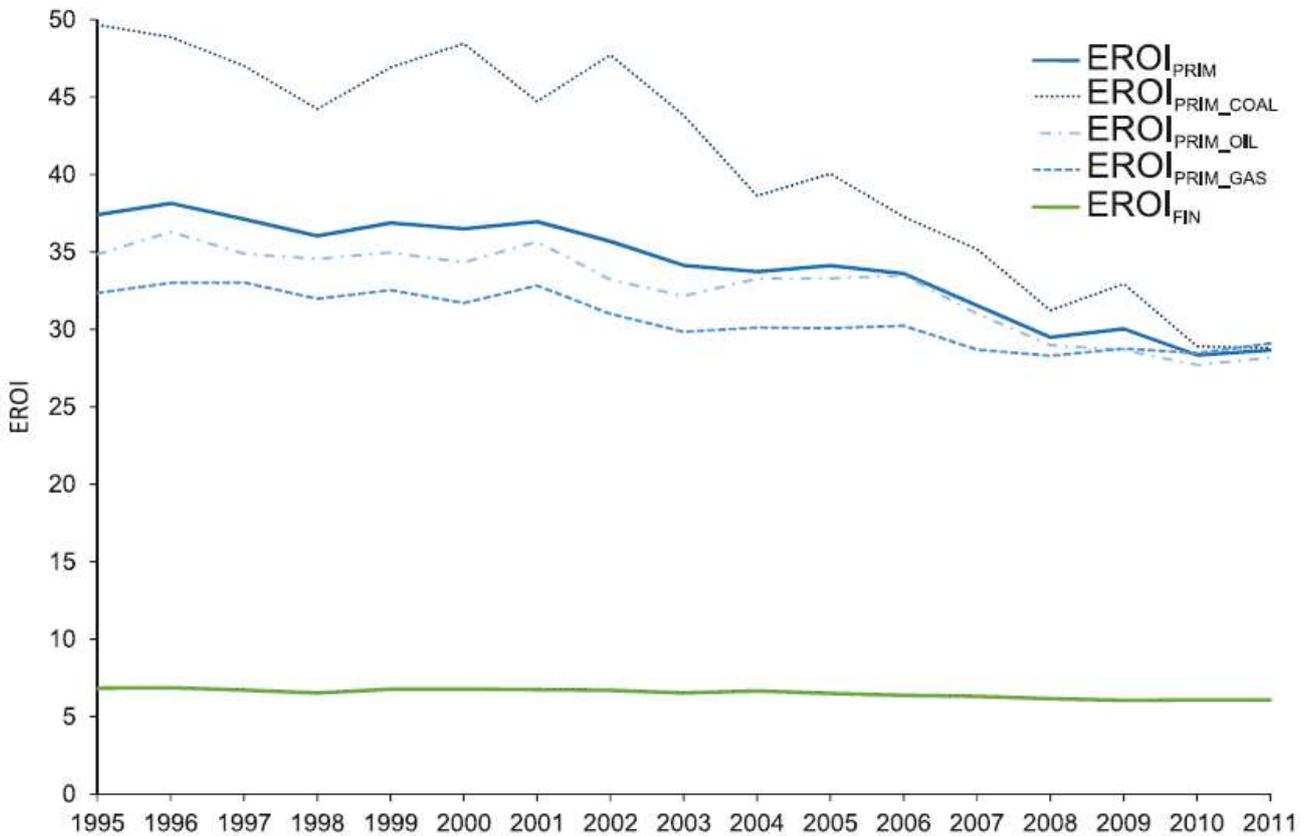
$$EROI_{FIN_FUEL} = \frac{\text{Total Final Consumption (TFC_FUEL)}}{E_{dE_FIN_FUEL} + E_{iE_FIN_FUEL}} \quad (5)$$

176 **Global fossil fuel energy-return-on-investment results**

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

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

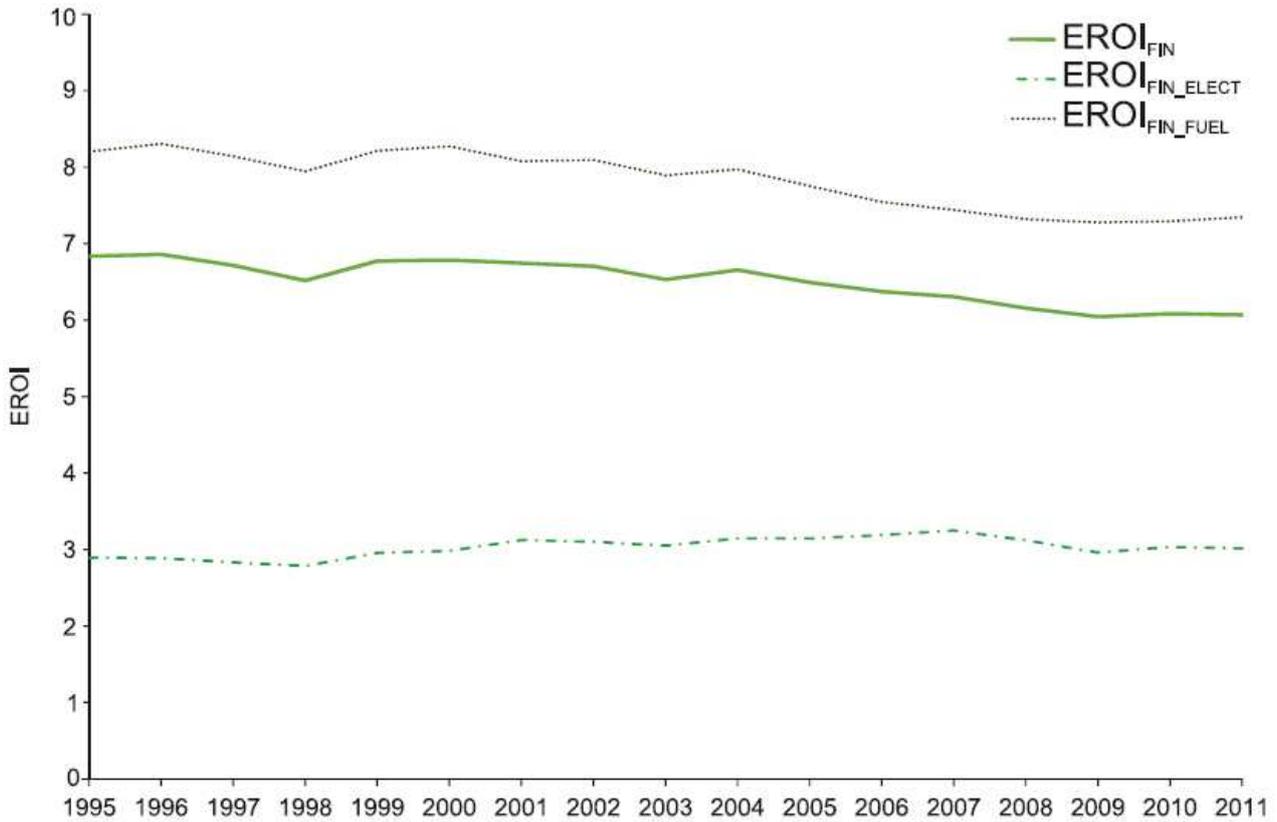
188



189

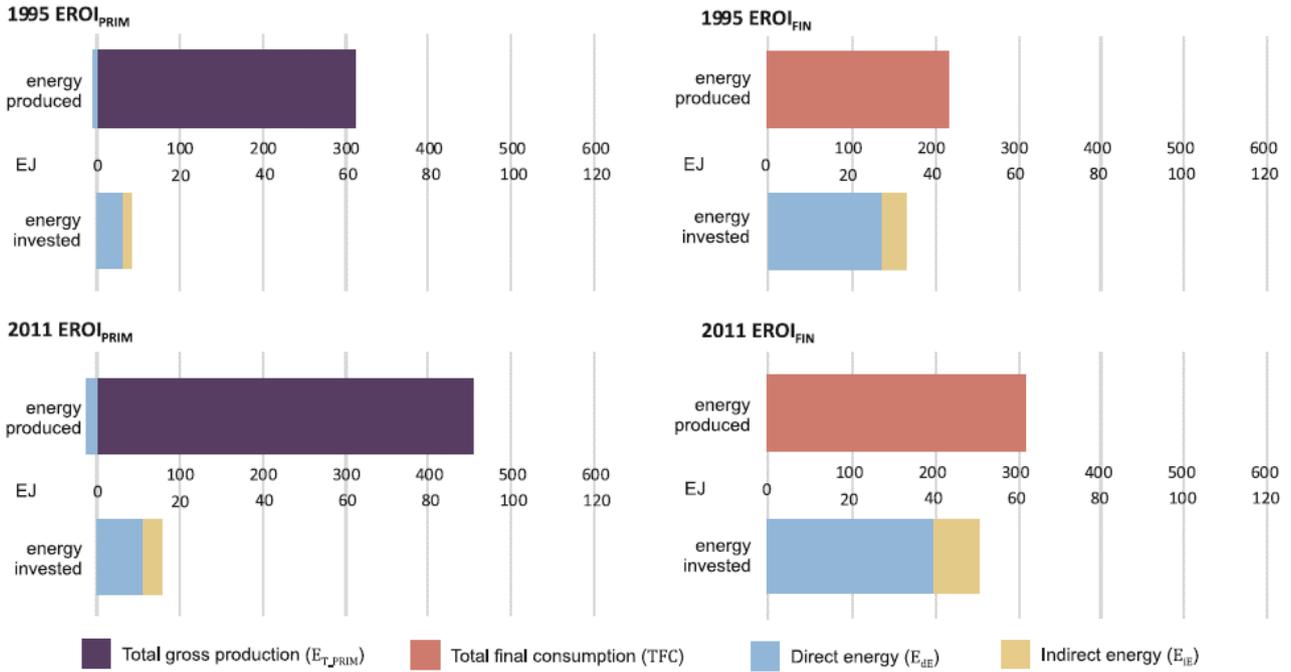
190 **Figure 3: Global primary stage fossil fuel energy-return-on-investment ratios from 1995 to 2011.** $EROI_{PRIM}$ is aggregate
 191 fossil fuel primary-stage EROI, with associated primary-stage EROI ratios for coal, oil and gas denoted by $EROI_{PRIM_COAL}$,
 192 $EROI_{PRIM_OIL}$ and $EROI_{PRIM_GAS}$ respectively. $EROI_{FIN}$ denotes aggregate final-stage fossil fuel EROI.

193 Figure 4 splits $EROI_{FIN}$ into two important sub-components, with EROI of fossil fuel based electricity
 194 ($EROI_{FIN_ELECT}$) around 3:1, versus other refined fuels ($EROI_{FIN_FUEL}$) \sim 8:1. The growth in world electricity
 195 consumption as a fraction of total final energy consumption (TFC) may therefore be one factor in the decrease
 196 of $EROI_{FIN}$. The value of $EROI_{FIN_ELECT}$ (\sim 3:1) is at the lower end of the range estimated via LCA analysis by
 197 Raugei and Leccisi¹⁸ given in Table 1 (4:1 for coal-based electricity and 11:1 for gas-based electricity), but is
 198 comparable given the majority of fossil fuel based electricity uses coal, and the inclusion of electricity
 199 distribution losses in our $EROI_{FIN_ELECT}$ ratio.



200
 201 **Figure 4: Global final stage fossil fuel energy-return-on-investment ratios from 1995 to 2011.** $EROI_{FIN}$ denotes
 202 aggregate final-stage fossil fuel EROI. $EROI_{FIN_ELECT}$ and $EROI_{FIN_FUEL}$ denote final-stage EROI for fossil fuel based
 203 electricity and other refined fossil fuels respectively

204
 205 Further insights can be gained by studying the EROI component terms in equations (2) and (3) given in Figure
 206 5. First, regarding their magnitudes, we find that $EROI_{FIN}$ is significantly lower than $EROI_{PRIM}$ mainly because
 207 the EROI denominator ($E_{dE}+E_{iE}$) is 4-5 times larger at the final energy stage than primary energy stage. This
 208 is mainly caused by a larger contribution from direct energy (E_{dE}), as the number of EIOU energy production
 209 sectors has broadened from 2 to 14. In addition, the numerator (E_T-E_{dE}) is around a third smaller at the final
 210 energy stage, which further reduces $EROI_{FIN}$. Second, the declining time-series trends exhibited by both
 211 $EROI_{FIN}$ and $EROI_{PRIM}$ are because the denominator ($E_{dE}+E_{iE}$) increases at a faster rate than the numerator
 212 (E_T-E_{dE}).



214

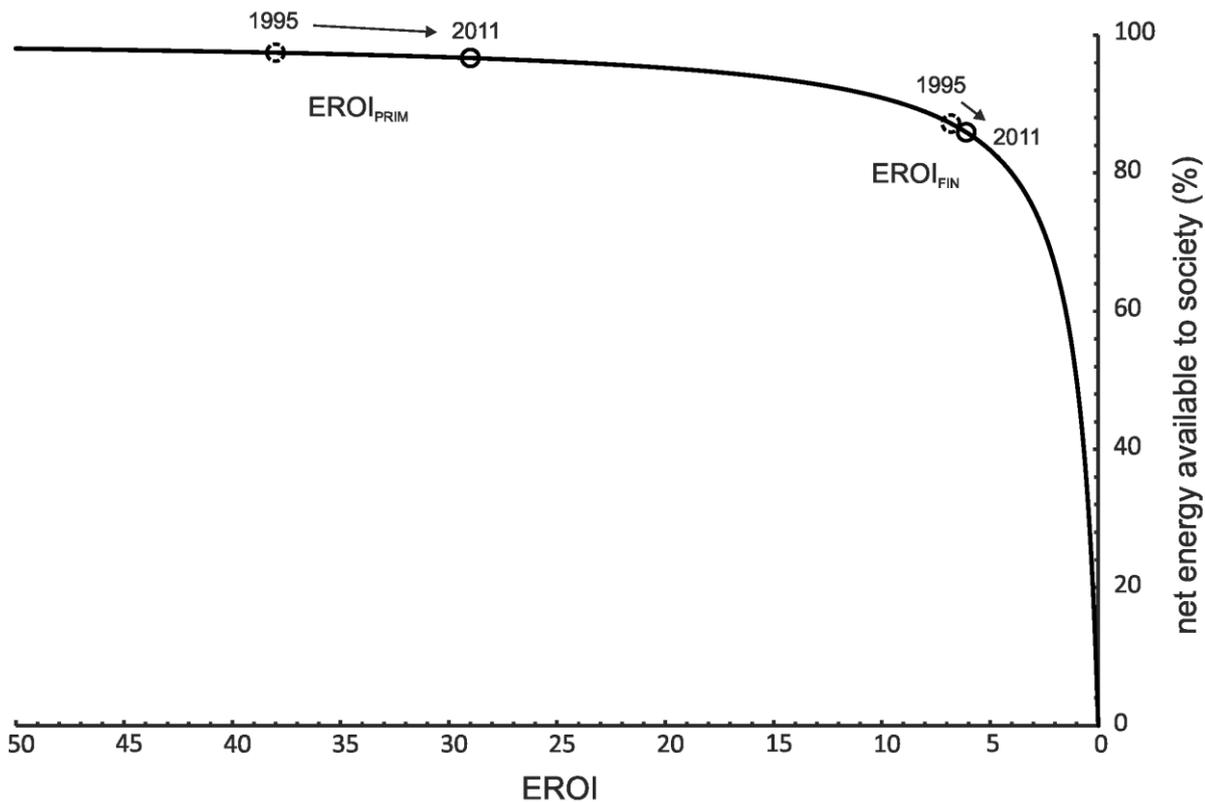
215 **Figure 5: Components of the energy-return-on-investment calculations.** EROI component terms in equations (2) and (3)
 216 shown for both primary and final energy stages for the start year of 1995 and end year of 2011. The elements contributing
 217 to the numerator and denominator are shown above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

219 **A more complete view of fossil fuel EROI**

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

221 Firstly, renewable-based electricity might not be as disadvantaged compared to fossil fuels - in EROI terms - as
 222 is often suggested in the literature¹². Our global fossil fuel EROI analysis suggests $EROI_{FIN_ELECT}$ (~3:1) may
 223 be below the EROI ratios estimated for modern renewables (e.g. PV and wind) when measured at the same
 224 final energy stage (see Table 1). These ratios are much lower than conventional, primary energy stage
 225 $EROI_{PRIM}$ (~30:1), supporting the driving concern and the rationale behind the paper. In addition, our
 226 estimates for $EROI_{PRIM}$ may actually be conservatively high, as the MRIO-based method does not include all
 227 aspects of fossil fuel industry capital investment and decommissioning. Our findings suggest a large-scale
 228 transition to renewable energy sources does not necessarily imply a significant reduction in economy-wide
 229 EROI. On the contrary, such low and declining $EROI_{FIN}$ ratios would mean the renewables transition may
 230 actually halt – or reverse - the decline in global EROI at the final energy stage.

231 Secondly, the low ratios (~6:1) of fossil fuel EROI at the final energy stage, and their declining nature (10%
 232 decrease 1995-2011) gives reason for concern. Figure 6 shows fossil-fuel EROI at the final energy stage is
 233 nearer the ‘net energy cliff’ than has been supposed at a primary energy stage⁶. This matters, as the net energy
 234 cliff is highly non-linear: the reduction in net energy availability by moving from an EROI ratio of 10:1 to 5:1 (-
 235 10%) is much greater than 40:1 to 20:1 (-2.5%). Our results suggest we may already have entered this zone of
 236 highly non-linear change, where further modest declines in $EROI_{FIN}$ ratios lead to increasingly rapid
 237 reductions in the available net energy to society.



238

239 **Figure 6: Analysis results superimposed on the ‘net energy cliff’.** X-axis denotes energy-return-on-investment (EROI)
 240 ratios between 0-50. Y-axis denotes the net energy available to society, calculated from the EROI ratios. For example, an
 241 EROI ratio of 10:1 means 90% of the energy obtained is available to society. Declining EROI ratios below 5:1 have rapidly
 242 reducing available net energy, hence the ‘net energy cliff’ term. The analysis results for 1995 and 2011 are then
 243 superimposed on the EROI – available net energy curve. $EROI_{PRIM}$ is aggregate fossil fuel EROI at the primary energy
 244 conversion stage. $EROI_{FIN}$ denotes aggregate fossil fuel EROI at the primary energy conversion stage (**adapted from**
 245 **Mearns⁴¹**).

246 Thirdly, given the low and declining final energy stage $EROI_{FIN}$ ratios and proximity to the net energy cliff, we
 247 should more seriously and urgently consider the potential societal impacts and response to reductions in the
 248 net energy available to society. These effects could be significant: reductions in energy supply and/or
 249 significant increases in energy prices in the past have often been associated with economic crises⁴²⁻⁴⁴. It is very
 250 unclear how these non-linear impacts of declining EROI on the availability of net energy will impact society
 251 and economy. However, it is likely that any impacts would unfold in a similarly non-linear fashion. The
 252 investigation of such net energy constraints on the socio-economy starts at a very low base. On the one hand,
 253 aspects of EROI (i.e. the relationship between gross energy, net energy and economic impacts) are generally
 254 not included in many of the energy-economy models^{45,46} that are used to investigate possible pathways to a
 255 low-carbon future⁴⁷. On the other hand, when EROI is included, such models do not include low (enough) EROI
 256 ratios for fossil fuels^{10,12}. As a result, socio-economic impacts are limited in the model (since high EROI ratios
 257 are included) and reinforces the perception that a transition to renewables will lower overall EROI.

258 One logical response to declining net energy availability of fossil fuels at an economy-wide level would be to
 259 increase total production of fossil fuels (E_{T_FIN}), to compensate for significant rises in direct energy associated
 260 with their production (E_{dE_FIN}), to maintain absolute net energy levels ($E_T - E_{dE}$) to the remaining productive
 261 part of the economy. This is the trap set by the net energy cliff, would be disastrous from the perspective of
 262 climate change, as higher overall levels of fossil fuel combustion will increase associated greenhouse gas
 263 emissions. That said, such increases in fossil fuel production may not be readily feasible, given the decreasing
 264 availability of large and easy-to-extract fossil energy reserves⁴⁸.

265 Two other responses could alternatively be employed, preferably together as they acts as complements.
 266 Firstly, the scale and speed of the renewables transition could be increased. If renewables-based EROI is higher

267 than fossil fuels, this provides added impetus for this option. However, fossil fuels still provide the large
268 majority of the global energy consumed and are likely to do so for the foreseeable future. Therefore, a rapid
269 transition to renewable energy sources will still require significant energy subsidies from fossil fuels, as
270 renewables have a significant temporal lag before they achieve net energy payback^{49,50}. Any transition period
271 featuring a large build-rate of new renewable capacity would therefore be characterised by incumbent fossil
272 fuels and their low EROI ratios. Secondly, following Cullen and others⁵¹, increasing attention is placed on how
273 we can become more efficient in utilising constrained (final) energy to deliver increased end energy services.

274 Conclusions

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

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

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

295 Methods

296 **Data.** Our analysis draws on two key data sources. The first source is the extended world energy balances provided by
297 the IEA for 142 countries and two rest-of-world regions³². All the energy data used in our study is based on IEA data. The
298 second source is the EXIOBASE MRIO database V3.4³³. EXIOBASE V3.4 provides global input-output transaction matrices
299 describing trade flows between 163 industries in 44 countries and 5 rest-of-world regions as well as details on final
300 demand expenditure on each industry in each country/region. All data is selected on an annual basis covering the years
301 1995 to 2011. The EXIOBASE data forms the basis of the input-output analysis that we perform to determine the indirect
302 energy used in the fossil fuel producing industries. EXIOBASE V3.4 contains energy extension vectors but these vectors
303 are not consistent with the data we used for the net energy and direct energy components of equations (2) and (3).
304 Therefore, for consistency and to suit our purposes, we constructed energy extension vectors based on the IEA extended
305 energy balances, one for each EROI stage (primary and final energy).

306 **From IEA energy balances to EXIOBASE vectors.** We use data from the IEA extended energy balances in all three steps
307 of our analysis. The relevant categories from IEA's extended energy balances are allocated to the 49 countries/regions in
308 EXIOBASE using a concordance matrix A in the data repository⁵².

309 At the primary energy stage we obtain the gross production of energy, E_{T_PRIM} , using IEA's 'production' category (a sub-
310 category of "total primary energy supply"). As the scope of our analysis is restricted to fossil fuels, only fossil fuel
311 production is considered (14 IEA energy products, see primary energy stage concordance matrix B in the data repository⁵².
312 We obtain the direct energy used by the fossil fuel extracting industries, E_{dE_PRIM} , from IEA's 'energy industry own use'
313 categories. Only those categories directly relating to the extractive energy industries are considered (Table 2). We
314 subtract the energy industry's own use of energy from the figures for gross production to avoid double-counting of the

315 direct energy use of the energy industry in our EROI calculations. Finally, we construct the extension vector required for
 316 the input-output analysis by allocating the gross production of energy from the IEA data to the four relevant energy-
 317 producing industries in EXIOBASE for each country/region.

318 At the final energy stage we use IEA's 'Total Final Consumption' (TFC) to calculate the numerator of the EROI in equation
 319 (3). As the scope of our analysis is restricted to fossil fuels, we include only the consumption of energy carriers derived
 320 from fossil fuels (29 IEA energy products, see final energy concordance matrix C in the data repository⁵². We then obtain
 321 the direct energy used by the fossil fuel extraction and energy production industries, E_{dE_FIN} , from IEA's 'energy industry
 322 own use' categories, as shown in Table 2. Finally, we create the extension vector for the MRIO analysis by allocating IEA's
 323 total final consumption by products (29 fossil fuel derived final consumption products) to (seven) EXIOBASE industries.
 324 Note that we do not allocate IEA's total final consumption by the categories in which energy is used, but rather by the
 325 products (or energy sources) that are used at that stage.

326 For splitting $EROI_{FIN}$ into $EROI_{FIN_ELECT}$ and $EROI_{FIN_FUEL}$ as given in equations (4) and (5), we require estimates of the
 327 three components. First, TFC is split into electricity (TFC_{ELECT}) refined fuels (TFC_{FUEL}) directly from the IEA data.
 328 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
 329 components of indirect energy ($E_{iE_FIN_ELECT}$ and $E_{iE_FIN_FUEL}$) is not possible directly due to the lack of required
 330 EXIOBASE sector granularity (e.g. oil refineries would need to be split between ELECT and FUEL use). Therefore, we
 331 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
 332 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.

333 **Input-output analysis.** The indirect energy used by fossil fuel industries is calculated using input-output analysis – a
 334 macroeconomic technique most commonly used for consumption-based accounting⁵³. The method builds on previous
 335 work by Brand-Correa et al.¹⁶. Referring to the IO framework in Figure 2, taking the EXIOBASE 4.3 MRIO database, we
 336 first express total economic output \mathbf{x} as a function of final demand \mathbf{y} . This process will demonstrate how every global
 337 industry contributes to the supply chain of a single final demand product and can consequently be used to understand
 338 the supply chain energy used by the fossil fuel sector.

339 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
 340 each industry, to both other industries and final demand, are recorded along the rows. The columns show expenditure
 341 by each industry on both intermediate goods, and taxes and wages (found in value added). For the purpose of this initial
 342 explanation, \mathbf{y} takes the form of a single column of total global final demand.

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

$$x_i = z_{i1} + z_{i2} + \dots + z_{in} + y_i \quad (6)$$

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

$$a_{ij} = \frac{z_{ij}}{x_j} \quad (7)$$

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

$$x_i = a_{i1}x_1 + a_{i2}x_2 + \dots + a_{in}x_n + y_i \quad (8)$$

349 which, if written in matrix notation is $\mathbf{x} = \mathbf{Ax} + \mathbf{y}$.

350 Solving for \mathbf{x} gives:

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

351 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
 352 Leontief inverse (denoted hereafter as \mathbf{L}). Now consider a row vector \mathbf{f} of energy assigned to industrial sectors. In this
 353 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
 354 (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
 355 (10):

$$\mathbf{e} = \mathbf{f}\hat{\mathbf{x}}^{-1} \quad (10)$$

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

$$\mathbf{e}\mathbf{x} = \mathbf{e}\mathbf{L}\mathbf{y} \quad (11)$$

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

$$\mathbf{f} = \mathbf{e}\mathbf{L}\mathbf{y} \quad (12)$$

359 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
 360 the energy inputs by sector and region into any product. If rather than representing global final demand, \mathbf{y} is the final
 361 demand of a particular country, k , \mathbf{F} is now the total energy required to meet consumption in country k . Hereafter we
 362 use individual country vectors for \mathbf{y} and results are calculated separately for each country in the database, before being
 363 summed to calculate a total global figure.

364 An individual element in the \mathbf{Z} matrix $z_{ij}^{r,s}$ describes the flow from sector i in country r to sector j in country s . Input-
 365 output tables usually contain some monetary flow in the cell $z_{i=j}^{r=s}$. This could represent, for example, Chinese Coal inputs
 366 to the Chinese Coal producing sector. Since this should be captured by E_{dE} (either at the primary energy or the final
 367 energy stage), we need to adjust the original EXIOBASE \mathbf{Z} matrix to remove these particular flows. We remove these flows
 368 (found on the diagonal) by setting the cell value to zero and recalculating the associated total output vector \mathbf{x} . This means
 369 that when energy consumption-based accounts are calculated, the direct energy is redistributed such that the result
 370 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
 371 be an indirect flow of Chinese Coal which involves a supply chain which passes the coal via some other sector before it is
 372 used again in the production of Chinese Coal products.

373 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
 374 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):

$$\mathbf{Z} = z_{i=j}^{r=s} = \begin{cases} 0 & \text{if } i \in \{e, \dots, g\} \\ z_{i=j}^{r=s} & \text{otherwise} \end{cases} \quad (13)$$

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

377 To calculate the *indirect fossil fuel energy* (E_{iE}) used at primary and final energy conversion stages, we calculate a new
 378 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*
 379 *particular fossil fuel energy sector*. The indirect energy used by fossil fuel industries is therefore the difference between
 380 \mathbf{F} and \mathbf{F}^0 .

381 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
 382 matrix is exactly the same as the adapted \mathbf{Z} but replaces monetary flows with zeros for any columns associated with that
 383 country’s fossil fuel energy products. We will call \mathbf{Z}^0 this further modified country-specific transaction matrix. This means
 384 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
 385 will not only register zero energy in the production recipe (column) of a fossil fuel product, but the energy flows
 386 throughout the rest of the matrix will not contain energy that interacted with the fossil fuel product supply chain.
 387 Consequently, when finding $E_{iE} = \sum \mathbf{F} - \mathbf{F}^0$, we are identifying any energy that interacted with any part of the fossil
 388 fuel product supply chain regardless of the final product made.

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

393 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
 394 corresponding to that country’s set of fossil fuel energy sectors e to g (from Table 3). For any sector j in the specific
 395 country k , these destination columns are zero if j is in the set of e to g , as given in equation (14):

$$\mathbf{M}^k = m_{ij}^{rk} = \begin{cases} 0 & \text{if } j \in \{e, \dots, g\} \\ 1 & \text{otherwise} \end{cases} \quad (14)$$

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

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

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

$$E_{iE} = \sum_{r,s}^n \sum_{i \in \{e, \dots, g\}, j}^m f_{ij}^{rs} - f_{ij}^{rs0} \quad (16)$$

400 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
 401 the data annually to generate a global E_{iE} value.

402 **EROI_{gross} vs EROI_{net}.** We note that EROI ratios can (correctly) be measured on either a net ($EROI_{net}$) or gross
 403 ($EROI_{gross}$) basis⁵⁴, and by dividing the terms in equation (1) by the energy input we find in equation (17) that $EROI_{net}$
 404 = $EROI_{gross} - 1$. Hence, whilst all our results are described in net terms, an EROI value of 10:1 on a net basis becomes
 405 11:1 on a gross basis, and so on. Therefore, the gist of the arguments made in our paper are however not affected by
 406 the adoption of 'net' (versus 'gross') definition of EROI.

$$EROI_{net} = \frac{\frac{\text{Gross energy output}}{\text{energy input}} - 1}{1} = EROI_{gross} - 1 \quad (17)$$

407 **EROI Boundaries.** The calculation of EROI ratios always requires the setting of boundaries around the scope of energy
 408 that is considered to be 'energy invested'. The choices made with regard to this boundary have an important influence
 409 on the EROI results calculated. Where to best set these boundaries is debated in the literature⁵⁵. There is no agreed set
 410 of rules and the potential choices depend on the method used³⁶. In our analysis the boundaries of 'energy invested' are
 411 largely defined by the characteristics of the data and methods that we employ.

412 The first component of energy invested in our analysis is drawn from the 'Energy Industry Own Use' flows from the IEA
 413 energy balances. The IEA's Database documentation³⁵ notes these flows cover "the amount of fuels used by the energy
 414 producing industries (e.g. for heating, lighting and operation of all equipment used in the extraction process, for traction
 415 and for distribution)" in each year. The IEA energy balances break down these flows into different categories. We
 416 included different categories of these flows for the primary and final EROI calculations (see Table 2).

417 In addition to the direct energy used in the energy industries, we also consider it important to include energy that is
 418 invested indirectly, via the embodied energy in goods and services that are used by the energy industries to produce
 419 energy. We estimate this indirect energy using an input-output approach that is commonly used for energy footprinting.
 420 Such an approach implies some clear boundaries on the embodied energy included. Most importantly, the input-output
 421 approach we employ only includes embodied energy associated with intermediate inputs in the supply chain. These
 422 intermediate inputs represent inputs into the production process that are "turned over at least annually"⁵⁶. Any energy
 423 that is embodied in the fixed capital goods, goods that are used in production over several years, is not included. This is
 424 a common limitation of global input-output models as there is a lack of detailed data on the amount and composition of
 425 capital expenditure at the industry level⁵⁷.

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

433 **Validation.** Important checks were performed on the components of the EROI calculations. First, for total energy (E_T)
 434 and TFC, we checked that the sum of country-level data (extracted from the IEA extended energy database and then
 435 mapped to EXIOBASE country structures) matched the World totals. Second, for direct energy use (E_{iE}) for EROI_PRIM
 436 and EROI_FIN, we performed a similar check that World total matched the EXIOBASE country summation. Third, for
 437 indirect energy (E_{iE}), the Matlab code included checks that the code was working correctly, whilst the fraction of indirect
 438 (i.e. supply-chain) energy versus direct energy (around 25-30%) accords with Chen and Wu's study of energy embodied
 439 in world trade⁵⁸. Last, our calculated primary-stage fossil fuel EROI values (~30:1) were found to be in broad agreement
 440 with other published estimates (refer also to Table 1).

441 **Limitations.** In addition to the limits that our data and methods pose regarding EROI boundaries discussed earlier, two
 442 other limitations need to be taken into account when interpreting our results. Firstly, our analysis is based on annual

443 energy (IEA) and economic (EXIOBASE - MRIO) data. Additional temporal components of indirect energy for our fossil fuel
444 analysis would include both capital investment and decommissioning phases. This is more commonly included in
445 renewables-based EROI and energy payback time (EPBT) studies^{38,50}. Secondly, we are confident in the accuracy of our
446 results at a global level, where long term trends prevail over yearly outliers. However, at a country level, we are less
447 confident of our results, since uncertainties associated with individual cells in EXIOBASE's transaction matrix can produce
448 significant distortions. Last, we have been able to provide EROI for coal, oil and gas at the primary energy stage, but not
449 at the final energy stage. This would require more detailed energy data at the final energy level.

450 **Data Statement.** The extended energy input datasets were obtained under licence from the International Energy Agency
451 (IEA). The IEA World Energy Statistics and Balances can be downloaded with institutional or other user licence from
452 <https://doi.org/10.1787/enestats-data-en>. The EXIOBASE 3.4 database is available at
453 (<http://exiobase.eu/index.php/data-download/exiobase3mon>). The concordance matrices used in the EXIOBASE-based
454 calculations are available in a University of Leeds data repository⁵². The aggregate EROI results datasets generated are
455 available from the corresponding author, upon reasonable request.

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

458 **Competing Interests**

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

460 **Acknowledgements**

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

466 **Author Contributions**

467 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
468 International Energy Agency data and undertook calculations to calculate total energy produced and direct
469 energy consumed. L.I.B-C. and A.O. performed the multi-regional input-output calculations to obtain indirect
470 energy estimates.

471

472 References

- 473 1. Gilliland, M. W. Energy Analysis and Public Policy. *Science* (80-.). **189**, 1051–1056 (1975).
- 474 2. Odum, H. T. Energy, Ecology, and Economics. *Ambio* **2**, 220–227 (1973).
- 475 3. United States Congress. Federal Nonnuclear Energy Research and Development Act of 1974. 1–18
476 (1974).
- 477 4. Bullard, C. W., Penner, P. S. & Pilati, D. A. Net Energy Analysis: Handbook for Combining Process
478 and Input-Output Analysis. *Resour. Energy* **1**, 267–313 (1978).
- 479 5. Mulder, K. & Hagens, N. J. Energy Return on Investment: Toward a Consistent Framework. *AMBIO A*
480 *J. Hum. Environ.* **37**, 74–79 (2008).
- 481 6. Kunz, H., Hagens, N. J. & Balogh, S. B. The Influence of Output Variability from Renewable
482 Electricity Generation on Net Energy Calculations. *Energies* **7**, 150–172 (2014).
- 483 7. The Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014: Mitigation of Climate*
484 *Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental*
485 *Panel on Climate Change* (2014). doi:10.1017/CBO9781107415416
- 486 8. Gagnon, N., Hall, C. A. S. & Brinker, L. A Preliminary Investigation of Energy Return on Energy
487 Investment for Global Oil and Gas Production. *Energies* **2**, 490–503 (2009).
- 488 9. Lambert, J. G. *et al.* *EROI of Global Energy Resources. Status, Trends and Social Implications. Report*
489 *prepared for the United Kingdom Department for International Development.* (2013).
- 490 10. King, L. C. & Van Den Bergh, J. C. J. M. Implications of net energy-return-on-investment for a low-
491 carbon energy transition. *Nat. Energy* **3**, 334–340 (2018).
- 492 11. International Energy Agency (IEA). *World Energy Outlook 2017.* (2017). doi:10.1016/0301-
493 4215(73)90024-4
- 494 12. Sers, M. R. & Victor, P. A. The Energy-missions Trap. *Ecol. Econ.* **151**, 10–21 (2018).
- 495 13. Hall, C. A. S., Balogh, S. & Murphy, D. J. R. What is the Minimum EROI that a Sustainable Society
496 Must Have? *Energies* **2**, 25–47 (2009).
- 497 14. Fizaine, F. & Court, V. Energy expenditure , economic growth, and the minimum EROI of society.
498 *Energy Policy* **95**, 172–186 (2016).
- 499 15. Hall, C. A. S., Lambert, J. G. & Balogh, S. B. EROI of different fuels and the implications for society.
500 *Energy Policy* **64**, 141–152 (2014).
- 501 16. Brand-Correa, L. I. *et al.* Developing an Input-Output Based Method to Estimate a National-Level
502 Energy Return on Investment (EROI). *Energies* **10**, **534**, 21 (2017).
- 503 17. Cleveland, C. J., Costanza, R., Hall, C. A. S. & Kaufmann, R. Energy use and the US Economy: a
504 Biophysical Perspective. *Science* (80-.). **225**, 890–897 (1983).
- 505 18. Raugei, M. & Leccisi, E. A comprehensive assessment of the energy performance of the full range of
506 electricity generation technologies deployed in the United Kingdom. *Energy Policy* **90**, 46–59 (2016).
- 507 19. Court, V. & Fizaine, F. Long-Term Estimates of the Energy-Return-on-Investment (EROI) of Coal,
508 Oil, and Gas Global Productions. *Ecol. Econ.* **138**, 145–159 (2017).
- 509 20. Brandt, A. R. Oil depletion and the energy efficiency of oil production: The case of California.
510 *Sustainability* **3**, 1833–1854 (2011).
- 511 21. Raugei, M., Fullana-i-Palmer, P. & Fthenakis, V. The energy return on energy investment (EROI) of
512 photovoltaics: Methodology and comparisons with fossil fuel life cycles. *Energy Policy* **45**, 576–582
513 (2012).
- 514 22. Leccisi, E., Raugei, M. & Fthenakis, V. The Energy and Environmental Performance of Ground-
515 Mounted Photovoltaic Systems—A Timely Update. *Energies* **9**, 622 (2016).
- 516 23. Kubiszewski, I., Cleveland, C. J. & Endres, P. K. Meta-analysis of net energy return for wind power

- 517 systems. *Renew. Energy* **35**, 218–225 (2010).
- 518 24. Raugei, M. Net energy analysis must not compare apples and oranges. *Nat. Energy* **4**, 86–88 (2019).
- 519 25. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014. Summary for Policy*
520 *Makers. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental*
521 *Panel on Climate Change. Climate Change 2014: Mitigation of Climate Change. Contribution of*
522 *Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*
523 (2014). doi:10.1017/CBO9781107415324
- 524 26. Capellán-Pérez, I. *et al.* Global Model: MEDEAS- World Model and IOA implementation at global
525 geographical level (No. D4.1 (D13)). Barcelona, Spain. (2017). Available at:
526 <http://www.medeas.eu/deliverables>.
- 527 27. Dale, M., Krumdieck, S. & Bodger, P. Global energy modelling — A biophysical approach (GEMBA)
528 part 1: An overview of biophysical economics. *Ecol. Econ.* **73**, 152–157 (2012).
- 529 28. Fagnart, J. F. & Germain, M. Net energy ratio, EROEI and the macroeconomy. *Struct. Chang. Econ.*
530 *Dyn.* **37**, 121–126 (2016).
- 531 29. King, C. W. & Hall, C. A. S. Relating financial and energy return on investment. *Sustainability* **3**,
532 1810–1832 (2011).
- 533 30. Guilford, M. C., Hall, C. A. S., Connor, P. O. & Cleveland, C. J. A New Long Term Assessment of
534 Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production. *Sustainability* **3**,
535 1866–1887 (2011).
- 536 31. King, C. W., Maxwell, J. P. & Donovan, A. Comparing World Economic and Net Energy Metrics, Part
537 2: Total Economy Expenditure Perspective. *Energies* **8**, 12975–12996 (2015).
- 538 32. IEA. ‘Extended world energy balances’, IEA World Energy Statistics and Balances (database),. (2017).
539 doi:10.1787/data-00513-en
- 540 33. Stadler, K. *et al.* EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended
541 Multi-Regional Input-Output Tables. *J. Ind. Ecol.* (2018). doi:10.1111/jiec.12715
- 542 34. Brandt, A. R., Dale, M. & Barnhart, C. J. Calculating systems-scale energy efficiency and net energy
543 returns: A bottom-up matrix-based approach. *Energy* **62**, 235–247 (2013).
- 544 35. International Energy Agency (IEA). *World Energy Balances: Database Documentation (2018 edition)*.
545 (2018). doi:10.2785/020714
- 546 36. Murphy, D. J., Carbajales-Dale, M. & Moeller, D. Comparing apples to apples: Why the net energy
547 analysis community needs to adopt the life-cycle analysis framework. *Energies* **9**, 1–15 (2016).
- 548 37. Palmer, G. An input-output based net-energy assessment of an electricity supply industry. *Energy* **141**,
549 1504–1516 (2017).
- 550 38. Palmer, G. & Floyd, J. An Exploration of Divergence in EPBT and EROI for Solar Photovoltaics.
551 *Biophys. Econ. Resour. Qual.* **2**, 15 (2017).
- 552 39. Barrett, J. *et al.* Consumption-based GHG emission accounting: a UK case study. *Clim. Policy* **13**,
553 451–470 (2013).
- 554 40. Owen, A. *et al.* Energy consumption-based accounts: A comparison of results using different energy
555 extension vectors. *Appl. Energy* **190**, 464–473 (2017).
- 556 41. Mearns, E. The global energy crisis and its role in the pending collapse of the global economy.
557 Presentation to the Royal Society of Chemists, Aberdeen, Scotland, 29 October 2008. (2008).
- 558 42. Bashmakov, I. Three laws of energy transitions. *Energy Policy* **35**, 3583–3594 (2007).
- 559 43. Kilian, L. The Economic Effects of Energy Price Shocks. *J. Econ. Lit.* **46**, 871–909 (2008).
- 560 44. Aucott, M. & Hall, C. Does a Change in Price of Fuel Affect GDP Growth? An Examination of the
561 U.S. Data from 1950–2013. *Energies* **7**, 6558–6570 (2014).
- 562 45. Bauer, N., Baumstark, L. & Leimbach, M. The REMIND-R model: The role of renewables in the low-

- 563 carbon transformation-first-best vs. second-best worlds. *Clim. Change* **114**, 145–168 (2012).
- 564 46. Bernard, A. & Vielle, M. GEMINI-E3, a general equilibrium model of international-national
565 interactions between economy, energy and the environment. *Comput. Manag. Sci.* **5**, 173–206 (2008).
- 566 47. Clarke, L. *et al.* Assessing Transformation Pathways. in *Climate Change 2014: Mitigation of Climate*
567 *Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental*
568 *Panel on Climate Change* (eds. Edenhofer, O. *et al.*) 413–510 (Cambridge University Press, 2014).
- 569 48. Capellán-Pérez, I., Mediavilla, M., de Castro, C., Carpintero, Ó. & Miguel, L. J. Fossil fuel depletion
570 and socio-economic scenarios: An integrated approach. *Energy* **77**, 641–666 (2014).
- 571 49. Bhandari, K. P., Collier, J. M., Ellingson, R. J. & Apul, D. S. Energy payback time (EPBT) and energy
572 return on energy invested (EROI) of perovskite tandem photovoltaic solar cells. *Renew. Sustain.*
573 *Energy Rev.* **47**, 133–141 (2015).
- 574 50. Dale, M. & Benson, S. The energy balance of the photovoltaic (PV) industry — is the PV industry a
575 net energy provider? *Global Climate and Energy Project (GCEP) Symposium 2012* (2012). Available
576 at: http://gcep.stanford.edu/pdfs/symposium2012/MikDale_Symp2012_web.pdf.
- 577 51. Cullen, J. M. & Allwood, J. M. Theoretical efficiency limits for energy conversion devices. *Energy* **35**,
578 2059–2069 (2010).
- 579 52. Brockway, P. E., Owen, A., Brand-Correa, L. I. & Hardt, L. Datasets for Nature Energy article
580 “Estimation of global final stage energy-return-on-investment for fossil fuels with comparison to
581 renewable energy sources” (University of Leeds Data Repository, 2019). (2019). Available at:
582 doi:linkTBC.
- 583 53. Miller, R. E. & Blair, P. D. *Input-output analysis: foundations and extensions*. (Cambridge University
584 Press, 2009).
- 585 54. Brandt, A. R. & Dale, M. A General Mathematical Framework for Calculating Systems-Scale
586 Efficiency of Energy Extraction and Conversion: Energy Return on Investment (EROI) and Other
587 Energy Return Ratios. *Energies* **4**, 1211–1245 (2011).
- 588 55. Moeller, D. & Murphy, D. Net Energy Analysis of Gas Production from the Marcellus Shale. *Biophys.*
589 *Econ. Resour. Qual.* **1**, 5 (2016).
- 590 56. Lenzen, M. & Treloar, G. J. Endogenising Capital: A comparison of Two Methods. *J. Appl. Input-*
591 *Output Anal.* **10**, 1–11 (2004).
- 592 57. Södersten, C. J. H., Wood, R. & Hertwich, E. G. Endogenizing Capital in MRIO Models: The
593 Implications for Consumption-Based Accounting. *Environ. Sci. Technol.* **52**, 13250–13259 (2018).
- 594 58. Chen, G. Q. & Wu, X. F. Energy overview for globalized world economy: Source, supply chain and
595 sink. *Renew. Sustain. Energy Rev.* **69**, 735–749 (2017).
- 596