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ANALYSIS

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Implications of net energy-return-on-investment for a low-carbon energy transition

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Low-carbon energy transitions aim to stay within a carbon budget that limits potential climate change to 2 °C—or well below—through a substantial growth in renewable energy sources alongside improved energy efficiency and carbon capture and storage. Current scenarios tend to overlook their low net energy returns compared to the existing fossil fuel infrastructure. Correcting from gross to net energy, we show that a low-carbon transition would probably lead to a 24–31% decline in net energy per capita by 2050, which implies a strong reversal of the recent rising trends of 0.5% per annum. Unless vast end-use efficiency savings can be achieved in the coming decades, current lifestyles might be impaired. To maintain the present net energy returns, solar and wind renewable power sources should grow two to three times faster than in other proposals. We suggest a new indicator, 'energy return on carbon', to assist in maximizing the net energy from the remaining carbon budget.

The role of energy in maintaining or improving lifestyles tends to be strong and fundamental, although frequently underestimated[1–4]. A precise accounting of energy requirements is critical to assess accurately the impact of potential transitions to a low-carbon economy. After the Paris Agreement, several global energy-transition scenarios have been presented, and tend to be analysed in terms of gross energy and aimed to maintain past rates of economic growth[5,6]. However, the literature on energy return on investment (EROI) argues the importance of distinguishing between net and gross energy when making judgements about energy and lifestyles[7,8]. Expressed as a ratio, EROI signifies the amount of useful energy yielded from each unit of energy input to the process of obtaining that energy. The lower an energy source's EROI, the more input energy is required to produce the output energy, which results in less net energy available for consumption.

Although there is some debate about the appropriate calculation and boundaries of EROI[9,10], it serves as a reasonable proxy for the biophysical utility of any particular energy source to society. It provides, at least in theory, a more-objective, stable and future-predictive assessment than information about costs and prices, as this is strongly influenced by erratic and short-term factors, such as subsidies, market power, strategic behaviour of suppliers and emotional responses by market participants. The average EROI of an economy's overall energy mix can, therefore, provide an indication of opportunities for economic activity[11].

Here, we analyse low-carbon energy transitions by considering net energy per capita as the basis of lifestyles. By accounting for differences between gross and net energy, we evaluate the potential consequences of a low-carbon energy transition on future lifestyles. This allows us to analyse different energy pathways in combination with optimistic and pessimistic estimates of EROIs in the literature.

Our results indicate that net energy per capita is likely to decline in the future without substantial investments in energy efficiency. To maintain net energy per capita at the current levels, renewable energy sources would have to grow at a rate two to three times that of current projections. We propose an 'energy-return-on-carbon' (EROC) indicator to assist in maximizing the potential net energy from the 2 °C carbon budget.

Illustrating the importance of EROI for lifestyles

To illustrate the economic and welfare importance of EROI, we analyse and compare two hypothetical high- and low-EROI economies. As illustrated in Fig. 1, both economies produce the same 550 EJ of gross energy. This approximates to the level of current global production in International Energy Agency (IEA) world energy balances[12]. The high-EROI economy has an average EROI equal to 20:1, which represents the present state. The low-EROI economy has an average EROI equal to 3:1, a level insufficient to operate societies at the current level of affluence in the global north[13], which might be interpreted as a hypothetical tar sand economy[14] or a severe peak oil scenario. Both economies suffer subsequent (downstream) proportional losses from the transformation and end-use losses of 58% (based on rates of 2011 'rejected energy' in world energy-flow charts[15]). Assuming that both societies first meet their requirements for essentials, such as food and water, which we keep constant at an illustrative value of 100 EJ, we calculate that the low-EROI economy would have less than half (54 EJ versus 119 EJ) the net energy of the high-EROI economy available for consumption and production of all 'non-essential' goods and services. This would have significant implications for lifestyles, and limit the ability to invest energy for future economic growth.

Should the low-EROI society wish to match the quantity of discretionary funding of the high-EROI society (119 EJ), it has, theoretically, three options: (1) increase the gross energy production to 785 EJ [$(523\times3)/(3-1)$], which would be a 43% increase from 550 EJ; (2) improve the end-use energy efficiency in the production and consumption of goods and services from 42% to 60% ($(100+119)/367$) or (3) improve the average EROI from 3 to 20 through technological improvements and investment in higher-EROI energy sources, such as coal. Although these ambitious goals may not be achievable in practice, a lower-level combination of the three types of changes is likely to have compensated for the slowly declining global average EROI of oil and gas experienced in recent

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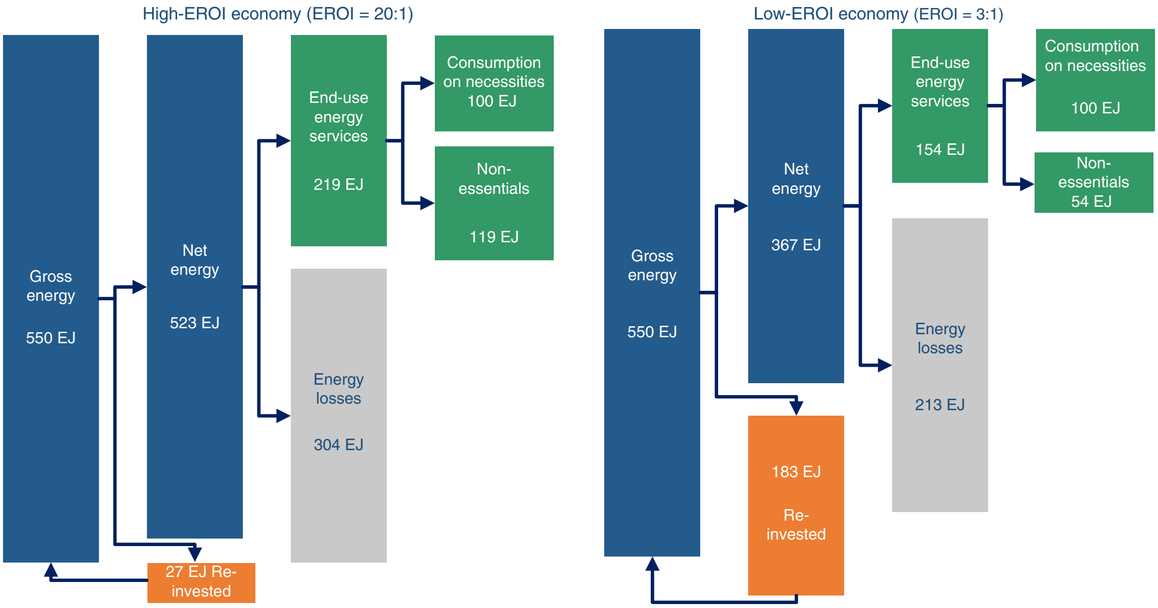

Fig. 1 | Illustrative comparison of high- and low-EROI economies. Blue boxes illustrate the flows of gross to net energy, green boxes illustrate end-use energy services, orange boxes illustrate energy used for reinvestment to produce more gross energy and grey boxes illustrate process energy losses. The two alternatives (high- and low-EROI economies) are hypothetical, aimed to illustrate the impact of two very different EROI scenarios on lifestyles given an end-use consumption on necessities fixed at 100 EJ. The low-EROI economy reinvests a far greater proportion of its gross production for future production than the high-EROI economy. After accounting for downstream energy losses and consumption on necessities, this results in only around half of the net energy being delivered for non-essential energy services. A gross energy production of 550 EJ is roughly consistent with that of the global economy[12], whereas energy losses are based on rates of 2011 'rejected energy' in world energy flow charts[15].

decades[16]. For example, there has been a rapid growth of coal since 2000, which has one of the highest EROI values of current energy options[17]. However, continuation of this strategy, at least without carbon capture and storage (CCS), is incompatible with the goals of the Paris Agreement[18] which require the vast majority of fossil fuels to remain in the ground[19]. The most significant challenge we face may, therefore, not be a declining EROI of fossil fuels itself, but continuing to supply enough net energy as we invest in a new energy system with relatively low net energy yields[20]. Moreover, population forecasts[21] indicate the world population will be approaching 10 billion by 2050, so the remaining fossil fuels will have to be spread among an even greater population. The challenge of a rapid transition to low-carbon energy is therefore twofold: staying within climate change targets while continuing to deliver net energy for the needs of a growing global society.

Analytical approach

Our approach to analysing future net energy returns involves four stages: defining a carbon budget exclusively for energy based on current literature, defining three energy pathway scenarios to 2050, defining 'optimistic' and 'pessimistic' sets of EROI assumptions to capture the range of values in the current literature and the creation of an original, dynamic EROI model to produce net energy projections for the pathway scenarios, and an EROC indicator.

Carbon energy budget. One of the most ambitious energy-transition scenarios published in response to the Paris Agreement is the 2017 joint report *Perspectives for the Energy Transition* by the IEA and the International Renewable Energy Agency (IRENA)[5]. Compared to previous IEA scenarios[22], it utilizes a more stringent probability, >66%, of staying within a 2 °C warming. Defining this carbon budget precisely is challenging, as calculation uncertainty has resulted in a wide variety of estimates, with a probable range of 590–1,240 $GtCO_2$ from 2015 onwards[23]. Moreover, this budget includes emissions from all sources (energy and non-energy). When we focus on energy policy, we need to derive a carbon energy budget that corrects for non-energy emissions. The most significant of these are future emissions from land-use change and industrial processes, such as cement production. The IEA/IRENA study[5] arrives at a carbon energy budget of 790 $GtCO_2$ (Methods gives details of the calculation) and presents a scenario to stay within it, primarily through a strong growth in renewables, improvements in end-use energy efficiency and the deployment of CCS for coal and natural gas.

Energy pathway scenarios. We correct gross energy to net energy for three scenarios to 2050: LCT, a low-carbon transition consistent with >66% probability of limiting warming to 2 °C that uses the IEA/IRENA scenario[5] as a reference; BAU, a business-as-usual scenario based on current trends and CNE, an optimized transition aiming to maintain current levels of net energy per capita. As we use global figures, many countries in the global south wish to grow their energy use per capita. The CNE scenario, therefore, may imply a fall in net energy consumption within the global north. We present per capita results as a proxy for lifestyle implications, which is important given the context of a growing global population. Details of the assumptions in each scenario are provided in Methods.

EROI assumptions. EROI values for different energy sources vary considerably from study to study. A recent meta-analysis[17] attempted to produce mean values of EROIs for thermal and electrical energy sources. However, there is much debate, particularly around EROI values for renewable sources, due to differing perspectives on calculation methods[24] and whether energy costs of storage and intermittency should be accounted for[25–27]. This has led to a range of EROI values for solar photovoltaics (PV) from as low as 0.8:1 (ref. [28]) to over 60:1 (ref. [29]). Respecting the various positions in this debate, we employ two sets of EROI perspectives, 'optimistic' and 'pessimistic', to produce an uncertainty range in our results. The latter perspective includes lower EROI values for biofuels and renewables and a declining EROI of oil and gas, in line with recent trends[17]. More details are provided in Methods.

The relationship of EROI to net energy is non-linear, and consequently its impact can potentially be misjudged, particularly at very high and very low EROI values. To illustrate this, Table 1 also provides the 'net energy percentage', equal to $1-\frac{1}{\mathrm{EROI}}$, to represent more clearly the amount of net energy obtained. The difference between coal and wind for instance—with EROIs of 46 and 18—becomes far less pronounced according to this metric, 98% and 95%, respectively. The net energy percentage begins to reduce rapidly below EROIs of 5:1, so the significance of an EROI below this value is especially great. This non-linear relationship is commonly termed the 'net energy cliff'[30], a concept first attributed to Mearns[31].

EROI figures for thermal fuels are often calculated at the mine mouth, not at the point of use. This makes comparisons with renewables difficult as they supply electricity directly, and for this reason some argue that renewables should be adjusted upwards[24]. Our approach to this problem here is to adjust the EROIs for fossil fuels that are used for electricity generation downwards, based on IEA efficiency percentages for power plants[12]. Utilization of CCS technology will further decrease these net energy returns significantly, although very little research to date has looked at the effect of CCS on EROI. The Intergovernmental Panel for Climate Change (IPCC) special report on CCS[32], however, suggests the capture energy requirements are 16% and 31% for natural gas and coal, respectively, so we produced CCS EROI estimates based on these figures. Although subject to some debate[33,34], an additional proposal to mitigate climate change is bioenergy with carbon capture and storage (BECCS) to produce net negative carbon dioxide emissions. The low EROI of most biofuels before trying to capture and store emissions presents an additional challenge, as the additional energy costs due to CCS would result in at best negligible, and conceivably negative, net energy to society. For this reason, BECCS is not considered in our analysis.

Dynamic EROI model. The relationship between EROI, gross energy and net energy for an individual energy source is represented by equation (1)[35]:

$$\text{Net energy} = \text{gross energy}\left(1-\frac{1}{\mathrm{EROI}}\right) \tag{1}$$

The total net energy delivered to society can be calculated by summing the net energy across all energy sources, as in equation (2):

$$E^{\mathrm{N}} = \sum_{i=1}^{n}\left[Q^{i}\left(1-\frac{1}{\mathrm{EROI}^{i}}\right)\right] \tag{2}$$

Here E^{N} = the net energy delivered to society and Q^{i} = the gross production of energy source i. However, this equation presents a static view of the net energy in society and thus fails to capture the dynamics during a rapidly changing energy transition. Importantly, it overlooks an additional challenge with converting to renewables. The growth rate of solar and wind renewables is limited due to the majority of energy costs being borne upfront in production and installation[36]. If the rate of growth is too fast, this would create a short-term net energy-sink effect. To capture the resulting dynamics, we model net energy supplied to society by separating EROI into operational (maintenance) and investment costs, captured by equation (3):

$$\begin{aligned} E_{t}^{\mathrm{N}} \;=\; & \sum_{i=1}^{n}\left[Q_{t}^{i}-\frac{\alpha Q_{t}^{i}}{\mathrm{EROI}_{t}^{i}}\right.\\ & \left.-\;\frac{(1-\alpha)L^{i}\,\mathrm{Max}\{0, Q_{t}^{i}-Q_{t-1}^{i}+\;Q_{t-L^{i}}^{i}-Q_{t-L^{i}-1}^{i}\}}{\mathrm{EROI}_{t}^{i}}\right] \end{aligned} \tag{3}$$

Table 1 | Comparison of mean EROIs for different energy sources

	Energy source		Optimistic EROI	Optimistic net energy percentage	Pessimistic EROI	Pessimistic net energy percentage
Coal	Thermal		46:1	98	46:1	98
	Electricity		17:1	94	17:1	94
	Electricity with CCS		13:1	92	13:1	92
Oil	Thermal		19:1	95	19:1[a]	95
	Electricity		7:1	85	7:1[a]	85
Gas	Thermal		19:1	95	19:1[a]	95
	Electricity		8:1	88	8:1[a]	88
	Electricity with CCS		7:1	86	7:1[a]	86
Biofuels & waste	Solids	Thermal	25:1	96	25:1	96
		Electricity	10:1	90	10:1	90
	Gases and liquids	Thermal	5:1	80	3:1	67
		Electricity	2:1	50	1.2:1	17
Nuclear			14:1	93	14:1	93
Hydroelectric			84:1	99	59:1	98
Geothermal			9:1	89	14:1	89
Wind			18:1	94	5:1	80
Solar PV			25:1	96	4:1	78
Solar thermal			19:1	95	9:1	89

Thermal EROI values for oil and gas are identical because the data from which they are derived is normally aggregated. Optimistic EROI values are taken from one article[17], except for solar thermal and solar PV. Solar thermal was not included in the meta-analysis, so we use an estimate from the literature[25]. Optimistic values for solar PV are based on the median values that rely on more recent data[29]. There is significant variance in the EROI between each particular biofuel; one study[17] calculate a mean of five, but it is skewed by several large outliers. Biofuels refers to all solid, liquid and gaseous fuels from any biomass source, which has then been split into 'solids' and 'gases and liquids' subcategories to account for the considerably higher EROIs of solid biomass (for example, 25:1 for wood)[42]. Pessimistic EROI values for renewables are adjusted downwards[25] to account for 'buffering' through energy storage. [a]Under pessimistic EROI assumptions, oil and gas follow a trend of −0.357 from a starting value of 35.4 in 1971 (extrapolated from oil and gas EROI trends between 1992 and 2006[17]).

Here $E_t^{\mathrm{N}} =$ the net energy delivered to society at time t, $Q_t^i =$ the gross production of energy source i at time t, $L^i =$ the lifetime of capital of energy source i, $\alpha =$ the proportion of energy costs attributable to operations and maintenance, and $1-\alpha =$ the proportion of energy costs attributable to investment. Energy investment costs in each time period are calculated by summing the growth of an energy source in this period $(Q_t^i - Q_{t-1}^i)$ plus the growth at $t - L^i$, which represents the investment needed to replace the capital that has now reached the end of its lifetime. The sum $(Q_t^i - Q_{t-1}^i + Q_{t-L^i}^i - Q_{t-L^i-1}^i)$ therefore represents the total needed investment, which is subject to the Max{0,·} function as it is only applicable when investment needs are positive. The value of α is typically larger for non-renewable than renewable energy sources, based on reported data[25]. Methods gives more details of the assumptions used in the dynamic EROI model. Historical and projected net energy supply per capita (Npc) is calculated by dividing equation (3) by the population in each time period to give equation (4):

$$E_t^{\mathrm{Npc}} = \frac{E_t^{\mathrm{N}}}{P_t} \tag{4}$$

Here $P_t =$ population at time t. Per capita figures are considered in our analysis to measure the effect on lifestyles in the context of a growing global population. The assumptions used in the dynamic EROI model are summarized in Table 2, and details are provided in Methods.

Model output for energy pathway scenarios

Figure 2 illustrates the historical trend and future projections of net energy supply per capita under the three energy pathway scenarios. Key indicators from the model output are also summarized in Table 3. As we are considering the potential impact on lifestyles under a growing population it is pertinent to focus on the per capita metrics. From 1990 to 2014, the net energy supply per capita rose at around 0.5% per annum, with a particularly high growth seen post-2000 as a result of a boom in coal production. However, under the LCT scenario, there is a strong reversal of this trend, with the net energy supply per capita declining between 24% and 31% from 2014 levels. To maintain or improve lifestyles there would therefore need to be unprecedented improvements in end-use efficiency to reduce the energy demand per capita. If efficiency improvements on this scale are unachievable, the net energy supply per capita will decline and be insufficient to meet demand. The supply of net energy may then become a limiting factor to maintain or improve the lifestyles for a growing global population.

The BAU scenario shows net energy per capita continuing to increase at current rates until 2050. However, due to the continued growth in fossil fuels, the carbon budget for 2 °C will have already been exhausted by 2022. The CNE scenario maintains the net energy per capita roughly constant at 2014 levels. However, this does not necessarily imply stagnation in lifestyles, as there is considerable potential for improvements in end-use efficiency to facilitate this[37]. Over the period 1990 to 2000, net energy supply per capita was rather constant, despite global economic growth over this period. Figure 2d compares the growth of gross solar and wind production in the LCT and CNE scenarios. To achieve a stable net energy supply, the rate of growth of solar and wind renewables would have to grow to a capacity level by 2050 that is 2.2–3.0 times that suggested by the LCT scenario. Table 4 summarizes the change in gross energy for the three scenarios from 2014 to 2050.

Under the LCT and BAU scenarios, we see a widening gap between gross and net production, and the uncertainty range for net energy also increases. The latter is not seen for the CNE scenario, as increased gross production compensates for the lower EROI values. If the pessimistic assumptions are correct, the implication is that 10% less net energy will be delivered in 2050 than if the optimistic assumptions hold. There is thus a strong argument for continued research into the EROI of future energy options.

The results show a trade-off between climate and lifestyles. The LCT scenario sacrifices net energy per capita, whereas the BAU sacrifices climate goals. The CNE scenario attempts to balance both objectives, at the cost of a much more rapid growth in solar and wind. The lower net energy percentages of the LCT and CNE scenarios indicate their less-favourable energy mix from a net energy

Table 2 | Model assumptions

	Energy source		Optimistic EROI assumptions	Pessimistic EROI assumptions	Lifetime (years)	Investment proportion of energy costs ($1-\alpha$)	Operation and maintenance proportion of energy costs (α)
Coal	Thermal		46	46	45	0.086	0.914
	Electricity		17	17	45	0.086	0.914
	Electricity with CCS		9	13	45	0.086	0.914
Oil	Thermal		19	19[a]	35	0.019	0.981
	Electricity		7	7[a]	35	0.019	0.981
Gas	Thermal		19	19[a]	35	0.019	0.981
	Electricity		8	8[a]	35	0.019	0.981
	Electricity with CCS		4	7[a]	35	0.019	0.981
Biofuels & waste	Solids	Thermal	25	25	40	0.003	0.997
		Electricity	10	10	40	0.003	0.997
	Gases and liquids	Thermal	5	3	40	0.003	0.997
		Electricity	2	1.2	40	0.003	0.997
Nuclear			14	14	50	0.168	0.832
Hydroelectric			84	59	75	0.961	0.039
Geothermal			9	9	25	0.900	0.100
Solar PV			25	4	25	0.900	0.100
Solar thermal			19	9	25	0.743	0.257
Wind			18	5	20	0.977	0.023

[a] Under pessimistic EROI assumptions, oil and gas follow a trend of −0.357 from a starting value of 35.4 in 1971 (extrapolated from oil and gas EROI trends from 1992 to 2006[17]).

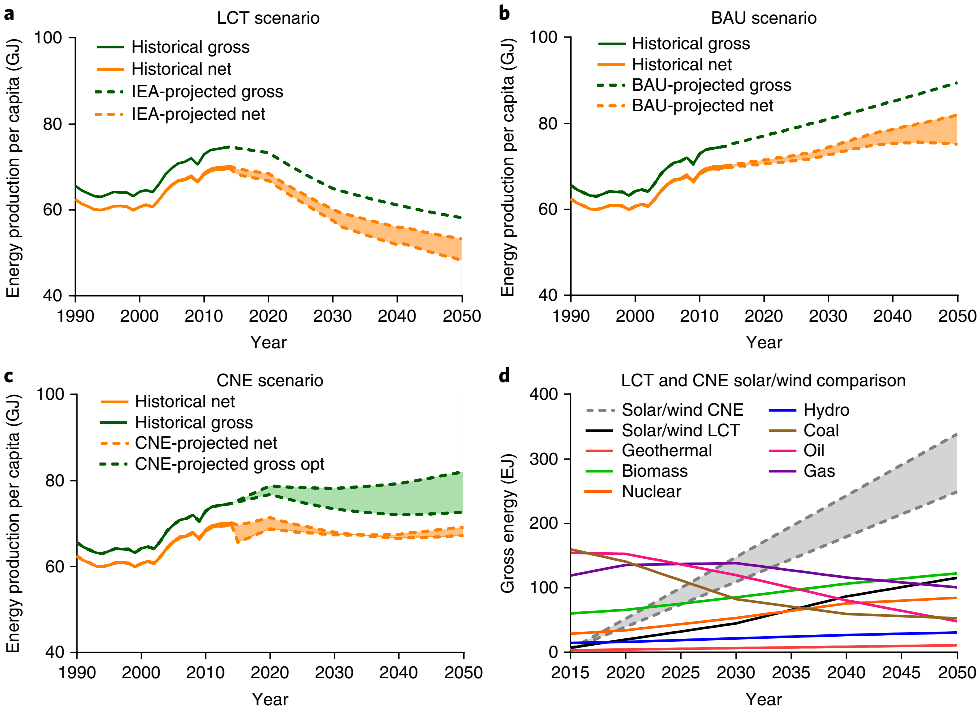

Fig. 2 | Model output. a–c, Gross and net energy production per capita for the LCT scenario (**a**), the BAU scenario (**b**) and the CNE scenario (**c**). **d**, Comparison of gross energy product by energy source between LCT and CNE scenarios. The black line in **d** represents the projected energy production under the LCT scenario of solar PV, solar thermal and wind combined. The grey area represents the comparative growth of these three energy sources in the CNE scenario needed to keep net energy per capita roughly constant. The CNE scenario requires growth of these to be 2–3 times that of the LCT scenario. The shaded area in each of the graphs denotes the uncertainty range between optimistic and pessimistic EROI assumptions. In the CNE scenario, gross energy has an uncertainty range as it is endogenous here, whereas gross energy is exogenous in the LCT and BAU scenarios.

Table 3 | Model output that illustrates a trade-off between stabilizing climate and continuing current lifestyles

Scenario	EROI assumptions	Growth in solar and wind renewables by 2050 (%)	Average net energy per capita 2015–2050 (GJ)	Net energy percentage of gross energy in 2050
2 °C LCT	Optimistic	2,754	60.4	91.5
	Pessimistic	2,754	57.3	82.9
BAU	Optimistic	553	75.8	93.5
	Pessimistic	553	73.2	85.7
2 °C CNE	Optimistic	6,228	68.3	92.5
	Pessimistic	8,500	67.8	84.2

perspective compared to BAU. In 2014, the net energy percentages were 94.0% and 93.3% for the optimistic and pessimistic EROI assumptions, respectively. We see a considerable decline by 2050 for all the scenarios under the pessimistic EROI assumptions.

Under the CNE scenario, growths in solar PV, solar thermal and wind are exogenous model variables that are dependent on the EROI assumptions used. The model output, therefore, produces a range of gross energy for these energy sources. The BAU scenario gross energy is produced by extrapolating trends based on 2005–2014 data.

EROC

Our analysis suggests that net energy is likely to move from an abundant to a scarce resource if effective measures are taken to remain within a 2 °C carbon budget. As in any economic problem of scarcity, efforts should be made to ensure the most-efficient use of resources. We therefore examine the strategy to maximize the net energy obtained from fossil fuels within the constraint of the carbon budget. To achieve this, we propose a measure of EROC (energy return on carbon) that uses a metric of net energy per tonne of CO_2, which allows a comparison of the performance of different energy sources under the constraint of climate change targets. EROC is calculated as [(1 – 1/EROI)/(carbon emission factor)]. The EROC takes into account both the net energy potential of a fossil fuel and its carbon emissions to produce a metric of the fuel's overall utility under climate change policy. Table 5 illustrates this indicator for the combustion of various fossil fuel options. It shows that tar sands and oil shale, for instance, represent an inefficient usage of our carbon budget.

This metric supports the current prioritization of fossil fuel reductions in the order of coal, oil and then gas. Their net energies per $GtCO_2$ are 10.3 EJ, 12.0 EJ and 16.9 EJ, respectively. Gas thus provides a significant 64% more net energy per CO_2 than coal, as the lower carbon content more than compensates for the lower EROI. The EROI of gas would have to fall dramatically to 2.3 for coal to become preferable to gas from a climate perspective. However, an even greater priority should be given to eliminating the exploitation of unconventional sources of oil, which have much lower EROIs than conventional sources[17]. This results in tar sands and oil shale providing only 7–8 EJ $GtCO_2^{-1}$ released. It is clear that investment in such unconventional sources is not a wise strategy from a combined net energy and climate change perspective. Although CCS shows promise to increase considerably the climate efficiency of fossil fuels, more research is required into the full energy costs associated with this technology.

Conclusions

Economic decisions are generally made from a monetary perspective. Adding a biophysical perspective, as we do here, is relevant to assess the gap between needs and the actual options of society.

Table 4 | Changes in gross energy for the three energy pathway scenarios

	Energy source		Gross energy in 2014 (EJ)	Change in gross energy from 2014 to 2050 (EJ)		
				TRA scenario	BAU scenario	CNE scenario
Coal	Thermal		68.5	−40.1	+15.3	−40.1
	Electricity		95.2	−95.2	+70.7	−95.2
	Electricity with CCS		0.0	+24.3	+24.3	+24.3
Oil	Thermal		144.0	−95.8	+33.9	−95.8
	Electricity		10.9	−10.9	−0.5	−10.9
Gas	Thermal		70.7	−2.6	+42.3	−2.6
	Electricity		45.2	−24.7	+38.7	−24.7
	Electricity with CCS		0.0	+12.3	+12.3	+12.3
Biofuels and waste	Solids	Thermal	48.4	0.0	0.0	0.0
		Electricity	4.1	0.0	0.0	0.0
	Gases and liquids	Thermal	4.4	+37.7	+22.4	+37.7
		Electricity	2.3	+25.7	+9.6	+25.7
Nuclear			27.7	+56.9	-14.7	+56.9
Hydroelectric			14.0	+16.7	+16.0	+16.7
Geothermal			3.0	+7.8	+2.2	+7.8
Solar PV			0.7	+29.0	+6.3	+65.1–88.8
Solar thermal			1.3	+40.8	+4.4	+92.0–125.6
Wind			2.6	+41.2	+11.2	+94.5–129.4

In particular, climate externalities are currently not reflected in the cost of fossil fuel energies. One way to signal biophysical differences effectively would be to impose a carbon price[38] that would discourage coal use more than oil, and oil more than gas. Thus, this would provide appropriate incentives to realize the mentioned fuel prioritization in a transition.

Regardless of the fossil fuel strategy, our analysis suggests that a greatly accelerated investment in renewable energies is needed alongside dramatic improvements in energy efficiency if we are to continue to supply enough net energy to match current lifestyles. If these changes are unable to be made, or deemed impracticable, the main conclusion to draw is that the 2 °C target is, in itself, highly unrealistic.

Table 5 | EROC of combusting different fossil fuels

Energy source	EROI	Carbon emission factor[36] ($kgCO_2\,TJ^{-1}$)	EROC ($EJ\,GtCO_2^{-1}$)
Coal	46:1	94.6	10.3
Coal with CCS	9:1	9.5	65.1
Oil	19:1	73.3	12.9
Oil shale	7:1	107.0	8.0
Tar sands	4:1	107.0	7.0
Natural gas	19:1	56.1	16.9
Natural gas with CCS	4:1	5.6	101.9

CCS carbon emission factors are based on capturing 85% of CO_2 emissions, the midpoint of 80–90% range stated in the IPCC special report on CCS[32].

Incidentally, the analysis may even underestimate the challenge and speed of the energy transition needed due to the currently high level of uncertainty in the estimations of both carbon budgets and of non-energy emissions. Particular obstacles to moving away from certain fossil fuels, such as petroleum use in aviation, may further require renewable energy to grow even faster than our projections. The net energy implications are complicated and, as discussed, much debate exists around the EROI values. Our analysis highlights how important it is to assess the net energy return to carbon and what this means for a low-carbon energy transition. These implications warrant further research into net energy issues to narrow the debate.

Methods

Carbon energy budget. The IEA/IRENA report *Perspectives for the Energy Transition*[5] determines a budget of 880 $GtCO_2$ from 2015 as a starting point, which falls in the middle of the range of 590–1,240 $GtCO_2$ from 2015 onwards[23]. From this starting budget, it deducts 90 $GtCO_2$ for industrial process up until 2100. Although other studies suggest that future emissions for land use, land-use change and forestry could mean a further reduction of 138 $GtCO_2$ (ref. [39]), the IEA/IRENA scenario assume these to be net zero over the century due to massive reforestation efforts. Despite this arguably optimistic assumption, in our analysis, to allow comparability, we chose to use the same carbon energy budget as in the IEA/IRENA scenario of 790 $GtCO_2$.

Energy pathway scenarios. Three scenarios of energy pathways until 2050 are considered. In the LCT scenario, gross energy projections for all the energy sources approximate values in the 2017 IEA/IRENA report[5]. In the BAU scenario, gross energy projections for all the energy sources are calculated by extrapolating trends in the ten-year period 2005–2014 from IEA energy production data[12]. Finally, the CNE scenario aims to calculate the minimum rate of growth in solar and wind required to maintain net energy per capita at 2014 levels.

Our interest in the CNE scenario is to measure how much extra investment in renewables, above that seen in the LCT scenario, would be needed to maintain net energy per capita at 2014 levels. Hydroelectric, geothermal, nuclear and biofuels all have limits to their potential for expansion, which makes significant growth beyond that already projected in the 2 °C scenario difficult[40]. There is a limited quantity of appropriate dam sites and potential geothermal locations, and biofuels suffer from land-use competition, which will become an even greater challenge as food production adapts to population growth[41]. Nuclear energy also has technical and resource requirements that are likely to constrain its growth beyond currents plans. In the CNE scenario, we therefore treat growth in hydroelectric, biofuels, geothermal and nuclear power to 2050 as exogenous, based on the LCT scenario, whereas solar and wind growth rates are endogenous, to compensate for any shortages in the net energy supply. Growth in solar and wind is unlikely to be constrained by technical limits, as the technology is already mature enough to be implemented quickly and on a large scale. Wind power, for instance, has an estimated potential of up to 600 EJ (ref. [40]), which is greater than current global energy production from all sources. We thus treat solar and wind as the low-carbon options for any additional growth in energy supply beyond the LCT scenario. Hence, the gross production of coal, oil, gas, biofuels and waste, nuclear, hydroelectric and geothermal are identical for the CNE and LCT scenarios. For the CNE scenario, solar and wind renewables are calculated by minimizing their growth rate subject to the net energy per capita from 2015 to 2050, which equals 36 (the number of years from 2014 to 2050) times 2014 values. This optimization problem is solved by employing a generalized reduced-gradient algorithm.

Historic gross energy production for the period 1990–2014 is obtained from IEA world energy balances[12], and recategorized into the ten energy categories in Table 2: coal, oil, gas, biofuels and waste, nuclear, hydroelectric, geothermal and solar PV, solar thermal and wind. ‘Peat and peat products’ and ‘heat,’ with shares of 0.03% and 0.016%, respectively, of 2013 total energy production, are discounted from the analysis due to their insignificant values.

EROI assumptions. EROI assumptions are summarized in Table 4 along with lifetime and α assumptions. The biofuels-and-waste category is split into two subcategories: solids, and liquids and gases. This is to reflect the much higher EROI estimates of solid biomass such as wood[42] compared to modern liquid biofuels[17]. Coal, oil, natural gas, and biofuels and waste categories are split into thermal and electricity subcategories. EROI values for electricity production are calculated by applying power plant efficiency factors from IEA world energy balances[12], which are 37%, 35%, 44% and 40%, respectively. To date, there is little research on the EROI of fossil fuels with CCS technology. The contribution of CCS to EROIs is therefore approximated by using the capture-energy requirement in the IPCC special report on CCS[32]—16% for natural gas (natural gas combined cycle plant) and 31% for coal (pulverized coal plant), which are cumulative to the electricity-efficiency losses. However, as it is not clear if these percentages represent a complete depiction of all the CCS energy costs, there may be an underestimation of the CCS net energy impact in our results.

Dynamic EROI model. We generated scenarios for future energy pathways to stay within a 2 °C carbon energy budget, while correcting for net versus gross energy delivered to society. Net energy is converted into per capita values to capture the effect of an increasing global population over the time period. Calculations were made using United Nations population data[21] and gross energy from IEA energy production data[12]. The resulting model was run for three energy forecast scenarios (TRA, BAU and CNE), each with the two sets of optimistic and pessimistic EROI assumptions, and thus produced six model outputs in total. Historical IEA energy production data from the IEA for 1971–2014[12] were used.

The proportions of investment and operational energy are based on data by Weißbach et al. (2013)[25]. Although the methodology used to calculate EROIs has been criticized[26,27], this criticism did not pertain to these assumptions. Lifetime assumptions are calculated by taking the mean of the three datasets offered in Table 11 in Tidball et al.[43], except for hydroelectric, as average values were not mentioned in this study. We therefore use a lifetime value of 75 years for hydroelectric, which is consistent with the IEA's range[44] of 50–100.

One factor not explicitly considered in the model is the early retirement of fossil fuel capital, which would potentially lower the net energy returns. However, as operational and maintenance costs are the vast majority of fossil fuel energy investment, this would not be one of the key drivers of the results.

Data availability. The historic energy production data analysed during the current study are available in the OECDiLibrary repository, https://doi.org/10.1787/25186442, and also at www.iea.org/statistics/. Projected energy production data are available from the corresponding author on reasonable request. Population forecast data are available from the United Nations Department of Economic and Social Affairs, https://esa.un.org/unpd/wpp/Download/Standard/Population/.

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Author contributions

L.C.K. and J.C.J.M.v.d.B. jointly designed the study and wrote the paper. L.C.K. performed the model calculations.

Competing interests

The authors declare no competing interests.

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