Energy Return On (energy) Invested (EROI)

and its importance in assessing the performance of energy systems

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Meeting the energy needs of our societies, in the context of the fight against global warming and the prospect of depleting stocks of fossil fuels and mineral resources, requires the implementation of low-carbon alternative solutions. The cost per MWh is undoubtedly a useful criterion, but physical criteria are essential for assessing technological solutions and possible energy scenarios.

The main of these criteria based on physical quantities is the "Energy Return on Invested" (EROI), which measures the efficiency of a system in providing society with useful energy for sectors other than the energy sector itself. Other aspects must also be considered, such as the availability of resources, the surface areas mobilised, mineral requirements, industrial risks and environmental and health impacts.

When it comes to managing their energy supply, human societies are subject to constraints similar to those faced by individuals with regard to their food. To maintain and develop, a society must devote only a fraction of its energy resources to obtaining these very resources. The development of our industrial societies was only made possible by the use of energy resources such as coal and oil, which multiplied our capacity to transform matter, while devoting only a small proportion of energy to obtaining these resources. Assessing access to the energy resources that enable our complex societies to function properly requires criteria based on objective physical quantities. Short-term economic criteria alone are insufficient and often misleading.

The first point to consider is therefore the quantity of energy available to a human society, taking into account the self-consumption of the energy sector itself. The concept of EROI (Energy Return on Investment) introduced below provides a physical approach to this fundamental point. However, it does not in itself take account of other essential aspects, including the potential and availability of resources in relation to the needs to be met. These aspects and their impact on the EROI will be discussed. The other criteria to be considered, such as mineral requirements, industrial and health risks, and environmental impact, will only be mentioned here as they are the subject of specific articles in Part 5.

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Energy return on investment (EROI)

Definition and methodology

To survive in a given environment, any animal must be able to use its metabolism to provide the energy associated with the work it has had to do to acquire food and food for its young, and the work associated with various vital activities (heartbeat, breathing, reproduction, nesting, burrowing, etc.), the heat needed to maintain its temperature (if it is warm-blooded) and the chemical energy needed to renew its cells. It is all the more likely to be able to carry out all these vital activities if the fraction of muscular energy expended in acquiring food is low, and if the proportion of energy consumed by the animal is high. This depends not only on the intrinsic performance of the organism, but also on the abundance of food and the ease with which it can be obtained.

It was in the context of ecology that a quantity was introduced to measure the ratio between the energy available for metabolism (food) and the energy invested in obtaining it from the environment. In the case of human metabolism, it is easy to understand how the energy expenditure of a group of hunter gatherers could vary quite considerably, depending on whether its members simply had to stretch out their arms to gather abundant food, or whether they had to travel vast distances to hunt rare game.

More generally, and for any energy system, it is interesting to consider the ratio of the energy made available, E_{out}, to the energy invested to obtain it, E_{in}. This dimensionless ratio is called EROI (Energy Return On Investment), or sometimes ERoEI (Energy Returned on Energy Invested):

$$EROI = E_{out} / E_{in}.$$

The EROI measures a system's ability to extract usable energy from its environment, which should not be confused with its efficiency in converting the heat obtained by burning a fuel (food) into other forms of energy, in particular mechanical energy, as measured by its thermodynamic efficiency. Living beings or thermodynamic systems are considered here as energy multipliers (or rather exergy[(a)] multipliers), the amplifying factor being defined by the EROI.

If we think in terms of society as a whole, E_{out} refers to the total primary energy made available by investing the energy E_{in}, which represents the self-consumption of the energy sector. From this, we can express the fraction of net energy remaining available for uses other than energy production by the relationship:

$$(E_{out} - E_{in}) / E_{out} = 1 - (1 / EROI)$$

The variation in available energy (in percent) as a function of decreasing EROI is shown in Figure 1. It shows a very rapid decrease below an EROI of around 5, hence the introduction of the term "energy cliff". This means that if the EROI falls below 5, there is very little energy left to satisfy needs other than those of energy research itself[(b)].

How can this EROI concept be used to characterise the energy systems used in our societies?

The first example concerns the supply of fossil fuels. The specific case of oil and the energy cost of extracting it even serves as a reference. This example also illustrates the various ways of characterising an energy system through the concept of EROI.

- *Standard EROI* ($EROI_{st}$). This is the ratio of the number of tonnes of oil extracted to the energy equivalent, in tonnes of oil equivalent (toe), spent on extracting it. In the heyday of oil extraction, this ratio was around 100:1. Today, the EROI of oil is around 30:1, and it falls below 10:1 for oil sands.
- *EROI point of use* ($EROI_{pu}$). Crude oil cannot be used as such. It has to be transported to a refinery (hence the energy cost), refined (another cost) and then transported to a distribution network (a third cost). The energy invested is therefore greater than in the previous case, so that $EROI_{pu} < EROI_{st}$.

EROI over time and by geography

The EROI of an energy resource varies over time. The availability of the resource, its abundance and technological progress affect both the numerator E_{out} and the denominator E_{in}. The question arises differently for stock and flow energies (see the article by J. Treiner, p. 9).

In the case of fossil fuels, the analysis of long series is made difficult by the lack of technical data that

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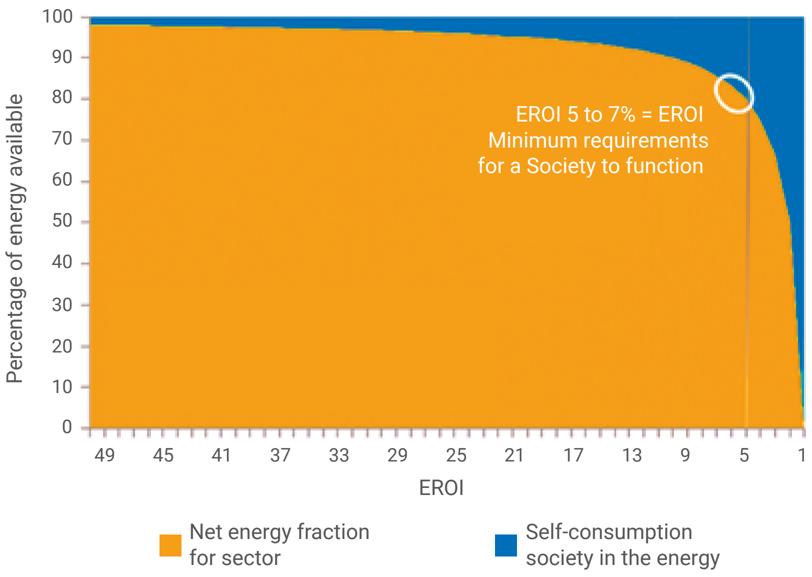

1. Cliff in the rate of energy available for uses other than its own production.
(Source: E. Mearns, https://cutt.ly/eroei-for-beginners).

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would allow accounting in purely energy terms. One approach is to use monetary costs (prices) as a good representation of energy costs. The idea is that all energy expenditure corresponds to transformations of matter, and these transformations involve labour and capital, which have a monetary value. This approach obviously contains biases, associated in particular with any purely speculative movement that introduces fluctuations that are insignificant from an energy point of view.

A recent analysis [1] presents different ways of smoothing these fluctuations in order to identify strong trends. It shows that the EROI for oil and gas peaked in the 1930s and 1940s at 50:1 and 150:1 respectively, but that the EROI for coal is still rising. These trends need to be correlated with the annual production of these resources: it is expected that, at the start of exploitation, the discovery of new deposits and the gradual mastery of their extraction will increase the EROI, but that with the depletion of a stock resource, however, extraction will become increasingly difficult and the deposits will be less rich, requiring the use of increasingly expensive techniques, which will reduce the EROI.

For flow energies, which are inexhaustible, the variability of EROI arises not only in terms of technological progress but also in terms of geographical availability and the ability to meet demand.

Two recent detailed studies [2, 3] look at the availability and quality of resources for wind and solar depending on geographical location. EROI is naturally expected to vary as a function of available flux depending on location. By using a complete grid of the earth's surface and taking into account the potential and available surface area per cell, the authors obtain the quantities of accessible energy. In the specific case of electricity production from solar flux, the authors obtain the quantities of energy accessible per EROI range for the different technologies (photovoltaic and concentrated solar power). At a global level, with an available surface area of around 5% of the total land surface, the maximum accessible photovoltaic potential with an EROI greater than 9 is $184\ 10^{18}$ J/year, or 51 150 TWh, 67% of which is in Africa and ... 0% for Europe (compared with some 27 000 TWh of electrical energy consumed worldwide today). However, the EROI calculated by the authors is already necessarily overestimated, as it does not take into account the energy costs of storage. The result for Europe is particularly significant: considering EROI values as low as 4, the maximum potential for photovoltaic solar energy is 10^{19} EJ/year, or 2780 TWh/year (compared with current annual electricity consumption of 3330 TWh). This result corresponds well with those of Prieto & Hall [4] and Weissbach *et al* [5] (without storage), as we shall see below.

Another example is biomass. Its use in electricity generation is considered in the next paragraph. But a more relevant approach, in terms of its use since the invention of agriculture (and the storage of resources), takes account of the main uses of biomass in the world: food and heat. Interesting analyses of energy rates of return for different types of agricultural practices can be found inrecent work by Carl Jordan [6] and S. Harchaoui and P. Chatzimpiros [7].

EROI of electrical energy sources

With electricity playing an increasingly important role, the question arises as to how to adapt the EROI concept to electricity generating sources, so that they can be compared.

In this case, E_{out} is the electrical energy produced. This is the standard EROI.

At this point, we should point out the need to take into account a fundamental difference between dispatchable sources such as traditional thermal power stations, and non-dispatchable generating sources such as wind turbines or photovoltaic farms. The variable electrical power delivered over time can only be taken into account as usable energy if it meets grid demand at any given moment. The situation can be compared to that of a living being which, in a given environment, is unable to collect its food at a rate corresponding to the needs of its metabolism. In the absence of storage facilities, some of the food collected would be irretrievably lost, with a major impact on EROI.

It should be noted, however, that the ability of an electricity network to integrate in real time the production of intermittent sources that cannot be controlled depends on the penetration rate of these sources. We can repeat the previous comparison. A farmer-breeder can occasionally take advantage of the game resources offered by the neighbouring forest, thereby avoiding having to draw on his reserves.

Calculations must be made for the entire life cycle of the installation, as illustrated in Figure 2. It is necessary to take into account the energy costs of the construction of the installation, its operation and maintenance, as well as its decommissioning. It is easy to see that the lifetime of the plant is a decisive factor in determining the final EROI. It should be noted that the often-used concept of *energy payback time* only measures the time required for the plant to have supplied, during its operation, the energy invested in its construction.

Assessing these different energy costs, which involves defining the costs of extraction, the use of materials and the plant's own consumption, is a difficult task. This is shown in red and orange in the commercial operation phase (Fig. 2). The complete study was carried out by a team of German physicists [5] and a summary of their results will be presented in the next section. Given the difficulty of determining each energy cost in a purely physical way, a number of authors, using the fact that prices play a role comparable to that of energy as a universal measure of the transformations of matter associated with the creation of goods and services, have proposed that the price of energy should be calculated as a function of the cost of energy. This leads to difficulties of comparison, since the energy costs are not necessarily the same as the energy costs. This leads to difficulties in comparison, especially if the link between monetary costs and energy costs is established in terms of primary energy.

Furthermore, a precise examination of the limits of the system to be considered reveals a fundamental difference between stock energy and flow energy. In the case of stock energy, which supplies dispatchable sources, the auxiliary equipment that consumes part of the energy produced by the installation is essentially that used for mining extraction and, in the case of nuclear fuel, enrichment equipment. In the case of flow energy, the storage devices needed to ensure that the electrical energy supplied actually meets a societal demand must also be taken into account as auxiliary equipment: electricity grids operate with *guaranteed* power, not *intermittent* power. This is not always taken into account, even though its impact on EROI is, as we shall see, anything but negligible.

Results and discussion

We report here (Fig. 3) the results obtained by Weissbach *et al.* Despite the inevitable margins of uncertainty, these results provide reliable indications for the main generating systems: thermal power stations fuelled by fossil carbon fuels, biomass or nuclear fuel; installations converting solar and windpower directly into electrical energy.

In the case of solar and wind power, the enormous impact on the EROI of taking into account devices for smoothing and balancing demand and electricity production (energy storage or back-up power, e.g. gas-fired power stations) can be seen. In this respect, it is worth noting the difference in order of magnitude between fluctuations in daily electricity demand (typically of the order of 10% of the average consumed power) and fluctuations in production from intermittent sources, which are of the order of the average power delivered (wind) or even the installed capacity (solar PV). This is why smoothing devices are taken into account. Unsurprisingly, the more diffuse the sources, the lower the EROI. As for nuclear power, we might expect an even higher EROI value given the concentration of this form of energy. This EROI limitation is essentially due to the high energy cost of uranium enrichment, combined with the low fuel utilisation rate in current reactors.

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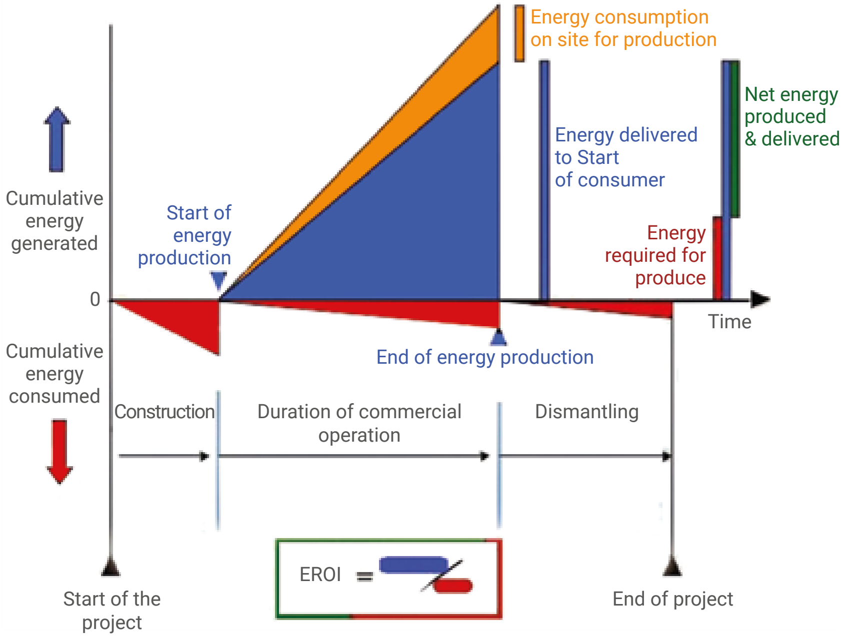

2. Simplified diagram for analysing the life cycle of an energy system.

1• V. Court et F. Fizaine, "Long-Term Estimates of the Energy-Return-on-Investment (EROI) of Coal, Oil, and Gas Global Productions", *Ecological Economics* **138** (2017) 145–159 (http://dx.doi.org/10.1016/j.ecolecon.2017.03.015).

2• E. Dupont *et al.*, "Global available wind energy with physical and energy return on investment constraints", *Applied Energy* **209** (2018) 322-338. (https://doi.org/10.1016/j.apenergy.2017.09.085).

3• E. Dupont *et al.*, "Global available solar energy under physical and energy return on investment constraints", *Applied Energy* **257** (2020) 113968, (https://doi.org/10.1016/j.apenergy.2019.113968).

4• P. Prieto et C. Hall, *Spain's Photovoltaic Revolution: The Energy Return on Investment*, Springer (2013).

5• D. Weissbach *et al.*, "Energy intensities, EROIs, and energy payback times of electricity generating power plants", *Energy* **52** (2013) 210-221 (http://dx.doi.org/10.1016/j.energy.2013.01.029);
"Energy intensities, EROI (energy returned on invested), for electric energy sources", *EPJ Web of Conferences* **189** (2018) 00016 (http://doi.org/10.1051/epjconf/201818900016).

6• C.F. Jordan, "The Farm as a Thermodynamic System: Implications of the Maximum Power Principle", *Biophys Econ Resour Qual* (2016) 1:9. (doi:10.1007/s41247-016-0010-z).

7• S. Harchaoui et P. Chatzimpiros, "Energy, Nitrogen, and Farm Surplus Transitions in Agriculture from Historical Data Modeling. France, 1882-2013", *Journal of Industrial Ecology* **232** (2018) 412-425. (doi: 10.1111/jlec.12760).

8• I. Capellán-Pérez *et al.*, "Dynamic Energy Return on Energy Investment (EROI) and material requirements in scenarios of global transition to renewable energies", *Energy Strategy Reviews* **26** (2019) 100399 (https://doi.org/10.1016/j.esr.2019.100399).

9• C. de Castro et I. Capellán-Pérez, "Standard, Point of Use, and Extended Energy Return on Energy Invested (EROI) from Comprehensive Material Requirements of Present Global Wind, Solar, and Hydro Power Technologies", *Energies* **13** (2020) 3036 (doi:10.3390/en130123036).

10• O. Vidal *et al.*, "Metals for a low-carbon society", *Nature Geoscience* **6** (2013) 894-896.

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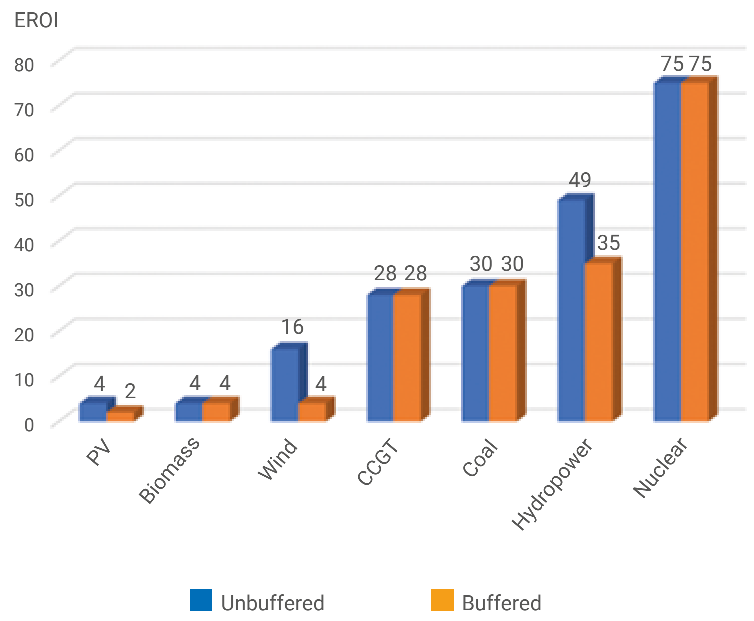
The poor performance of photovoltaic solar energy could raise questions. It is the subject of fierce debate, but the values obtained by Weissbach *et al* [5] (for Germany) are comparable to those of Prieto and Hall [4] (for Spain), obtained using a different methodology. A detailed comparison of the two approaches has been carried out, which is made difficult by the variety of assumptions made, in particular concerning the boundary conditions considered and whether or not management of intermittency is taken into account. In fact, the results of analyses limited to a single photovoltaic panel, although interesting for comparing technologies, cannot be directly compared with those that consider the installation as a whole, including its integration into the electricity grid.



3. EROI of the main electricity generating technniques [2, 3](e).
For dispatchable sources, the buffered and unbuffered values are identical. For intermittent sources, the energy storage allowing a production in equilibrium with demand is taken into account.
CCGT stands for Combined Cycle Gas Turbine. In the case of hydroelectricity, the buffered value corresponds to the installation of an energy transfer by pumped water, see page 119. In the case of nuclear, a lifetime expectancy of 60 years is assumed, and enrichment is operated by centrifugation.

Societal EROI(d)

An estimate of societal EROI can be obtained from the weight of the energy sector in the Gross Domestic Product (GDP). For OECD countries, this weight is around 7%. Its inverse gives a value of between 14:1 and 15:1. If we weight this value by the ratio between primary and final energy, which in France is 1.9, this gives a societal EROI of 7.5:1. This value is much lower than the EROI values for energy sources, most of which are fossil fuels. This difference can be explained by the fact that societal EROI takes into account the systems needed to make energy usable by consumers, unlike standard EROI.

The low weight of the energy sector in GDP should not be taken as an indication of its low economic importance. In fact, energy is not a separate field; it is involved in all sectors of activity, since it measures their production capacities (see the article by G. Bonhomme and H. Safa, p. 18).

One aspect that should not be overlooked is the impact of the EROI of the sources used, and its evolution over time, on total energy consumption. The lower the EROI of these sources, the greater the need to increase total energy production in order to maintain the amount of net energy needed to cover the energy services required by society. Two recent studies [8, 9] examine this in the context of scenarios developed to substitute renewable resources for fossil fuels in the production of electrical energy.

Other analysis criteria

Let's take a quick look at the other criteria that need to be considered to characterise energy systems, which will be the subject of specific articles in this issue.

Mineral resources

The issue of natural resource extraction is very different for stock energy and flow energy. In the first case, it's a question of supplying the fuel itself (carbon or nuclear), whereas in the second case, it's a question of the mineral resources needed to manufacture the devices for capturing and converting the flows (mainly solar or wind power). These flows are indeed inexhaustible, but the facilities needed to convert them into electrical energy mobilise a large number of material resources [10], which are all the more important in terms of quantity because they are low-intensity energies. This crucial issue of mineral resources - which constitute exhaustible stocks - is the subject of a specific article in the fifth part of this issue (p. 144).

Other environmental impacts and health risks

In addition to the major environmental impact of greenhouse gas emissions resulting from the use of fossil fuels, which alone justifies the need for a transition to carbon-free processes, there are other categories of impact associated either with the implementation and operation of installations and possible accidents, or with the production of waste, inherent in any type of technology. Here too, an article in Part Five (p. 162) is devoted to the health impact of energy production and consumption.

Although they do not burn carbon fuels, renewable energies and nuclear power also generate carbon emissions, particularly during the construction and decommissioning phases. ADEME's data, in line with international assessments, are as follows:

- onshore wind: emission rate of 14.1 g CO_2 eq / kWh;
- offshore wind: emission rate of 15.6 g CO_2 eq / kWh;
- solar photovoltaic: emission rate of 55 g CO_2 eq / kWh.

In comparison, according to IPCC estimates, nuclear power generates 12 g CO_2 eq/kWh[f], gas-fired power plants 490 g CO_2 eq/kWh and coal-fired power plants 820 g CO_2 eq/kWh.

Conclusion

Many energy transition scenarios, seeking to comply with the Paris climate agreements and aiming for carbon neutrality by 2050, are based solely on cost criteria for the implementation of decarbonised sources. We have shown in this article that it is necessary to rely on objective physical criteria, first and foremost an assessment using the EROI. This is a fundamental issue for any society, because the maintenance and functioning of its structures and services (education, health, arts, etc.) can only be guaranteed if there is sufficient net energy - total available energy minus self-consumption by the energy sector. In this respect, the much-debated case of renewable energies, in particular electricity generation, must be analysed according to this criterion. This is all the more important given that other essential aspects need to be analysed separately, such as the availability of flows, the surface areas mobilised and mineral resource requirements. This is why specific articles are devoted to them in this issue.

> **"The maintenance and functioning of our society's structures and services can only be guaranteed if there is sufficient net energy available"**

(a) Energy is the physical quantity that quantifies all internal transformations and all exchanges with the external environment for any thermodynamic system. The concept of energy can therefore take many different forms. Of course, we are all familiar with the fundamental difference between heat and work, which the concept of energy made it possible to bring together at the start of the construction of thermodynamic science and the discovery of its fundamental laws (first and second principles). The concept of exergy was introduced to take into account the capacity of a given form of energy to be converted into mechanical work. Exergy thus refers to the maximum amount of work that can be recovered, and hence to the quality of a given form of energy can be characterised by the fraction of exergy contained in the quantity of energy in question. Assessing this fraction involves considering a thermodynamic transformation. The energy stored in fossil fuels, and measured by the enthalpy of combustion (lower or higher calorific value depending on the reference state), is in principle and ideally pure exergy, which then corresponds to Gibbs' free energy, because we can imagine its total transformation into work in a Carnot cycle, whose conversion efficiency is given by $1 - T_0/T$, within the limit of an infinite temperature ratio between the cold source and the hot source, which is of course never the case in reality. But this enthalpy content is not enough to characterise the quality of a form of energy carried by an energy vector (electricity, heat, etc.). Electricity is also pure exergy, but for heat, only part of which can be converted into mechanical work in a thermodynamic cycle, the exergy fraction is measured by the efficiency of the ideal Carnot cycle, and obviously depends on its temperature. (See for example V. Court, "An Estimation of Different Minimum Exergy Return Ratios Required for Society", *BioPhysical Economics and Resource Quality* (2019) **4**:11, https://doi.org/10.1007/s41247-019-0059-6).

(b) A living being converts part of its daily food intake into muscular energy enabling it to act on its environment and thus to move and collect its food. A threshold EROI would then correspond to the situation where it would have to mobilise all of this muscular energy to collect food, which would obviously leave it with no surplus. For a human being, if we calculate the ratio between the average power dissipated of 125 W and around 25 W of average muscle power, we find a threshold EROI of 125/25 = 5. This is, of course, the inverse of the efficiency of converting food intake into muscle energy. This minimum value shows that there is already an essential threshold corresponding to the need to satisfy all the metabolism's own energy requirements. The same applies to a society that must be able to feed itself and beyond at the lowest energy cost, without negatively impacting the needs of its own metabolism, its supply of energy and resources from the environment.

(c) Remember that a mass of matter involved in a nuclear reaction involves an energy several million times greater than that of the same mass involved in a chemical reaction.

(d) An assessment of a societal EROI based on physical quantities would require, by analogy with the muscular energy expended by a living being to take its food from its environment, accounting for all the exergy expenditure made to extract from the environment the resources needed to fuel the boilers, build the capture and storage facilities and the distribution infrastructures for all the forms of energy taken and made available to society. An absolute threshold could be estimated by considering that all the mechanical and electrical energy available would be consumed by the energy sector, which would obviously leave nothing to satisfy other needs essential to the functioning of society.

(e) It can be argued that the procedure fo calculating the EROI of different electric generation sources separately (buffered values in Fig. 3) does not correspond to any practical situation, since an electric mix is made up of a mixture of different sources, both dispatchable and non-dispatchable: the need for storage must be calculated for a given mix. Preliminary studies by D. Grand et al. show that, in case of a large fraction of intermittent sources in the mix, the amount of storage needed to adapt production to consumption is governed by inter-seasonal variations — and not by short-term fluctuations. In case of an equal mixture (in terms of annual production) of dispatchable and non-dispatchable sources, the EROI can be reduced by a factor of around 3, compared with a mix dominated by dispatchable sources.

(f) 6 g CO_2 eq/kWh in France according to ADEME data.