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Estimation of useful-stage energy returns on investment for fossil fuels and implications for renewable energy systems

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The net energy implications of the energy transition have so far been analysed at best at the final energy stage. Here we argue that expanding the analysis to the useful stage is crucial. We estimate fossil fuels' useful-stage energy returns on investment (EROIs) over the period 1971–2020, globally and nationally, and disaggregate EROIs by end use. We find that fossil fuels' useful-stage EROIs (~3.5:1) are considerably lower than at the final stage (~8.5:1), due to low final-to-useful efficiencies. Further, we estimate the final-stage EROI for which electricity-yielding renewable energy would deliver the same net useful energy as fossil fuels (EROI equivalent) to be approximately 4.6:1. The EROIs of electricity-yielding renewable energy systems, based on published estimations, are found to be higher than the determined EROI equivalent, even considering the effects of intermittency under a range of energy transition scenarios. Results suggest that the energy transition may happen without a decline in net useful energy, countering the view that renewable energy systems cannot replace fossil fuels without incurring a substantial energy penalty.

Whereas energy is fundamental to human societies, only a fraction of the produced energy (gross energy) is available for productive and socially beneficial activities (net energy)[1]. Indeed, some energy needs to be consumed by the energy system itself to convert a primary energy source (for example, crude oil) into a final energy carrier (for example, gasoline)[2]. A common metric to quantify the net energy returns of a given energy system is the energy return on investment (EROI), defined as the ratio of the energy delivered divided by the energy invested in the considered energy system[3]. Tackling the climate change emergency requires a considerable change in the structure of energy systems and to replace fossil fuels by renewable energy sources. Concerns have been raised recently regarding the net energy[4–6] and macroeconomic implications of the energy transition[7–11], because renewable energy systems have been traditionally thought to have substantially lower EROIs than fossil fuel-based energy systems[12]. Recent works have shown that such an understanding may be misguided, due to inconsistent comparisons whereby the primary-stage fossil fuel EROIs (fuels extracted, quantified at the mine or well mouth) are compared to the final-stage renewable energy EROIs (energy carrier delivered to the end user)[13,14].

However, the energy valuable to society is energy at the *useful* stage (for example, light, motion, heat)[15,16], that is, energy after conversion in an end-use device (lamp, engine, heater and so on) to deliver an energy service[17,18]. We therefore assert that the energy valuable to society is the *net useful* energy and that the net energy implications of the energy transition should be analysed at the useful stage. Indeed, final energy-stage analysis overlooks the fact that final energy carriers (for example, electricity, coal and gasoline) have different characteristics and are used with different final-to-useful efficiencies[15,19].

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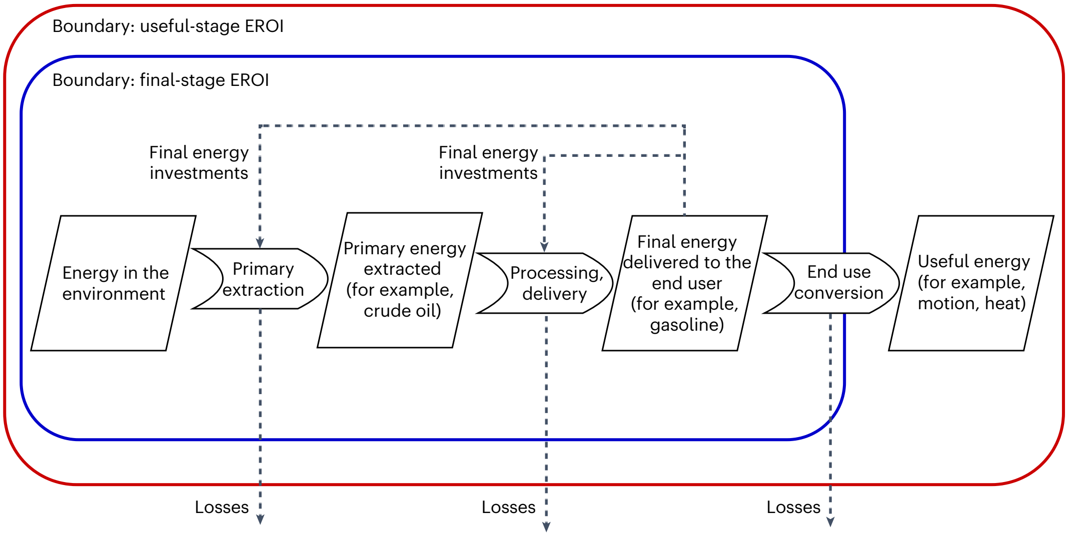

Fig. 1 | Energy stages and analysis boundaries. Diagram of the primary, final and useful energy stages and boundaries used for the final- and useful-stage EROI calculations in this study. The primary stage is sometimes referred to as the point of extraction, or mine mouth (relevant for fossil fuels), and the final stage as the point of use. The useful stage may be regarded as the consumption stage, to the extent that this stage captures the efficiency with which the final energy is consumed and contributes to the delivery of an energy service.

Therefore, two energy systems with the same final-stage EROI may deliver very different amounts of net useful energy. Thus, we expand previous work[14] to estimate the useful-stage EROIs of fossil fuels for different end uses (1971–2020), both globally and nationally (153 regions). Such estimates allow us to assess, for different end uses, the final-stage EROI for which electricity-yielding renewable energy systems would deliver the same amount of net useful energy as fossil fuels (that is, the final-stage EROI equivalent). When expanding the analysis to the useful stage, we find that fossil fuel EROIs considerably drop, from an average of 8.5:1 (final stage) to 3.5:1 (useful stage) at the global level in 2020. Additionally, results show that reaching an EROI ratio of 4.6:1 (the denominator 1 is implicit in the rest of this article) would be sufficient for electricity-yielding renewable energy systems to deliver the same amount of net useful energy as fossil fuels. Comparing this EROI equivalent value to the EROIs reported in the literature indicates that at the useful stage, electricity-yielding renewable energy systems present on average higher net energy returns than traditional fossil fuel-based systems, even considering the effects of intermittency. Such findings contradict the conventional narrative, according to which the energy transition will imply a decrease in the net energy available, and suggest instead that renewable energy systems may deliver sufficient net useful energy to provide decent living standards for all.

Analytical approach

There are three relevant energy conversion stages. First, the primary energy stage refers to energy as extracted from the environment (for example, crude oil). Second, the final energy stage refers to energy carriers delivered to the end user for consumption (for example, gasoline or electricity). Third, the useful stage refers to the energy actually available to the end user to deliver an energy service after conversion in an end-use device (for example, the motion of a car)[18,20]. Analysis at the useful stage is gaining importance due to the energy transition (for example, ref. 21), as the effects of electrification and of the shift towards renewable energy on efficiency may be considerable[19]. Figure 1 shows the three energy stages and the boundaries used for the final- and useful-stage EROI calculations (equations (1) and (2)).

The first part of this work builds on previous work by Brockway et al.[14], which estimated global final-stage EROIs for fossil fuels using data from the International Energy Agency (IEA) Extended World Energy Balances (EWEB) and from the Exiobase Multi-Regional Input Output model[22]. We expand this work in two main directions. First, by using a recently developed Multi-Regional Physical Supply Use Table (MR-PSUT) framework[23,24] and applying it to the IEA's EWEB, we are able to determine fossil fuel final-stage EROIs over the time period 1971–2020 for a wide range of energy products, at the global and national levels. Second, using a recently developed country-level primary–final–useful energy and exergy database[25] enables us to determine the average final-to-useful efficiencies for each energy product, both at the economy-wide and end-use (for example, low-temperature heating, mechanical drive and so on) levels. Then, we are able to determine fossil fuel useful-stage EROIs for each end use. We define the final-stage EROI as:

$$\mathrm{EROI_f} = \frac{\text{Final energy output}}{\text{Final energy invested}}, \tag{1}$$

and the useful-stage EROI as:

$$\mathrm{EROI_u} = \frac{\text{Useful energy output}}{\text{Final energy invested}}, \tag{2}$$

which can therefore be expressed as:

$$\mathrm{EROI_u} = \eta \mathrm{EROI_f}, \tag{3}$$

where η is the average final-to-useful efficiency with which a given energy product is used, either economy-wide or for a particular end use. A few clarifications on the calculated EROIs are noteworthy: (1) the energy output (numerator) is expressed in gross energy terms and hence includes the output that would need to be reinvested in the energy sector (gross EROI[14,26]), (2) losses in transportation and distribution are modelled as decreasing the final energy output (Methods) and (3) energy investments include energy self consumption when reported in the EWEB, such as gasoline produced in a refinery and used in situ by the refinery, as opposed to external measures of energy returns, which subtract self consumption from the energy output[26].

In this work, EROIs are calculated including both direct energy requirements (energy use in situ by the fossil fuel industry) and indirect energy requirements (energy use in the fossil fuel industry supply chain). Direct energy requirements are calculated using the MR-PSUT

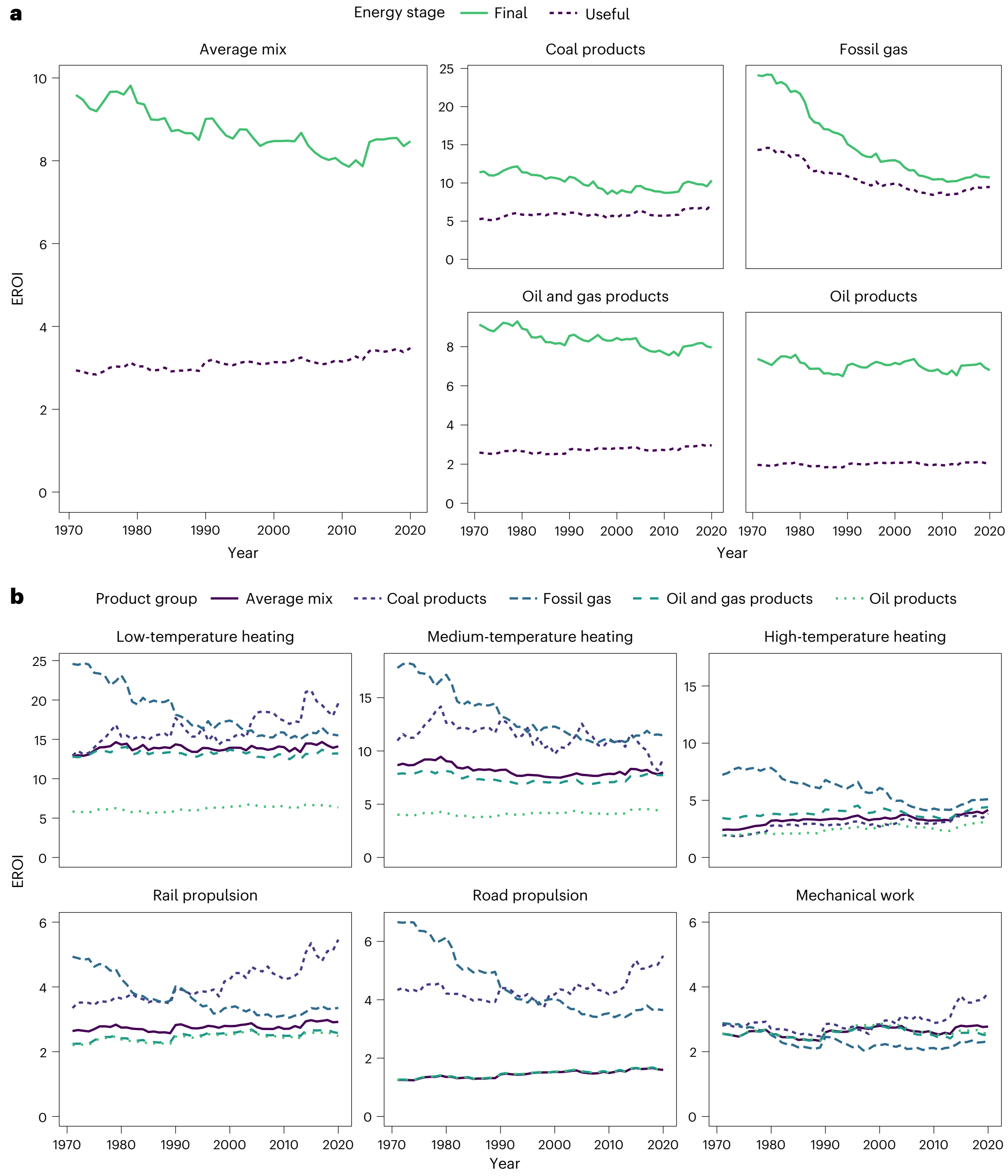

Fig. 2 | Fossil fuel EROI values. a, Final- and useful-stage average EROI by fossil fuel group at the global level. **b**, Useful-stage EROI by end-use category by fossil fuel group at the global level. Calculations consist of a weighted average of fossil fuels used as fuels, electricity and heat. This explains the non-null value for coal products used in road propulsion, which represents coal products used in the form of electricity for road propulsion (that is, in electric vehicles).

applied to the IEA's 2022 EWEB for the period 1971–2020, and indirect energy requirements are calculated using a hypothetical extraction method[27,28] in combination with Exiobase[22,29]. Energy requirements due to fossil fuel industry capital investments (for example, equipment, buildings, infrastructure) are not quantified in this analysis as the gross capital formation final demand vector is not available by industry of consumption in Exiobase. The fossil fuel EROI values we find are therefore an upper bound excluding capital investments, making our results conservative. As we use yearly energy flows (annual-flow framework) instead of energy flows over the lifetime of an installation, estimated EROIs may be considered a power return on investment[30].

In the second part of this work, we determine the final-stage EROI equivalent for which electricity-yielding (implicit in the rest of this article) renewable energy systems (hydropower, wind power, solar photovoltaics and concentrated solar power) would deliver the same amount of net useful energy as fossil fuels. The variation in the net useful energy available Δe_u resulting from investing one unit of final energy in a renewable energy technology instead of in fossil fuel energy can be expressed as:

$$\Delta e_u = e_{u,re} - e_{u,ff}, \tag{4}$$

where $e_{\mathrm{u,re}}$ and $e_{\mathrm{u,ff}}$ refer, respectively, to the net useful energy obtained when investing one unit of final energy in the renewable energy technology and fossil fuel considered. Using equation (2), one can express the net useful energy output for one unit of final energy invested for any energy system as:

$$\begin{aligned} e_{\mathrm{u}} &= \mathrm{EROI}_{\mathrm{u}} - e_{\mathrm{u,invested}} \\ &= \mathrm{EROI}_{\mathrm{u}} - \eta_{\mathrm{es}} e_{\mathrm{f,invested}} \\ &= \mathrm{EROI}_{\mathrm{u}} - \eta_{\mathrm{es}}, \end{aligned} \tag{5}$$

where $e_{\mathrm{u,invested}}$ stands for the useful energy invested, $e_{\mathrm{f,invested}}$ for the final energy invested (and is equal to unity) and η_{es} for the average final-to-useful efficiency with which final energy is used by the energy system. Then, if we assume that renewable energy technologies need to be ultimately sustained using energy from renewable energy technologies themselves, $e_{\mathrm{u,re}}$ can be expressed as:

$$\begin{aligned} e_{\mathrm{u,re}} &= \mathrm{EROI}_{\mathrm{u,re}} - \eta_{\mathrm{elec}} \\ &= \mathrm{EROI}_{\mathrm{f,re}} \eta_{\mathrm{elec}} - \eta_{\mathrm{elec}}, \end{aligned} \tag{6}$$

where $\mathrm{EROI}_{\mathrm{f,re}}$ and $\mathrm{EROI}_{\mathrm{u,re}}$ refer to the final- and useful-stage EROI of renewable energy technologies, respectively, and η_{elec} to the average final-to-useful efficiency of using electricity. Next, $e_{\mathrm{u,ff}}$ can be expressed as:

$$e_{\mathrm{u,ff}} = \mathrm{EROI}_{\mathrm{u,ff}} - \eta_{\mathrm{ff}}, \tag{7}$$

where η_{ff} refers to the average final-to-useful efficiency of using fossil fuel-based carriers. (The alternative assumption that renewable energy technologies are manufactured with fossil fuels and the methodology used to determine η_{elec} and η_{ff} can be found in Methods.) Then, we determine the final-stage EROI equivalent $\mathrm{EROI}_{\mathrm{f,eq}}$ for which renewable energy systems would deliver the same amount of net useful energy as fossil fuels (that is, null Δe_{u}), as:

$$\mathrm{EROI}_{\mathrm{f,eq}} = \frac{\mathrm{EROI}_{\mathrm{u,ff}} - \eta_{\mathrm{ff}} + \eta_{\mathrm{elec}}}{\eta_{\mathrm{elec}}}. \tag{8}$$

We also estimate the equivalent EROIs by end-use category (Methods show the adaptation by end-use category of equation (8)). Then we compare the EROI equivalent values obtained with the EROI values reported in a recent literature review and harmonization[31] for wind power and solar photovoltaics (PV), which are expected to be the prominent future renewable energy technologies[32,33]. (Supplementary Information Section 4 explains the methodology ensuring consistency of the comparison.) Last, we adjust the comparison for the effects of intermittency by considering the storage requirements and forecasted curtailment (voluntary reduction of renewable energy production in times of excess supply) for a range of energy transition scenarios covering the European Union[34], France[35], the United Kingdom[36] and the United States[37] (Methods).

Some caveats should be noted regarding this comparison. First, the calculations conducted here use an annual-flow framework, whereas the literature-sourced EROIs use a process-based framework (life-cycle analysis approach). However, the fact that the energy requirements of capital investments in the fossil fuel industry are excluded from our analysis mitigates that caveat. Indeed, the use of an annual-flow framework may distort the results when the energy requirements of capital investments are accounted for (particularly in the case of an industry that is not in a steady state, for which industry-scale energy flows will account for the industry growth or decline[30]). Second, the literature-sourced EROIs, which use process-based analysis, may yield underestimated energy requirements due to truncation errors[38,39]. Further studies on renewable energy systems adopting a hybrid life-cycle analysis (LCA) would be needed to conduct a more consistent comparison; Gamarra et al.[40] finds, for instance, an increase between 13% and 33% in energy use when moving from a standard to a hybrid LCA.

Throughout the main paper, the EROIs we estimate consist of a weighted average of all fossil usage, whether used as fuels, electricity or heat. Results considering only fossil fuels used as fuels (for example, gasoline, gas) are shown in Extended Data.

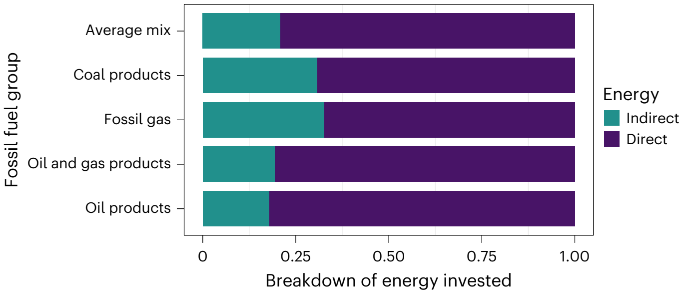

Fig. 3 | Final energy requirements breakdown. Average (1995–2015) breakdown of final energy requirements in terms of direct (energy use in situ) and indirect energy (energy use by the supply chain) requirements by fossil fuel group, at the global level.

Fossil fuels' useful-stage EROI

Figure 2 shows the final- and useful-stage EROIs obtained at the global level for fossil fuels over time, both economy-wide (Fig. 2a) and by end-use category at the useful stage (Fig. 2b). (Extended Data Fig. 1 shows the equivalent graph considering only fossil fuels used as fuels). A few findings can be drawn from this figure. First, Fig. 2a shows that there is a considerable drop in fossil fuel EROIs when moving from the final to the useful stage, which is due to the low average final-to-useful efficiencies with which fossil fuels are used in society. Indeed, the average fossil fuel mix declines from approximately 8.5 at the final stage to approximately 3.5 at the useful stage in 2020, although the decline is much more moderate in the case of fossil gas (from 10.7 at the final stage to 9.5 at the useful stage). Supplementary Fig. 1 shows the useful-stage EROIs obtained for a selection of countries.

Second, and as a consequence, the useful-stage EROIs of fossil fuels are much lower than the final-stage EROIs reported in the literature. Indeed, we find an average global value in 2020 of approximately 3.5 for the average fossil fuel mix, 9.5 for fossil gas, 7.2 for coal products, 3.0 for oil and gas products and 2.0 for oil products. Further, Fig. 3 shows that the energy requirements are primarily due to direct energy requirements (energy use in situ), with indirect energy (energy use by the supply chain) accounting for a share ranging from 18% (oil products) to 33% (fossil gas) of energy requirements.

Third, whereas final-stage EROIs have moderately decreased over time (approximately from 9.6 in 1971 to 8.5 in 2020), useful-stage EROIs may have slightly increased for the average fossil fuel mix (from 2.9 from 3.5), coal products (from 5.3 to 7.2) and oil products (from 1.96 to 2.04). Only for fossil gas can one observe a clear decrease in useful-stage EROIs over time (from 14.3 to 9.5). These trends are due to the effect of increasing final-to-useful efficiencies offsetting the decrease in final-stage EROIs. Such findings contradict the view according to which fossil fuels have high, although rapidly decreasing, net energy returns, which may be derived from a primary energy stage analysis (for example, refs. 41–44).

Last, Fig. 2b shows that the useful-stage EROIs differ considerably across end-use categories. Energy returns are particularly high for heating end uses (particularly, low- and medium-temperature heating; 14.1 and 8.0 in 2020, respectively) and much lower for mechanical

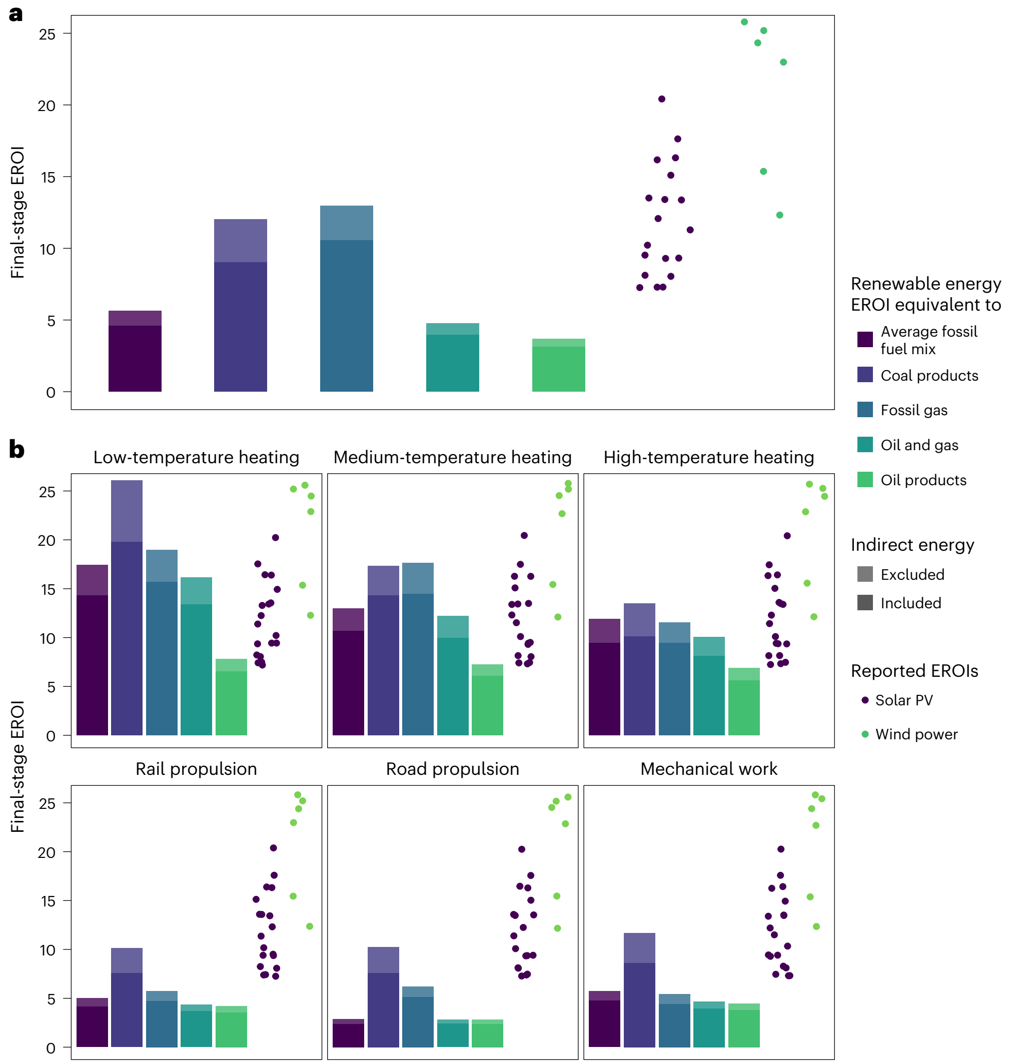

Fig. 4 | Renewable energy EROI equivalent. a,**b**, Final-stage EROI equivalent calculated for 2020 (that is, the value above which renewable energy systems would deliver more net useful energy than fossil fuels) at the global level alongside literature-sourced EROIs (from ref. 31) of solar photovoltaics (PV) and wind power economy-wide (**a**) and by end-use category (**b**). Dark shades correspond to the EROI equivalent when indirect energy requirements are included in fossil fuels' EROI calculations. Light shades correspond to the EROI equivalent when indirect energy requirements are excluded. Calculations consist of a weighted average of fossil fuels used as fuels, electricity and heat.

end uses, such as road propulsion and mechanical work (1.6 and 2.8 in 2020, respectively). The difference in EROIs between end uses is due to (1) higher average final-to-useful efficiencies for heating end uses than for mechanical end uses and (2) a very different fossil fuel mix across end uses, with high EROI fossil gas accounting for a much higher share of fossil fuel use in heating end uses than in mechanical end uses. Conversely, low-EROI oil products account for a very high share of fossil fuel use in mechanical uses (particularly, road transportation).

Implications for renewable energy systems

Figure 4 shows the final-stage EROI equivalent values for which renewable energy systems would deliver more net useful energy than fossil fuels in 2020, alongside the literature-sourced EROIs of solar (PV) and wind power. (Extended Data Fig. 2 shows the equivalent figure considering only fossil fuels used as fuels.)

When including indirect energy requirements, Fig. 4a shows that the EROI equivalent is as low as 4.6 for the average fossil fuel mix, 9.0 for coal products, 10.6 for fossil gas, 4.0 for oil and gas products and 3.1 for oil products. Figure 4b shows that the EROI equivalent is very dependent on the end use considered, much higher for heating end uses (as high as 14.3 and 10.7 for low- and medium-temperature heating, respectively) than for mechanical end uses (as low as 4.7 and 2.4 for mechanical work and road transportation, respectively). Extended Data Fig. 3 shows that only a minor variation occurs in the EROI equivalent values when changing the origin of manufacturing energy assumption (Methods), and Extended Data Fig. 4 shows the evolution of the EROI equivalent values over time. Figure 4a also shows that the literature-sourced EROIs of renewable energy technologies are, in most cases, higher than the economy-wide EROI equivalent. For the average fossil fuel mix, oil and gas products and oil products, even the lowest literature-sourced EROI for both wind power and solar PV is higher than the EROI equivalent. For coal products and fossil fuels, over half of the solar PV literature-sourced EROIs are higher than the EROI equivalent, and all the wind power literature-sourced EROIs are higher than the EROI equivalent (in both cases, when indirect energy is included in the determination of the EROI equivalent). Supplementary Fig. 2 shows that the main result remains valid when comparing the estimated EROI equivalent with the EROI estimation for solar PV and wind power by de Castro and Capellán-Pérez[45]. These findings suggest that on average, renewable energy systems currently deliver more

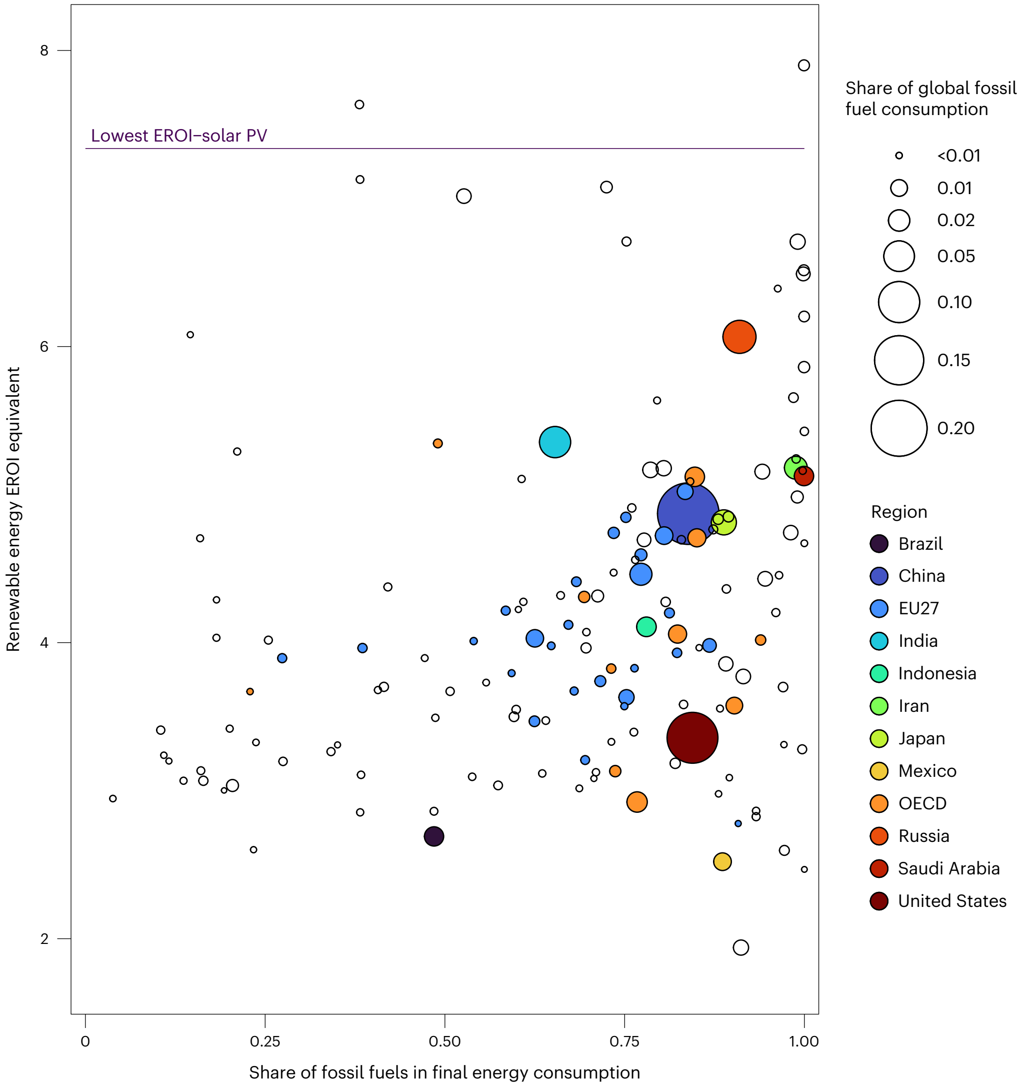

Fig. 5 | National-level EROI equivalent for the average fossil fuel mix. National-level final-stage renewable energy EROI equivalent (average 2000–2020) to the average fossil fuel mix (*y* axis) alongside the share of final energy consumption from fossil fuel origin in 2020 (*x* axis). The solid line represents the lowest of the literature-sourced EROIs (from ref. 31) for solar photovoltaics (PV) (the value for wind power (12) is outside the scale of the graph). Median values for solar PV and wind power stand at 11.4 and 23.6, respectively, and are outside the scale of the graph. The size of the dots are a function of the share of each country's global fossil fuel consumption. Calculations consist of a weighted average of fossil fuels used as fuels, electricity and heat. Republic of Congo, Uzbekistan and North Korea are outliers and outside the scale of the graph. EU27, European Union (27 members, excluding UK); OECD, Other members of the Organisation for Economic Co-operation and Development.

net useful energy per unit of final energy invested than fossil fuels. Figure 4b shows, however, that the results are highly dependent on the end use considered, with the EROI equivalent reaching high values for heating end uses (particularly for low-temperature heating).

Next, Fig. 5 shows the average final-stage EROI equivalent in each country alongside the country's share of fossil fuel use in final energy consumption. In addition, the lowest value of literature-sourced EROIs is shown as solid line for solar PV (the value is 12 for wind power and outside the scale of the graph). The figure shows that the lowest literature-sourced EROI for solar PV and wind power are higher than the EROI equivalent values calculated for almost all countries. Therefore, renewable energy can be expected to return more net useful energy than fossil fuels in almost all countries (with the caveat that the final-stage EROIs of renewable energy are not determined for each country but taken from the existing literature). Extended Data Fig. 5 shows with the equivalent graph broken down by fossil fuel group that this situation is mostly due to the low EROI equivalent values for oil products—the values are higher for coal products and fossil gas.

Whether the energy requirements of dealing with intermittency should be included in EROI calculations has been heavily discussed[46–48]. Such energy requirements are a feature of the broader energy system and cannot be ascribed to a single technology[47,48] and have so far been excluded intermittency from the analysis. However, we recognize that the implications of intermittency may be substantial, and therefore, we quantify these effects using a range of published energy transition scenarios covering the European Union[34], France[35], the United Kingdom[36] and the United States[37] (two scenarios by region). To do so, we estimate the curtailment and storage fractions implied by each energy transition scenario, which stand for the fraction of renewable energy output (from solar PV and wind power) that needs to be curtailed and stored, respectively. Table 1 shows the curtailment and storage fractions obtained for each scenario. The approach taken is conservative as we ascribe storage requirements exclusively to renewable energy technologies (Methods).

Figure 6 shows that for all the energy transition scenarios considered, the results are robust to the consideration of the effects of

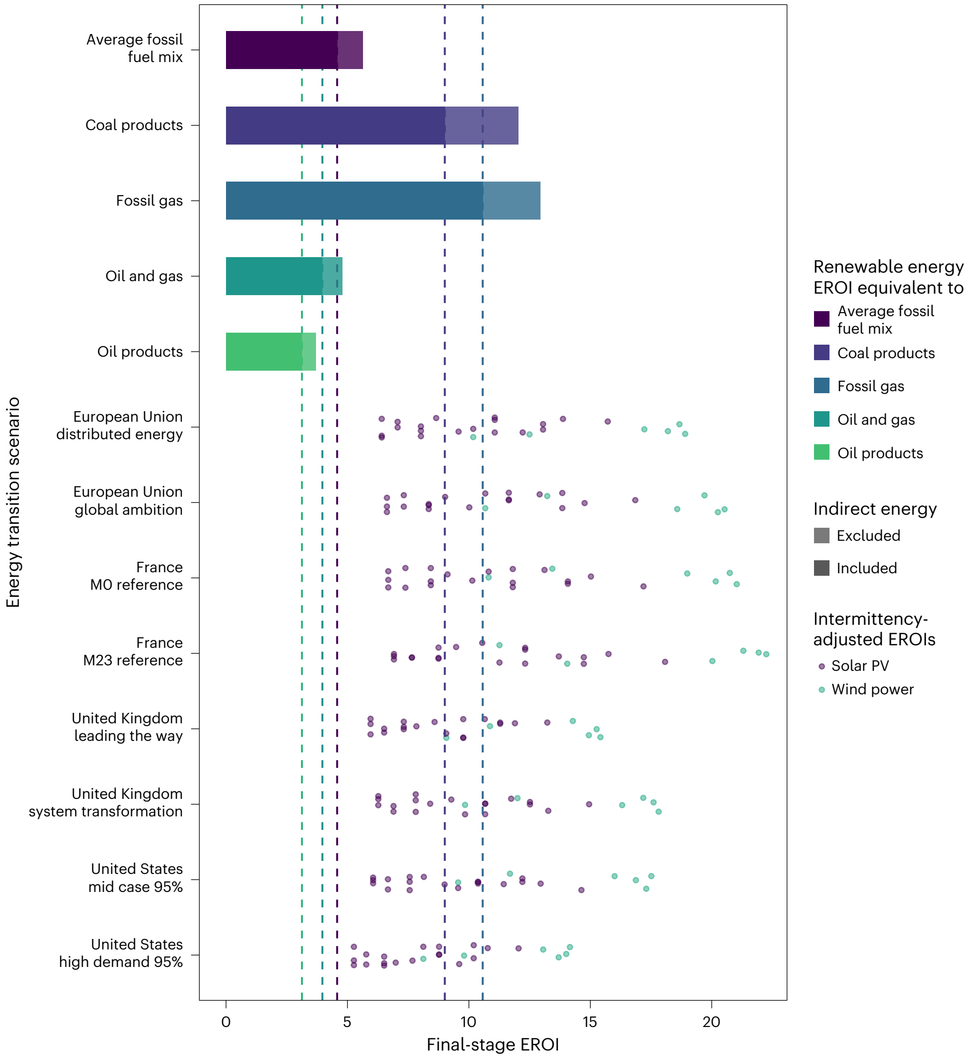

Fig. 6 | Effects of intermittency on renewable energy EROI. Final-stage EROI equivalent calculated for 2020 (that is, the value above which renewable energy systems would deliver more net useful energy than fossil fuels) at the global level alongside the literature-sourced EROIs (from ref. 31) for solar photovoltaics (PV) and wind power, adjusted for the effects of intermittency according to different low-carbon energy transition scenarios. Dark shades correspond to the EROI equivalent when indirect energy requirements are included in fossil fuels' EROI calculations. Light shades correspond to the EROI equivalent when indirect energy requirements are excluded. Calculations consist of a weighted average of fossil fuels used as fuels, electricity and heat.

Table 1 | Curtailment and storage fractions obtained for each energy transition scenario analysed

Region	Scenario	Curtailment (%)	Storage (%)
European Union	Distributed energy	3	14.7
European Union	Global ambition	3	9.9
France	M0–reference	3.1	8.6
France	M23–reference	1.1	6.7
United Kingdom	Leading the way	0.1	30.0
United Kingdom	System transformation	2.4	18.8
United States	Mid case	7.0	16.6
United States	High demand	14.2	24.8

The curtailment fractions for EU scenarios are assumptions, as no data were available.

intermittency, which are moderate. Indeed, the intermittency-adjusted literature-sourced EROIs remain higher than the EROI equivalent above which renewable energy systems return more net useful energy than the average fossil fuel mix. This is, however, not the case when looking specifically at fossil gas and coal products, particularly for solar PV (the EROIs of wind power remain higher than the EROI equivalent values in most cases and scenarios). The renewable energy EROIs decline particularly in the case of the US 'High Demand' scenario[37], which presents a storage and curtailment fraction of 24% and 14%, respectively. This scenario, which combines a high increase in electricity demand with a 95% decarbonization of the power sector and no deployment of emergent technologies, stands however on the high end of storage and curtailment requirements, as shown in Supplementary Fig. 3 and Supplementary Table 4).

Overall, the findings obtained contradict the view that the energy transition will imply a decrease in the net energy available to society.

Further considerations

A few caveats and limitations are worth mentioning. First, the energy transition may entail a different composition of end-use devices than the ones we assumed. For instance, a quick uptake of heat pumps may substantially increase the average final-to-useful efficiency of electricity. As an example, Extended Data Fig. 6 shows how the final-stage EROI equivalent of renewable energy systems decreases to a value of 2.2 under the assumption that heat pumps will replace low and medium-temperature (up to 100° C) heating processes (except cooking).

However, there is a trade-off between increased efficiency and energy investments, as switching to more efficient end-use devices and electrifying end uses may entail additional (up-front) energy requirements. Analysing potential synergies between the transition to a renewable energy system and the uptake of more efficient end-use devices is essential to fully capture the net useful energy implications of the energy transition.

Second, the present analysis is static and does not take into consideration the dynamic effects of the energy transition. Renewable energy systems require much larger up-front energy investments than traditional fossil fuel systems (for which the operational energy requirements are much higher). Dynamic effects may therefore result in a situation in which the net useful energy available to society temporarily drops as energy investments in the energy system take place and then recover once the majority of investments are done[5,6]. Hence, this study only provides insights on the net useful energy implications of the energy transition in the long term, once the up-front investments have been made. For example, the literature-sourced EROI values we use suggest energy payback times in the range 0.7–3.1 and 0.9–1.9 years for solar PV and wind power, respectively. However, we note that the results of our study suggest that the energy payback time may be lower when quantified at the useful stage (Methods). Extended Data Fig. 7 shows that at the useful stage, the energy payback time decreases substantially (by 23%) when substituting the average fossil fuel mix.

Third, the future evolution of the EROI of renewable energy technologies will be crucial. Whereas some studies have argued that their energy returns are likely to decrease over time as the best locations are used first[49,50], technological factors can also play an important role in offsetting such effects[51]. For instance, the capacity factors of wind turbines and efficiencies of solar modules have substantially increased in recent years[52,53]. A consideration of these effects is crucial for further work that attempts to dynamically assess the net energy implications of the energy transition.

Conclusion

This work has shown that the EROI of fossil fuels drops considerably when moving from a final stage (approximately 8.5) to a useful stage analysis (approximately 3.5). The low overall EROI value at the useful stage, however, hides large differences across fossil fuel groups and end uses, with average useful stage energy returns being much higher for heating compared with mechanical end uses. In addition, we find that fossil fuel useful-stage energy returns have remained fairly constant on average over time (except for fossil gas) and may even have slightly increased. Such findings contradict the conventional narrative according to which fossil fuels present very high, although rapidly decreasing, energy returns.

Next, we find that the EROI equivalent value for which electricity-yielding renewable energy systems deliver the same net useful energy as fossil fuels is as low as 4.6, due to the substantially higher final-to-useful efficiency of electricity compared to those of fossil fuel-based energy carriers. This value is, however, highly variable across the fossil fuels and end uses considered. We also find that most literature-sourced EROI values for electricity-yielding renewable energy technologies are higher than the EROI equivalent we have calculated, even when adjusting the values for the implications of intermittency using a wide range of energy transition scenarios. This result suggests that renewable energy may deliver more net useful energy than their fossil fuel counterparts for the same amount of final energy invested.

Our study has important implications. First, most energy-economy models that adopt a net energy perspective may find overly pessimistic implications of the energy transition by overlooking the effects of the difference in final-to-useful efficiencies across energy carriers, which strongly favour the energy returns of electricity-yielding renewable energy technologies. In some cases, primary-stage EROI values for fossil fuels are even mixed with final-stage values for renewable energy. Conducting the analysis at the useful energy stage appears crucial to understand fully the net energy and economic and social implications of the energy transition.

Second, our results suggest that renewable energy systems have high enough energy returns to allow the energy transition to happen without a long-term decrease in the net useful energy delivered to society, even accounting for the implications of intermittency. Further work conducting a dynamic analysis would be needed to assess the short-term implications of the energy transition. Considered alongside recent literature on the energy requirements of providing decent living standards[54–58], these findings suggest that renewable energy systems can provide sufficient net useful energy to allow everyone to have decent living standards. However, identifying ambitious mitigation pathways ensuring a quick phase-out of fossil fuels while meeting decent living standards for all remains an urgent challenge.

Methods

Calculation of fossil fuels' final-stage EROIs

From the International Energy Agency's (IEA) Extended World Energy Balances (EWEB), we construct a Physical Supply Use Table (PSUT) framework[23] (for calculations at the global level) and a Multi-Regional Physical Supply Use Table (MR-PSUT) framework[24] (for calculations at the regional level). Such frameworks represent the Energy Conversion Chain in terms of physical energy flows, from the primary extraction of energy resources to the delivery of final energy carriers to end-use sectors. The set of basic matrices that constitute these frameworks are the resource matrix R, which represents the primary extraction of energy, the use matrix **U**, which represents the use of energy products by each energy industry, the supply matrix **V**, which represents the supply of energy products by each energy industry, and the final demand matrix **Y**, which represents the final demand of energy carriers by end-use sector (for example, road, iron and steel and so on). The vectors of total output by industry **g** and of total output by product **q** stem directly from this set of matrices and are defined, respectively, as the sum across industries of the **V** matrix and of the sum across energy products of the **R** and **V** matrices. Previous work by Heun et al.[23] and Aramendia et al.[24] provides further clarification on the PSUT structure and on subsequent calculations.

Then, input–output matrices are specified following the industry technology assumption, which is the most appropriate for describing the energy industry, due to numerous cases of joint and by-production[59]. Particularly, we define the set of matrices shown in Table 2.

The next step is to determine the vector of final energy intensities by energy industry, that is, the consumption of final energy required for each energy industry to deliver one unit of energy output. To do so, we split the use matrix **U** in its feedstock component $\mathbf{U}_{\mathrm{feed}}$ (representing energy products used for transformation processes by industry) and its energy self-consumption component $\mathbf{U}_{\mathrm{eiou}}$ (representing energy products used for energy purposes by the energy industry).

Then, we determine the vector of final energy consumption by unit of energy output (each coefficient standing for a given energy industry), as:

$$\mathbf{e}_{\mathrm{eiou}} = \hat{\mathbf{g}}^{-1}(\mathbf{U}^{\mathrm{T}}_{\mathrm{eiou}}\mathbf{i}), \tag{9}$$

where the hat notation refers to a diagonalized vector, for example, a matrix with coefficients in the diagonal equal to the vector's coefficients and coefficients outside the diagonal equal to zero, and where **i** refers to a column vector filled with ones. Next, we determine the vector of final energy requirements for the production of one unit of each energy product as:

$$\mathbf{m}^{\mathrm{T}} = \mathbf{e}^{\mathrm{T}}_{\mathrm{eiou}}\mathbf{D}(\mathbf{I}-\mathbf{A})^{-1}, \tag{10}$$

Table 2 | Input–output matrices definition and coefficients meaning

Matrix definition	Matrix name	Matrix coefficients meaning
$\mathbf{Z} = \mathbf{U}\widehat{\mathbf{g}}^{-1}$	Direct requirement matrix (product-by-industry)	Coefficient (*k*, *l*) represents the needed input of product *k* to produce one unit of output of industry *l*.
$\mathbf{D} = \mathbf{V}\widehat{\mathbf{q}}^{-1}$	Market shares matrix	Coefficient (*k*, *l*) represents the share of product *l* by industry *k* in total supply of product *l*.
$\mathbf{A} = \mathbf{ZD}$	Direct requirement matrix (product-by-product)	Coefficient (*k*, *l*) represents the directly (excluding supply chain) needed input of product *k* to produce one unit of product *l*.

Matrices' names, definitions and equations are taken from Aramendia et al.[24].

where $^{\mathrm{T}}$ stands for the transpose of a vector or matrix. Then the EROI for each energy product is simply calculated as the inverse of the coefficient corresponding to the given product in the vector **m**. These calculations are conducted alike both when using the global PSUT framework (single world region) and the MR-PSUT framework, yielding in the first case the global final-stage EROIs by energy product and in the second case the final-stage EROIs for the manufacture of a given product in a given country (in the multi-regional framework, the names of energy products are specified according to the region of production). Next, we aggregate these EROIs to determine average values for five fossil fuel groups (average fossil fuel mix, coal products, oil products, fossil gas and oil and gas products) using the shares of use of each energy product within each fossil fuel group, which we calculate directly from the IEA's EWEB for both the global and national levels.

It is worth noting that for all these calculations, we are limited by the accuracy of the IEA's EWEB, which are compiled using national-level data and may include second-order or derived statistics. A caution note regarding the EROIs determined for oil and fossil gas is that the IEA does not report distinctly the energy requirements of processing gas, which are instead reported in 'Oil and gas extraction'. Hence, we are not able to ascribe these energy requirements exclusively to fossil gas, and they are instead evenly split between oil and gas. This makes potentially the EROI of oil somewhat underestimated and the one of fossil gas slightly overestimated but does not affect the EROI determined for oil and gas as a category.

In practical terms, the PSUT framework is constructed using the IEATools[60] and ECCTools[61] R packages, input–output calculations (including product-level EROI calculations) are conducted using the Recca[62] R package and the aggregation of EROIs by fossil fuel group is conducted using the EROITools[63] R package.

Accounting for losses and energy self consumption

To account for transportation and distribution losses as a factor reducing the final energy output (equation (1)), we model losses as an additional industry. More specifically, for each energy product *p*, we create a 'losses' industry that represents the losses of product *p* reported in the IEA's EWEB. For instance, in the case of electricity, a 'Losses (of Electricity)' industry is added, that takes as input 'Electricity (before Losses)' and produces 'Electricity (after Losses)'. We then apply equation (10) to the product 'Electricity (after Losses)'.

The IEA's EWEB does not differentiate between final energy purchased by the energy sector and energy self consumption by the energy sector (for instance, refineries traditionally use a portion of their output in situ for their own needs[64]) in its Energy Industry Own Use (EIOU) flows. Hence, both final energy purchased and final energy self consumption (when reported in the IEA's EWEB) are included as final energy investments in our EROI calculations. We note that there is no agreement on how self-consumption energy flows should be accounted for in net energy analysis.

Including energy self consumption as energy investments (internal measure of energy returns), as we do (following recent works[65,66]), may yield a 'more comprehensive measure of the total energy return from a production pathway'[26]. Conversely, excluding energy self consumption from energy investments (external measure of energy returns) may yield a measure more representative of the potential of the energy system to increase the net energy supply to society[2,26]. Some authors argue that energy self consumption should be excluded from energy investments, as it represents energy that would not have been available to humanity anyway if the energy system considered was not operating[67]. On the other side, excluding energy self consumption from energy investments may yield extremely high values of EROI in the case of highly self-sufficient systems[68], overlooking their energy requirements. We note that both options comply to a well-established framework in net energy analysis as long as the assumptions are made clear and transparent[2,26].

Calculation of useful-stage EROIs

After the seminal work of Ecclesia et al. for the whole Portuguese energy system[69], our work attempts the first estimation of fossil fuels useful-stage EROIs, disaggregating by fossil fuel group and end use, both at the global and national levels. We do so using a recently developed country-level primary–final–useful energy and exergy database[25]. To obtain the useful-stage EROI values, we determine both the economy-wide and end-use specific average final-to-useful efficiencies of each energy product, globally and by country. The country-level primary–final–useful database is structured as a list of national PSUT matrices in which end-use conversion devices (cars, heaters and so on) are considered industries (alongside conventional primary energy extraction and energy processing industries) and final demand sectors consume useful energy products (for example, high temperature heating, mechanical drive and so on) instead of final energy products (for example, gasoline, electricity and so on). We note that the PSUT matrices used in this section stand for those of the country-level primary–final–useful database and therefore differ from those used in the section 'Calculation of fossil fuels final-stage EROIs', which are built from the IEA's EWEB. The present section describes the determination of average final-to-useful efficiencies for each energy product in each country and of their global average, both economy-wide and by end use. (The method for conducting final demand sector specific calculations is described in Supplementary Section 6, alongside an example in Supplementary Fig. 9).

Economy-wide useful-stage EROIs. To determine the average final-to-useful efficiencies for each energy product in each country, we first introduce the amended national $\tilde{\mathbf{U}}$, $\tilde{\mathbf{V}}$ and $\tilde{\mathbf{Y}}$ matrices, which correspond respectively to the **U** and **V** matrices from which only the end-use conversion devices have been kept as industries (so, an industry refers to an end-use device in what follows) and to the **Y** matrix from which only final demand for useful energy products are kept (so it excludes, for instance, exports of final energy products). (Energy products used for non-energy uses are also excluded for the definition of $\tilde{\mathbf{U}}$, $\tilde{\mathbf{V}}$ and $\tilde{\mathbf{Y}}$.) The $\mathbf{q}'$ vector stands for the amended **q** vector calculated from the $\tilde{\mathbf{U}}$ and $\tilde{\mathbf{Y}}$ matrices and the $\mathbf{g}'$ vector for the amended **g** vector calculated from the $\tilde{\mathbf{V}}$ matrix. We also introduce the vector of total input by industry $\mathbf{f}'$ calculated from the $\tilde{\mathbf{U}}$ matrix by summing inputs across industries. Then we define the use shares matrix $\tilde{\mathbf{D}}^*$ as:

$$\tilde{\mathbf{D}}^* = \tilde{\mathbf{U}}^{\mathrm{T}}\widehat{\mathbf{q}'}^{-1} \tag{11}$$

where each coefficient $\tilde{d}_{k,l}{}^*$ stands for the share of product *l* used as input to industry *k*. We also introduce the vector containing the final-to-useful efficiencies of each end-use conversion device **n**:

$$\mathbf{n} = \widehat{\mathbf{g}'}^{-1}\mathbf{f}'. \tag{12}$$

Next, the national average final-to-useful efficiency for each energy product p can be determined, as:

$$\eta_p = \frac{\sum_{i\in\mathcal{J}} \tilde{d}^*_{i,p} n_i}{\sum_{i\in\mathcal{J}} \tilde{d}^*_{i,p}}, \tag{13}$$

where $\mathcal{J}$ stands for the subset of industries corresponding to end-use conversion devices. To determine the global average final-to-useful efficiency for each product, we compute the shares of use of each energy product by country using the IEA's EWEB and use these shares to calculate the weighted average final-to-useful efficiency at the global level. Then applying equation (3) using the final-stage EROIs previously calculated (inverse of equation (10)) and the average final-to-useful efficiencies yields the useful-stage EROI for each energy product, in each country and at the global level.

End-use specific useful-stage EROIs. The end-use specific national average final-to-useful efficiency for each energy product p in each end-use c is similarly determined from the matrix $\tilde{\mathbf{D}}^*$ and the vector $\mathbf{n}$:

$$\eta_{p,c} = \frac{\sum_{i\in\mathcal{C}} \tilde{d}^*_{i,p} n_i}{\sum_{i\in\mathcal{C}} \tilde{d}^*_{i,p}}, \tag{14}$$

where $\mathcal{C}$ stands for the subset of end-use conversion devices that deliver the specific end-use c. To determine the end-use-specific global average final-to-useful efficiency, we determine the share of use of each product by country within a given end-use c, using the $\tilde{\mathbf{U}}$ matrices. Applying equation (3) using the end-use specific final-to-useful efficiency then yields the end-use-specific useful-stage EROI for each energy product, in each country and at the global level.

Like for the final stage, the calculated useful-stage EROIs are then aggregated by fossil fuel group using the shares of use of each energy product within each fossil fuel group and within each end use for end-use specific calculations (these are calculated directly from the country-level primary–final–useful database).

Addition of indirect final energy requirements to EROIs

We determine the indirect final energy required for the production (including primary extraction and downstream transformation and refining) of fossil fuels using a hypothetical extraction method[27,28] adapted from previous EROI studies[14,70] in combination with the Exiobase Multi-Regional Input Output model[22,29]. Indirect energy requirements are calculated for the period 1995–2015 (time coverage of the Exiobase model) and thereafter extrapolated for the remaining years using the average ratio of indirect energy requirements to final energy output over the period, which is found to be relatively stable (Supplementary Fig. 6).

Calculations are conducted at the global level only, for each fossil fuel group (all fossil fuels, coal products, fossil gas, oil products, and oil and gas products). Note that the indirect final energy requirements associated with fossil fuel industries' capital investments have not been quantified. The reason is that the capital investment vector (part of the final demand matrix) in the Exiobase model is not disaggregated by investing industry (that is, the industry where the gross fixed capital formation occurs), which hinders the quantification of indirect energy associated with capital investments. Supplementary Section 3 presents the details of the methodology used to determine the indirect energy requirements.

Then, we normalize the indirect final energy requirements obtained from input–output calculations by unit of final energy produced for each fossil fuel group. We determine the final energy output by fossil fuel group using the IEA's EWEB, processed with the IEATools[60] and ECCTools[61] R packages by adding all fossil fuel final energy consumption flows, including electricity and heat from fossil fuel origin—calculation done with the EROITools[63] package. The ratio of indirect final energy requirements by final energy output $\mathrm{iE_f}$ is then simply calculated and the final-stage EROI including indirect final energy requirements $\mathrm{EROI_{f,iE}}$ for each fossil fuel group is determined as:

$$\mathrm{EROI_{f,iE}} = \left(\mathrm{EROI_{f,dE}^{-1}} + \mathrm{iE_f}\right)^{-1}, \tag{15}$$

where $\mathrm{EROI_{f,dE}}$ refers to the final-stage EROI including only direct energy requirements, calculated as described in the section 'Calculation of fossil fuels final-stage EROIs'. To determine the indirect final energy requirements of delivering one unit of useful energy of each fossil fuel group $\mathrm{iE_u}$, we use the average final-to-useful efficiency of each fossil fuel group as follows:

$$\mathrm{iE_u} = \frac{\mathrm{iE_f}}{\eta}, \tag{16}$$

and the useful-stage EROI including indirect final energy requirements $\mathrm{EROI_{u,iE}}$ is then calculated as:

$$\mathrm{EROI_{u,iE}} = \left(\mathrm{EROI_{u,dE}^{-1}} + \mathrm{iE_u}\right)^{-1}, \tag{17}$$

where $\mathrm{EROI_{u,dE}}$ stands for the useful-stage EROI including only direct energy requirements. To include indirect final energy requirements at the useful stage by end-use category c, we proceed in the same way, but use the end-use c specific final-to-useful efficiency η_c in equation (16).

Last, we use the global indirect final energy requirements per unit of fossil fuel output, both at the final stage ($\mathrm{iE_f}$) and at the useful stage ($\mathrm{iE_u}$) as proxy for the indirect final energy requirements per fossil fuel output in each country. Hence, we calculate the national EROIs including indirect final energy requirements by replacing the global EROI with the national specific final- and useful-stage EROIs in equations (16) and (17), while using the value determined at the global level for both $\mathrm{iE_f}$ and $\mathrm{iE_u}$.

Final-stage EROI equivalent by end-use category

Equation (8) can be adapted to each end-use category c as:

$$\mathrm{EROI_{f,c,eq}} = \frac{\mathrm{EROI_{u,c,ff}} - \eta_{\mathrm{ff}} + \eta_{\mathrm{elec}}}{\eta_{c,\mathrm{elec}}}, \tag{18}$$

where $\mathrm{EROI_{f,c,eq}}$ refers to the final-stage EROI equivalent of renewable energy systems for the end-use c, $\mathrm{EROI_{u,c,ff}}$ refers to the useful-stage EROI of fossil fuels for end-use c and $\eta_{c,\mathrm{elec}}$ to the average final-to-useful efficiency with which fossil fuels would be substituted by electricity in the end-use c.

Alternative manufacturing assumption

Alternatively, one can assume that renewable energy technologies currently need to be manufactured dominantly with fossil fuel energy so that the net useful energy $e_{\mathrm{u,re}}$ delivered by investing one unit of energy in a renewable energy technology becomes:

$$\begin{aligned} e_{\mathrm{u,re}} &= \mathrm{EROI_{u,re}} - \eta_{\mathrm{ff}} \\ &= \mathrm{EROI_{f,re}}\eta_{\mathrm{elec}} - \eta_{\mathrm{ff}}, \end{aligned} \tag{19}$$

which replaces equation (6). Then finding the value of $\mathrm{EROI_{f,eq}}$ for which the variation in net useful energy Δe_{u} resulting from investing one unit of energy in a renewable energy technology instead of fossil fuel energy is null leads to the following expression of EROI equivalent:

$$\mathrm{EROI_{f,eq}} = \frac{\mathrm{EROI_{u,ff}}}{\eta_{\mathrm{elec}}}, \tag{20}$$

which can be adapted for each end-use category as:

$$\mathrm{EROI}_{\mathrm{f},c,\mathrm{eq}} = \frac{\mathrm{EROI}_{\mathrm{u,c,ff}}}{\eta_{c,\mathrm{elec}}}. \tag{21}$$

Average final-to-useful efficiencies η_{ff} and η_{elec}

To determine the average final-to-useful efficiency of using fossil fuels in the energy system η_{ff}, we use as proxy the average economy-wide final-to-useful efficiency of fossil fuels, determined using the weighted average (including fossil fuel use as electricity and heat) of the product-level final-to-useful efficiencies determined as in equation (13). The average economy-wide final-to-useful efficiency of fossil fuels is reported in Supplementary Table 2.

Regarding η_{elec}, we define it as the average final-to-useful efficiency with which fossil fuel-based carriers would be substituted by electricity. In the country-level primary–final–useful database[25], end-use devices (for example, car engines, light bulbs and so on) convert final energy carriers into an end-use energy product (for instance, propulsion, low-temperature heat and so on). For each device, we assume an alternative substituting device, which corresponds to the device that would be used for substituting fossil fuels, according to current trends. For instance, an internal combustion engine car would be replaced by an electric car, a gas boiler by an electric heater, etc. We therefore use the current 'natural' replacement of each device and do not consider those emerging technologies that are not the dominant substituting devices. So, for instance, we do not include heat pumps as a substituting device because their deployment is currently marginal at the global level and we assume the substituting device to be an electric heater instead. (The repository associated with the paper provides a table of devices alongside the assumed substituting device).

Then we determine the proportion of each energy product used by each end-use device in each country (and in each end use for end-use-specific calculations). Next, we apply the final-to-useful efficiency of the alternative, substituting device in each country to determine the average final-to-useful efficiency with which each fossil fuel-based energy product would be substituted in each country (and in each end use for end-use-specific calculations). Last, we determine the weighted average final-to-useful efficiencies of substitution by fossil fuel group using the use shares of each energy product in each fossil fuel group (either within each country or at the global level). The average final-to-useful efficiencies of substituting each fossil fuel at the global level are shown in Supplementary Section 1.1, both at the economy-wide (η_{elec}) and end-use-specific levels ($\eta_{c,\mathrm{elec}}$) (Supplementary Table 1).

Effects of intermittency on renewable energy systems' EROIs

There are different ways to deal with the intermittency of renewable energy systems, including demand-side management, overcapacities, curtailment and storage[71]. Here we quantify the potential effects of curtailment and storage requirements on the EROI of renewable energy technologies using energy transition scenarios to 2050 for the European Union[34], France[35], the United Kingdom[36] and the United States[37]. For each region, we select two scenarios representing different narratives, representing both a highly ambitious energy transition scenario relying heavily on renewable energy technologies for decarbonization. These scenarios are discussed in more detail in Supplementary Table 3.

Following Barnhart et al.[72], we introduce the storage and curtailment fractions φ and ν, which stand for the share of the electricity produced from variable renewable energy technologies (solar PV and wind power) that need to be stored and curtailed, respectively. Some assumptions are needed to derive the storage fraction in each of these scenarios. First, we assume that all the electricity stored is of variable renewable energy origin (solar PV or wind power), which is conservative and tends to overestimate the storage fraction. Second, we regard as electricity stored the electricity input to stationary batteries, to EVs when used as vehicle to grid (V2G) and to pumped hydro storage (PHS). The electricity used as power-to-hydrogen (P2H) is, however, excluded. The reason is that demand for hydrogen is expected to soar in the future to decarbonize specific sectors and end uses (for instance, steelmaking), so that the service provided by P2H cannot be regarded as mere storage (Supplementary Section 2 and Supplementary Table 5). Table 1 shows the curtailment and storage fractions derived for each energy transition scenario (Supplementary Table 4 shows the detail by storage technology). More details regarding the determination of the storage and curtailment fractions for each scenario are available in Supplementary Section 2. A sensitivity analysis showing the results when including P2H in storage requirements is also presented in Supplementary Fig. 5.

We then use the storage and curtailment fractions determined to adjust the literature-sourced EROIs (Fig. 4) to account for the implications of intermittency. To do so, we use the energy stored on energy invested (ESOI) concept, which stands for the amount of final energy stored and returned for one unit of final energy invested in a storage system[72]:

$$\mathrm{ESOI} = \frac{\text{Final energy returned}}{\text{Final energy input}}. \tag{22}$$

We then define the EROI of dispatchable renewable energy (that is, renewable energy once the effects of dealing with intermittency are considered) adapting previous work from Barnhart et al.[72] as:

$$\mathrm{EROI}_{\mathrm{f,disp}} = \frac{\varphi\varepsilon e_{\mathrm{f,output}} + (1-\varphi-\nu)e_{\mathrm{f,output}}}{e_{\mathrm{f,invested}} + e_{\mathrm{f,storage}}}, \tag{23}$$

where ε denotes the round-trip efficiency of the storage system (the fraction of the energy input returned), $e_{\mathrm{f,output}}$ stands for the final energy output of a renewable energy technology, $e_{\mathrm{f,invested}}$ stands for the final energy invested excluding storage requirements and $e_{\mathrm{f,storage}}$ for the final energy that had to be invested to store the fraction φ of $e_{\mathrm{f,output}}$. Noting that:

$$e_{\mathrm{f,storage}} = \frac{\varphi\varepsilon e_{\mathrm{f,output}}}{\mathrm{ESOI}}, \tag{24}$$

one can write:

$$\begin{aligned}\mathrm{EROI}_{\mathrm{f,disp}} &= \frac{\varphi\varepsilon e_{\mathrm{f,output}} + (1-\varphi-\nu)e_{\mathrm{f,output}}}{\frac{e_{\mathrm{f,output}}}{\mathrm{EROI}} + \frac{\varphi\varepsilon . e_{\mathrm{f,output}}}{\mathrm{ESOI}}}\\ &= \frac{\varphi\varepsilon + (1-\varphi-\nu)}{\frac{1}{\mathrm{EROI}} + \frac{\varphi\varepsilon}{\mathrm{ESOI}}}.\end{aligned} \tag{25}$$

Noting that storage may be disaggregated in terms of battery-based (including V2G) storage and PHS, the previous equation may be written as:

$$\mathrm{EROI}_{\mathrm{f,disp}} = \frac{\sum_k \varphi_k \varepsilon_k + (1-\varphi-\nu)}{\frac{1}{\mathrm{EROI}} + \sum_k \frac{\varphi_k \varepsilon_k}{\mathrm{ESOI}_k}}, \tag{26}$$

where k stands for either battery-based storage (including V2G) or PHS and $\varphi = \sum_k \varphi_k$. In terms of values, we use the estimates of Sgouridis et al.[73], that is, an ESOI value of 11 for battery-based storage and 249 for PHS-based storage, and a round-trip efficiency of 83% for battery-based storage and 80% for PHS. (These round-trip efficiencies are very close to those provided by the US National Renewable Energy Laboratory[37]; 80% for PHS and 85% for batteries.) We note that an ESOI of 11 is in the medium range of the values reported for different technologies by Barnhart et al.[72], and an ESOI of 249 for PHS-based storage is substantially lower than the value (704) reported by Barnhart et al.[72]. However, the values estimated by Pulido et al.[74] are much lower (in the range 1.1–2.3; Supplementary Section 2). We therefore conduct a sensitivity analysis using the values of Pulido et al.[74] (Supplementary Fig. 4). Last, we note that the approach taken is conservative in regards to the energy requirements of PHS, because the PHS infrastructure is already built to a large extent, so that the actual energy requirements are much lower than those considered here. Regarding our results, we note that they are in line with Raugei et al.[75], which finds a moderate increase in energy requirements (in the range 5–30%) of solar PV when considering storage requirements at storage fractions between 7.5 and 30%.

Energy payback time at the useful energy stage

At the final energy stage, the energy payback time $\mathrm{EPT_f}$ may be defined as the time required for an energy system to deliver the energy that had to be invested. Under the approximation that the energy requirements of renewable energy technologies are entirely up-front and that the output of renewable energy technology does not decline over time (as a result of depreciation), one can express the $\mathrm{EPT_f}$ as:

$$\mathrm{EPT_f} = \frac{e_{\mathrm{f,invested}}}{\dot{e}_{\mathrm{f,output}}}, \tag{27}$$

where $\dot{e}_{\mathrm{f,output}}$ stands for the yearly output of final energy when investing one unit of final energy in a renewable energy technology and $e_{\mathrm{f,invested}}$ for the final energy invested (equal to unity), following equation (5). Noting that $e_{\mathrm{f,output}} = L.\dot{e}_{\mathrm{f,output}}$, where L stands for the average lifetime of the renewable energy technology considered and replacing $e_{\mathrm{f,invested}}$ in the previous equation, one obtains:

$$\mathrm{EPT_f} = \frac{L}{\mathrm{EROI_f}}. \tag{28}$$

The energy payback time may also be defined at the useful energy stage (EPT_u) as the time required to deliver the same amount of useful energy that could have been delivered by the final energy that was invested in the renewable energy technology. Assuming that renewable energy technologies are currently manufactured using dominantly fossil fuel energy, such definition yields the following equation:

$$\begin{aligned}\mathrm{EPT}_u &= \frac{e_{\mathrm{f,invested}}\eta_{\mathrm{ff}}}{\dot{e}_{\mathrm{u,output}}}\\ &= \frac{e_{\mathrm{f,invested}}\eta_{\mathrm{ff}}}{\dot{e}_{\mathrm{f,output}}\eta_{\mathrm{elec}}}\\ &= \mathrm{EPT_f}\frac{\eta_{\mathrm{ff}}}{\eta_{\mathrm{elec}}},\end{aligned} \tag{29}$$

where $\dot{e}_{\mathrm{u,output}}$ stands for the yearly output of useful energy when investing one unit of final energy in a renewable energy technology. We note that η_{ff} is taken equal to the average final-to-useful efficiency of the average fossil fuel mix (as it represents the efficiency of manufacturing renewable energy technologies via fossil fuels) and η_{elec} is specific to the fossil fuel being substituted. Using the set of EROIs provided by Murphy et al.[31] as in the rest of the paper and assuming an average lifetime of 25 years for both solar PV and wind power, Extended Data Fig. 7 shows the obtained EPT. The final-stage EPTs are in line with the range reported by Bhandari et al. 2015[76] (mean value in the range 1.0–4.1) and Koppelaar 2017[77] (mean value in the range 2.9–3.9 for solar PV). Further, Extended Data Fig. 7 shows that the EPT of renewable energy technologies decreases substantially (by 23%) when conducting the analysis at the useful stage (when looking at the average fossil fuel mix). Therefore, conducting the analysis at the useful stage suggests that the energy transition may imply a shorter temporal drop in the net useful energy delivered than a final stage analysis may suggest. A dynamic analysis remains nevertheless needed to fully understand these temporal aspects.

Data availability

The IEA's Extended World Energy Balances were obtained under license from the IEA. The country-level primary–final–useful energy and exergy database used is available at https://doi.org/10.5518/1199 (ref. 25). The Exiobase Multi-Regional Input Output model is available at https://zenodo.org/record/5589597. The generated dataset, which included fossil fuels final- and useful-stage EROIs and the EROI equivalent values for renewable energy, is available via Figshare at https://doi.org/10.6084/m9.figshare.25311358 (ref. 78).

Code availability

The R code used for this work is fully available at https://github.com/earamendia/NENERGY-23061207.

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Author contributions

E.A. and P.E.B. designed the study. E.A. conducted the calculations and analysis. Z.M., M.K.H., P.E.B. and E.A. constructed the country-level primary–final–useful energy and exergy database used as input data. P.E.B., P.G.T. and J.B.N. supervised the study and provided regular feedback and support. E.A., P.E.B., P.G.T., J.B.N., M.K.H. and Z.M. contributed to writing and revising the paper.

Competing interests

The authors declare no competing interests.

Additional information

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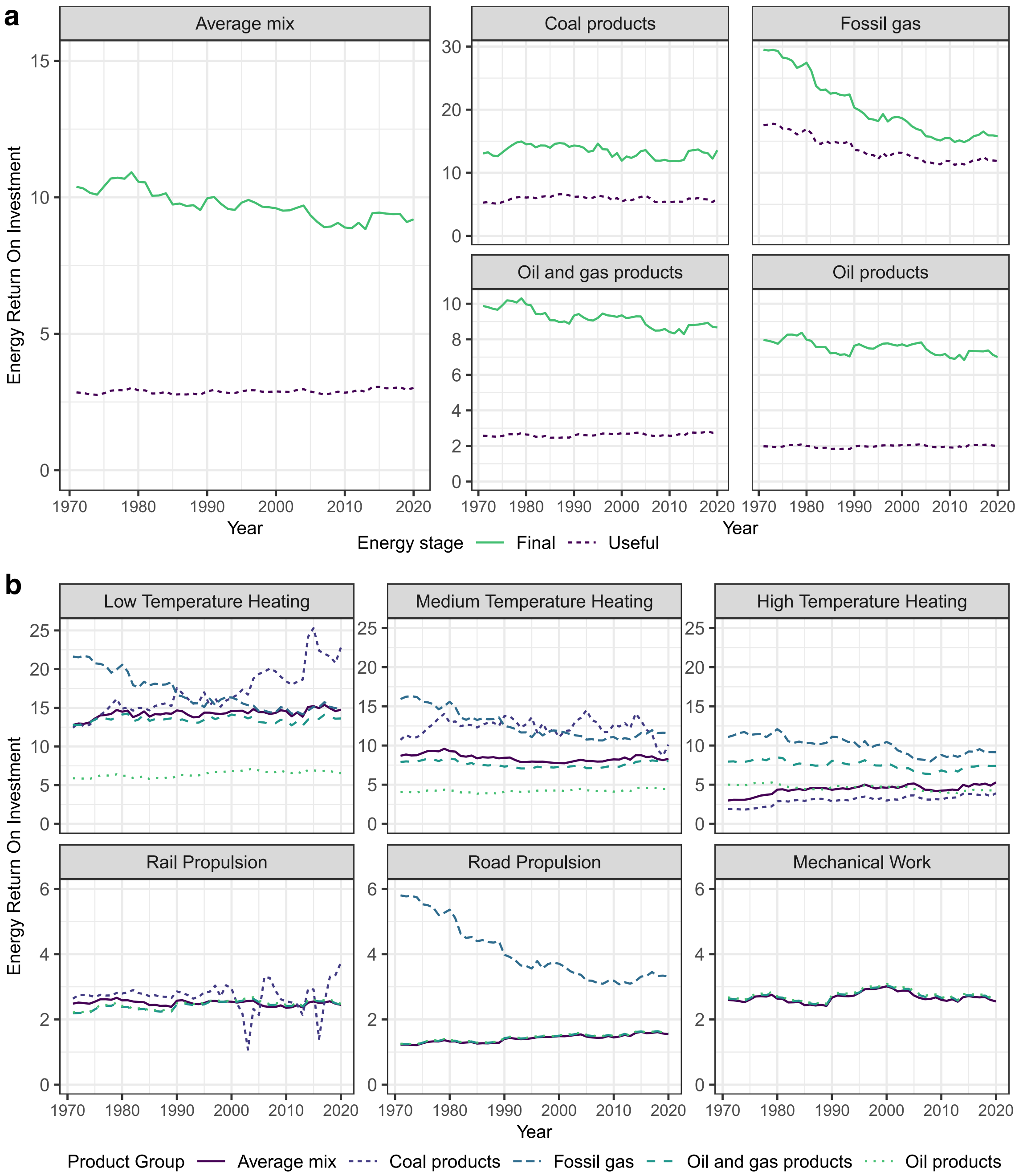
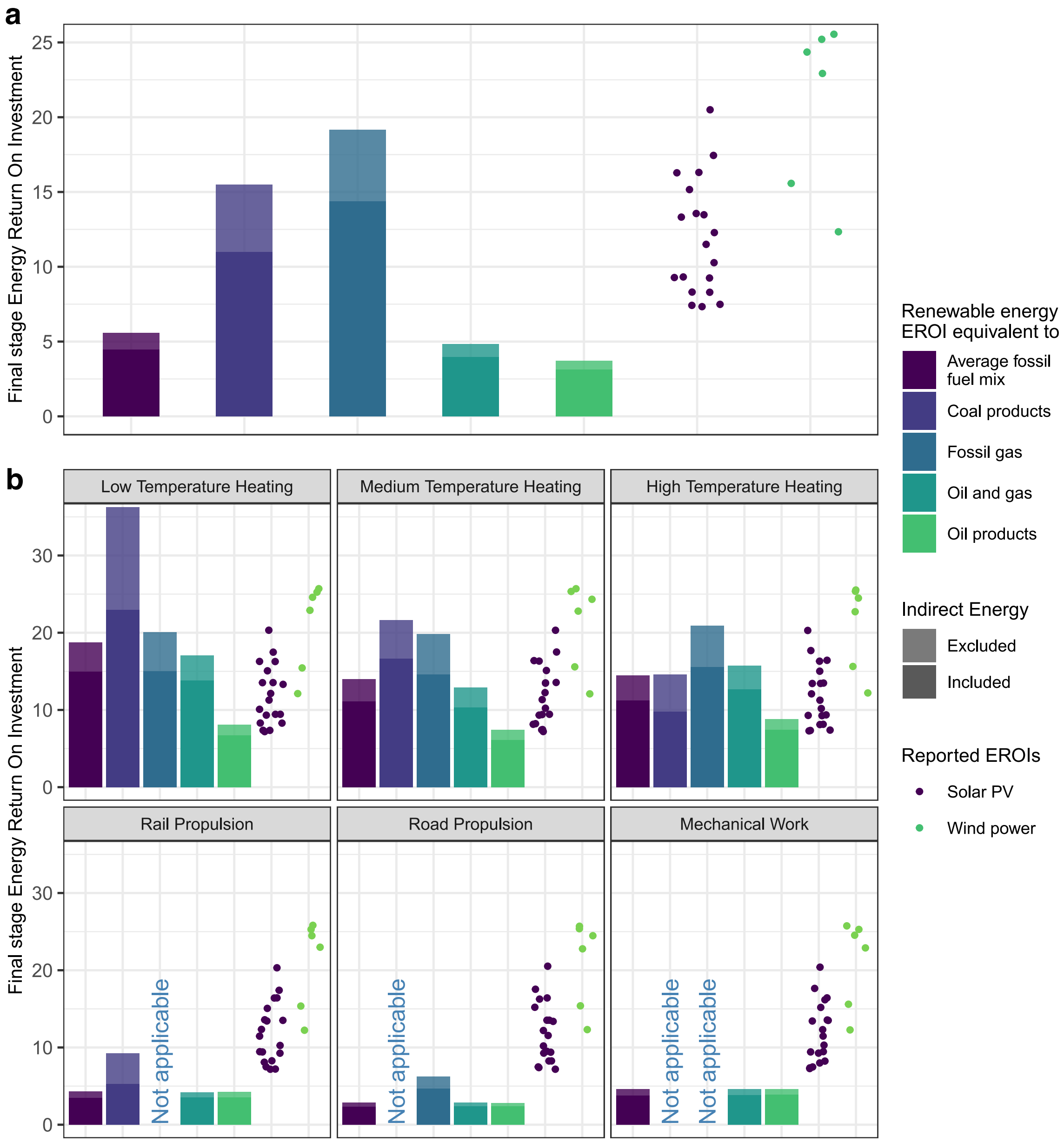
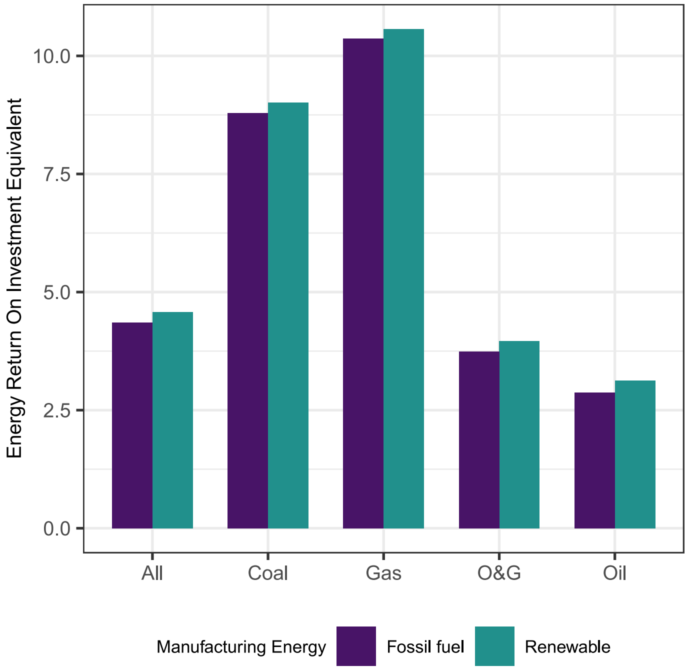


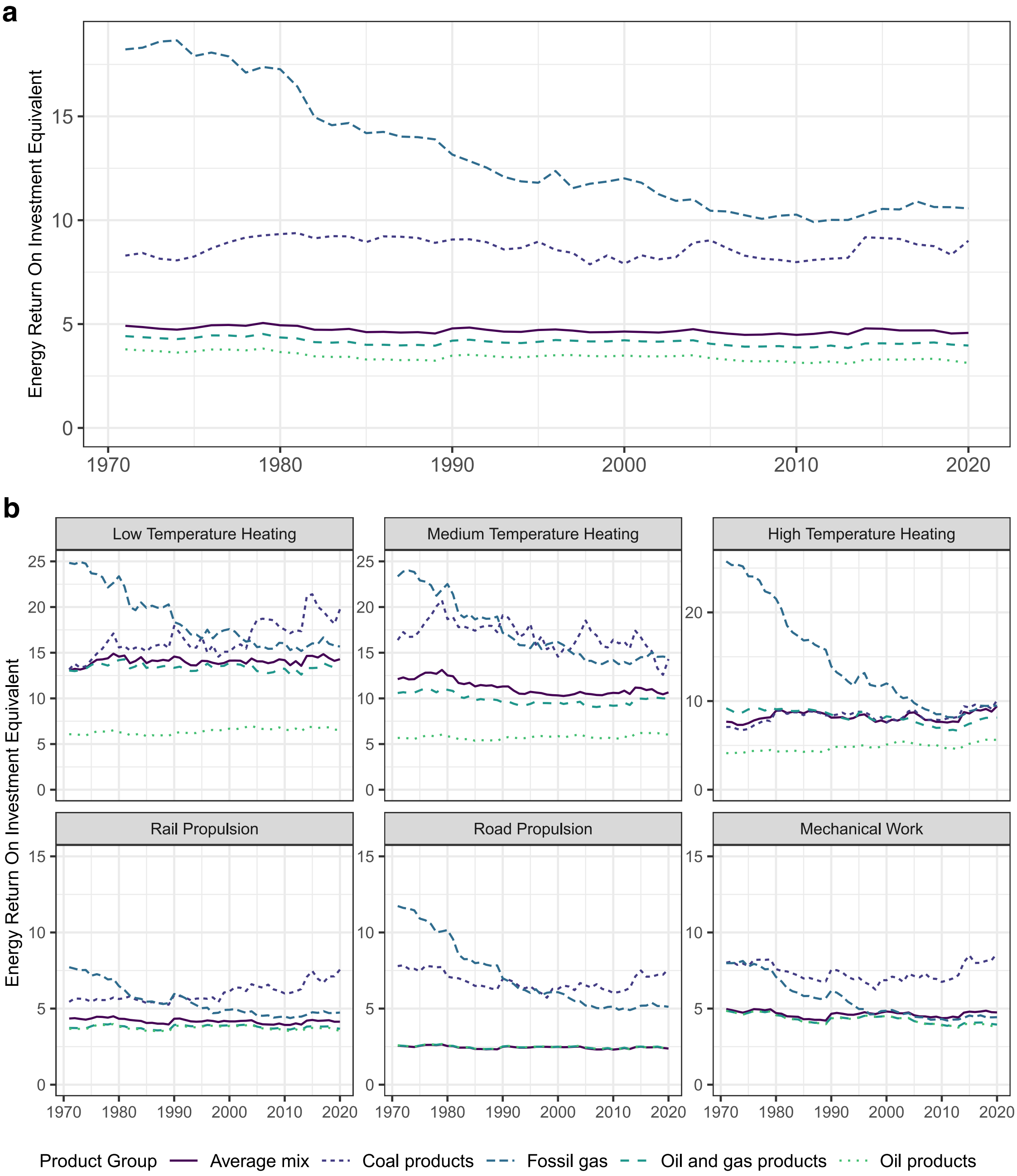
Extended Data Fig. 1 | Fossil fuels Energy Return On Investment (EROI) values when used as fuels only. a, Final- and useful-stage average EROI for the five fossil fuel groups, at the global level. b, Useful-stage EROI by end-use category for the five fossil fuel groups, at the global level. Calculations consist of a weighted average of fossil fuels used as fuels only.



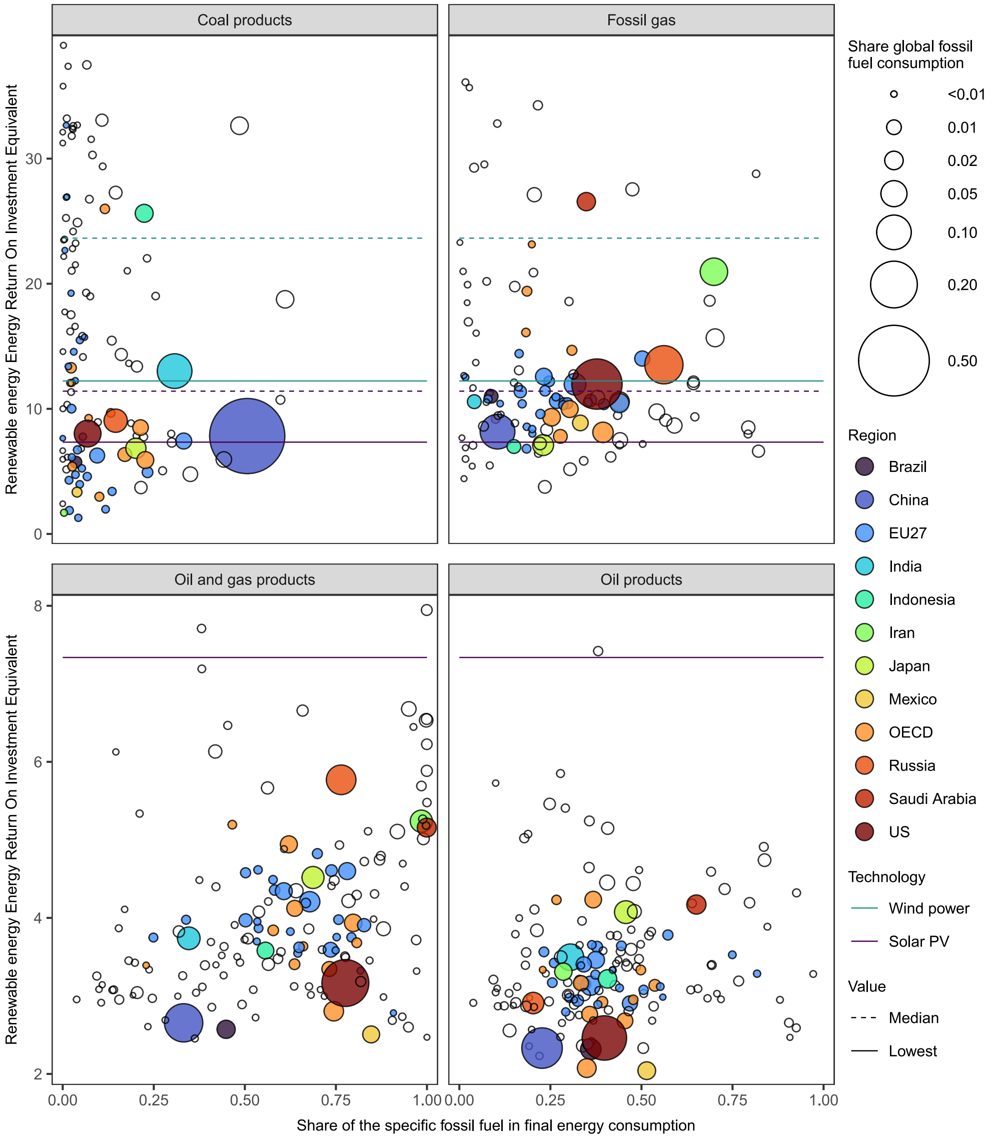
Extended Data Fig. 2 | Renewable energy Energy Return On Investment (EROI) equivalent to fossil fuels used as fuels only. Final-stage EROI equivalent (that is, the value above which renewable energy systems would deliver more net useful energy than fossil fuels) calculated for 2020 at the global level alongside literature-sourced EROIs (from[30]) of solar photovoltaics (PV) and wind power, a, economy-wide, and b, by end-use category. Dark shades correspond to the EROI equivalent when indirect energy requirements are included in fossil fuels' EROI calculations. Light shades correspond to the EROI equivalent when indirect energy requirements are excluded. Calculations consist of a weighted average of fossil fuels used as fuels only.



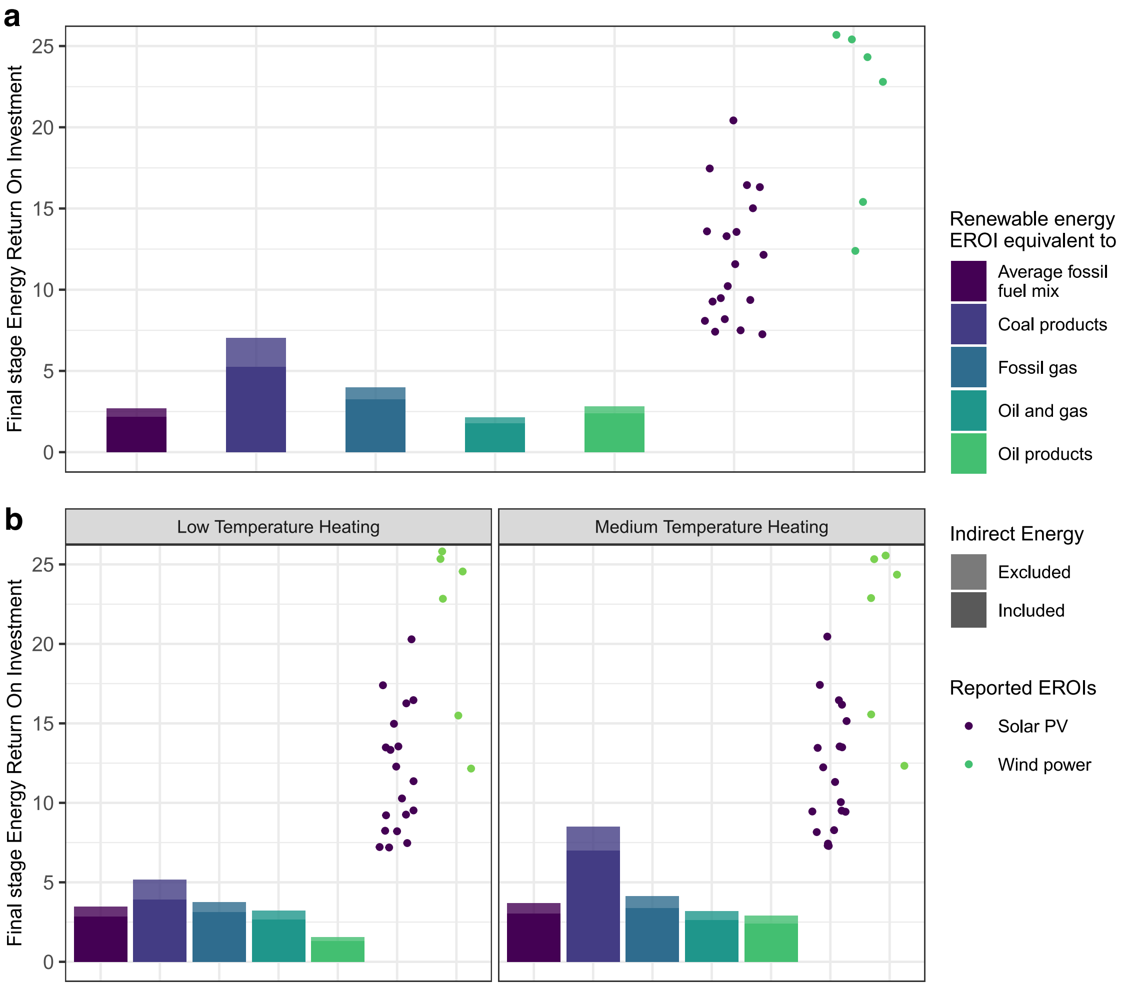
Extended Data Fig. 3 | Comparison of manufacturing assumptions. Variation in the final-stage Energy Return On Investment equivalent (that is, the value above which renewable energy systems would deliver more net useful energy than fossil fuels) when using the renewable-based manufacturing assumption (Equation (6)) versus the fossil fuel-based manufacturing assumption (Equation (20)). Calculations consist of a weighted average of fossil fuels used as fuels, electricity, and heat. Values calculated for 2020 at the global level.



Extended Data Fig. 4 | Renewable energy Energy Return On Investment (EROI) equivalent over time (1971-2020). Final-stage EROI equivalent for renewable energy systems (that is, the value above which renewable energy systems would deliver more net useful energy than fossil fuels) over time at the global level, a, economy-wide, and b, by end-use. Calculations consist of a weighted average of fossil fuels used as fuels, electricity, and heat.



Extended Data Fig. 5 | National-level Energy Return On Investment (EROI) equivalent for each fossil fuel group. National-level final-stage renewable energy EROI equivalent (average 2000-2020 shown on y-axis) to each fossil fuel group alongside the share of final energy consumption from the specific fossil fuel group in 2020 (x-axis). The EROI equivalent values are compared to the literature-sourced EROIs (from[30]) for solar photovoltaics (PV) and wind power in solid (lowest value) and dashed (median value) lines. The size of the dots are function of the share of each country's global fossil fuel group consumption. Republic of Congo, Uzbekistan, and North Korea are outliers and do not appear in the graph. In addition, values above 40 (which appear for a few countries due to inconsistent energy consumption data), are excluded for coal products. Calculations consist of a weighted average of fossil fuels used as fuels, electricity, and heat.



Extended Data Fig. 6 | Renewable energy Energy Return On Investment (EROI) equivalent assuming the use of heat pumps. Final-stage Energy Return On Investment (EROI) equivalent (that is, the value above which renewable energy systems would deliver more net useful energy than fossil fuels) calculated for 2020 at the global level under the assumption that heat pumps will substitute low and medium (up to 100°C) heating processes, except cooking. Renewable energy EROIs reported in the literature are displayed alongside. a, Economy-wide, and b, by relevant end-use category (low and medium-temperature heating). The results for the remaining end-use categories do not change. Dark shades correspond to the EROI equivalent when indirect energy requirements are included in fossil fuels' EROI calculations. Light shades correspond to the EROI equivalent when indirect energy requirements are excluded. Calculations consist of a weighted average of fossil fuels used as fuels, electricity, and heat.

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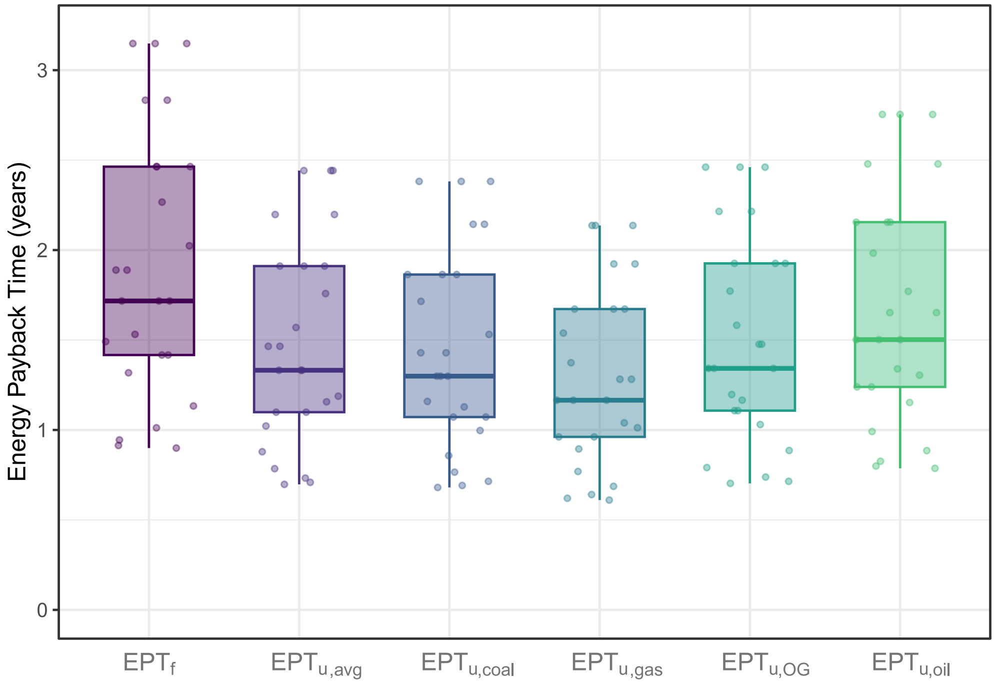

Extended Data Fig. 7 | Energy payback time of renewable energy systems. Range of final-stage energy payback times (EPTf) alongside useful-stage energy payback times (EPTu) when renewable energy (wind power and solar photovoltaics) substitutes the average fossil fuel mix (avg), coal products, fossil gas, oil and gas products (OG), and oil products. Final-stage energy payback times are calculated from the EROI values reported in [30], using an average lifetime of 25 years. Boxplots determines with n = 29. EPTf: min=0.90, Q1=1.42, median=1.72, Q3=2.46, max=3.15. EPTu,avg: min=0.69, Q1=1.10, median=1.33, Q3=1.91, max=2.44. EPTu,coal: min=0.68, Q1=1.07, median=1.30, Q3=1.86, max=2.38. EPTu,gas: min=0.61, Q1=0.96, median=1.17, Q3=1.67, max=2.14. EPTu,OG: min=0.70, Q1=1.11, median=1.34, Q3=1.93, max=2.46. EPTu,oil: min=0.79, Q1=1.24, median=1.50, Q3=2.16, max=2.75.