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Evolution of EROIs of Electricity Until 2050: Estimation Using the Input-Output Model THEMIS

Adrien Fabre[1] , **PRELIMINARY VERSION**

Abstract

The EROI –for Energy Returned On Invested– of an energy technology measures its ability to provide energy efficiently. Previous studies draw a link between the affluence of a society and the EROI of its energy system, and show that EROIs of renewables are lower than those of conventional fossil fuels. Logically, concerns have been expressed that system-wide EROI may decrease during a renewable energy transition. First, I explain theoretically that the EROIs of renewables themselves could then decrease as energy-efficient fossil fuels would be replaced by less energy-efficient renewables in the chain of production. Then, using the multiregional input-output model THEMIS, I estimate the evolution of EROIs and prices of electric technologies from 2010 to 2050 for the baseline and the Blue Map scenarios of the International Energy Agency, and for the 100% renewable Greenpeace's electricity [r]evolution scenario. Global EROI of electricity is predicted to remain quite stable, going from 8 in 2010 to 6 or 7 in 2050, depending on the scenario. Finally, I study the economic implication of a declining EROI through its relation with price. I show that in theory both quantities can decrease at the same time. This suggests that the inverse relation found empirically represents an average tendency which should not overshadow the high unexplained variability and the theoretical finding that "anything can happen".

Keywords: EROI; input-output; THEMIS; MRIO; sustainability; energy transition

Acknowledgments. I am grateful to Thomas Pregger and his team at DLR for graciously providing me the tables of future energy consumption in the Greenpeace [R]evolution scenarios. I am indebted to Thomas Gibon, Anders Aversen and the Norwegian University of Science and Technology (NTNU) for providing me the data of THEMIS and helping me using it. I am thankful Arjan de Koning for answering my questions related to Cecilia 2050. I hail the work of Konstantin Stadler on pymrio, an invaluable open-source python library when dealing with Multi-Regional Input-Output Tables (MRIO). I am grateful to Cyril François for his thoughtful comments on this project. I am thankful to the Isterre for providing me an office at Grenoble to conduct this research. I am grateful to Olivier Vidal and Mouez Fodha for their support.

Code. All the code is on-line, and can be accessed from a notebook at: bit.ly/future_eroi_code. A substantial share of this work has been to contribute to the python library *pymrio*: github.com/bixiou/pymrio. Using my fork of pymrio, one can now easily undertake EROIs and related computations on Exiobase and THEMIS.

1. Introduction

As the harmful impacts of climate change call for a prompt energy transition away from fossil fuels —not to mention their depletion that shall ultimately make this transition unavoidable, concerns have been expressed that, in a decarbonized energy system, the lower efficiency of renewable energy might not allow to sustain advanced standards of living [26, 34].[2] We measure the energy efficiency of a technology or energy system using the Energy Returned On Invested (EROI), which is the ratio between the energy it delivers throughout its lifetime and the energy required to build, operate and dismantle it. A minimal requirement for a technology or energy system to be energetically sustainable is to have an EROI above 1, meaning that it provides more energy than it requires.

One issue to assess future energy systems is that the future EROI of a given technology cannot be readily deduced from current estimates. Indeed, as King [22] remarked, the EROI of a technology is not intrinsic, but depends on the whole technological structure of the economy. To see this, let us suppose that the plants where solar panels are built employed renewable electricity instead of electricity from coal as their sources of energy. Then, provided that the EROI of renewable electricity is lower than that from fossils, the energy required to build solar panels will increase, and their EROI will

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[2] The energy expert Jean-Marc Jancovici also expressed concerns over this subject during a presentation at the École Normale Supérieure in 2018: "What happens to the EROI when you have only wind and solar panels to build wind and solar panels? I think it crashes."

decrease. Surprisingly, it seems that no study has aimed at estimating future EROIs while taking this system dependency into account, although some have called for such studies [4].[3] Yet, granted that EROIs of renewables are lower than EROIs of fossils and that decreasing EROIs jeopardize prosperity, the evolution of EROIs during the energy transition is of critical importance: let us review these two motivations in turn.

Many estimations of EROIs have been made, and among the various different figures derived from diverse data sets and methodologies, none stands out as singularly authoritative. Dale [9] reviews all EROI estimates until 2010, while Hall et al. [16] aggregate the estimates of the literature in a meta-analysis. I choose to present the results of Weißbach et al. [35] (see Figure 1), because they compute the EROIs of different technologies in a comparable manner. In addition, the *buffered* EROIs of Weißbach et al. [35] take into account the supplementary capacity, grid and storage required for the deployment of renewable technologies, which yields lower but presumably more accurate estimates for their EROIs. As anticipated, the EROIs of renewable electricity sectors they find are significantly lower than those of electricity from fossil fuels, except for hydro.

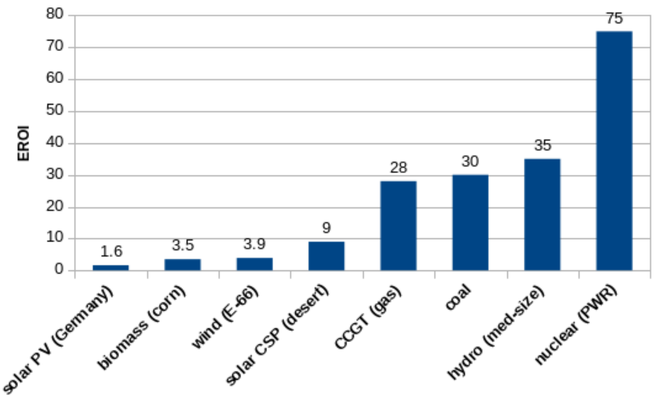

Figure 1: Estimates of EROIs of different electricity technologies, from Weißbach et al. [35], where supplementary capacity and storage required for the deployment of these technologies is accounted for.

Furthermore, some authors argue that the value of EROI is of primary relevance, as they draw a link between the system-wide EROI and affluence of a society [15, 25, 26, 11]. Here is how Hall [14] summarizes the argument:

> Think of a society dependent upon one resource: its domestic oil. If the EROI for this oil was 1.1:1 then one could pump the oil out of the ground and look at it. (...) Hall et al. [15] examined the EROI required to actually run a truck and found that if the energy included was enough to build and maintain the truck and the roads and bridges required to use it (i.e., depreciation), one would need at least a 3:1 EROI at the wellhead. Now if you wanted to put something in the truck, say some grain, and deliver it that would require an EROI of, say, 5:1 to grow the grain. (...) 7 or 8:1 to support the families. If the children were to be educated you would need perhaps 9 or 10:1, have health care 12:1, have arts in their life maybe 14:1 and so on.

The reasoning of Hall relies on the observation that all sectors of the economy require energy, and that the more efficient is the energy production (i.e. the higher is the EROI), the more energy is available to the rest of the economy. In strict logic, Hall's argument relies on two questionable assumptions: that factors of production (and especially the labor force) are used at their full capacity, and that technical and organizational progress will not be sufficient to sustain current level of prosperity with significantly less labor (or other factors of production in limited supply). In rejection of these assumptions, one can imagine a sustained level of prosperity with a lower system-wide EROI, provided that a higher share of factors of production be devoted to the energy sector. That being said, given that current system-wide EROI is already declining due to the decline in fossil fuels quality [8, 31, 7] and that technical progress is incremental, the aforementioned analyses should not be neglected. Under the current system of production, which will persist in the short term, EROI should stay largely above 1 and not decrease too much for prosperous standards of living to be sustained. Admittedly, a system-wide EROI close to the theoretical lower bound of 1 might fuel an industrial civilization in the very long run as long as the resources required for the massive deployment of energy systems are available (this is not guaranteed, as human labor, land and materials are in limited supply and may be required for other use). However, in the medium term and with more sensible scenarios, a diminishing EROI would probably imply that a substantial share of the labor force will shift their occupation to the energy sector.

In view of the potential implications of a declining EROI, this paper provides an assessment of the EROI of different electricity technologies in various prospective scenarios, which includes a 100% renewable electricity system. To this end, I employ input-output analysis and I rely on a prospective series of multi-regional Input-Output Tables (IOT): THEMIS [13], which models two scenarios from the International Energy Agency [20]: Baseline and Blue Map. Then, I further modify THEMIS' IOTs to embed two decarbonized scenario of power generation: Greenpeace's Energy [R]evolution (ER) and Advanced Energy [R]evolution (ADV) [33]. Although Pehl et al. [30] and Arvesen et al. [2] computed energy requirements similar to mine in some respects, this work is the first to estimate EROIs in a scenario with 100% renewable electricity (the ADV scenario).

Then, I analyze the economic implications of a declining EROI through its relation with price. Admittedly, previ-

[3] Admittedly, King [22] provided a numerical application of the system dependency of EROI (see his Table 4), but his computations had a purely illustrative purpose and his input values were not supposed to be accurate: this is why he did not even comment on the result that the EROI fell incidentally below 1 in his 100% renewable mix.

ous studies suggest an inverse relation between EROIs and energy prices, and such an average relation is retrieved empirically using prices observed and predicted from THEMIS. Yet, such a simple rule does not withstand a careful theoretical analysis. Indeed, while explaining to what extent EROI and price are related, I will show that they do not necessarily move in opposite directions. This calls for taking prices predictions from input-output analysis with more caution than EROI estimates, because IOT is better suited to handle physical notions than economic ones. Finally, the economic analysis weakens the view that a decrease in EROI would necessarily lead to a surge in energy expenditures and hence to a contraction of GDP.

Section 2 explains theoretically why the EROI of a technology is not an intrinsic property; section 3 presents the methodology and the results; section 4 studies the implications of declining EROIs on prices and GDP; section 5 concludes.

2. The EROI of a Technology Is Not Intrinsic

2.1. A Simple Model With A Unique Energy Technology

The element $a_{i,j}$ of the technology matrix A represents the quantity of input i required to produce one unit of output j. Below is an illustrative technology matrix with three inputs (and the same three outputs): an energy technology, materials, and energy. m_e denotes the quantity of materials (m) required to produce one unit of energy technology (e), and this notation extends naturally to all elements of A. The numerical values of the coefficients have a purely pedagogical purpose and have been arbitrarily chosen; taking other figures would not change qualitatively the results.

$$A = \begin{pmatrix} 0 & 0 & 1 \\ m_e & m_m & 0 \\ E_e & E_m & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 \\ m_e & 0.2 & 0 \\ 0.1 & 0.5 & 0 \end{pmatrix} \begin{matrix} \text{energy techno.} \\ \text{materials} \\ \text{energy} \end{matrix}$$

The system-wide EROI, or Energy Returned On Invested, is the ratio between the energy delivered by the system, and the energy required to build, operate, maintain and dismantle it. In other words, it is the inverse of the amount of energy required to produce one unit of energy, when the series of all embodied inputs are taken into account.

The embodied inputs x required for a final demand y can be calculated using the well known formula [27, 10, 28]:

$$x(y) = (I - A)^{-1} \cdot y.$$

We denote by $\mathbb{1}_S$ the vector with 1 at the positions of the sectors $s \in S$, and zeros everywhere else. As energy E is the last input of our list, $\mathbb{1}_E = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$ and the gross embodied energy required for a final demand y is the last element of x: $\mathbb{1}_E^T \cdot (I_n - A)^{-1} \cdot y$. Thus, the EROI is

$$\begin{aligned} \text{EROI} &= \frac{\text{delivered energy}}{\text{net embodied energy}} \\ &= \frac{1}{\mathbb{1}_E^T \cdot \left((I - A)^{-1} \cdot \mathbb{1}_E - \mathbb{1}_E \right)}. \end{aligned}$$

After some calculations, we find:

$$\begin{aligned} \text{EROI} &= \frac{(1 - E_e)(m_m - 1) + E_m m_e}{E_e (m_m - 1) - E_m m_e} \\ &= \frac{0.72 - 0.5 m_e}{0.08 + 0.5 m_e} \end{aligned}$$

Unsurprisingly, one can see in Figure 2 that the EROI decreases with the material intensity of the energy technology, because extracting and processing material requires energy.

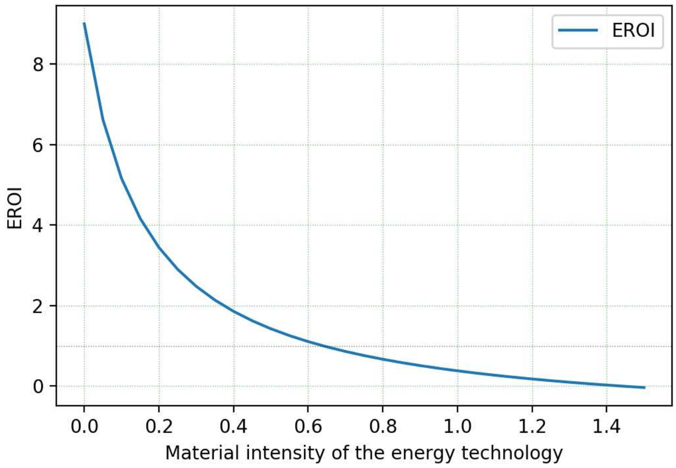

Figure 2: EROI in the simple model in function of the material intensity m_e of the energy technology.

For an intensity above 0.6, the EROI is below 1. An EROI below 1 means that the energy technology is not worth developing, because (in net) it consumes energy rather than providing it. Such a system is not sustainable (and not realistic): for it to happen the society should have accumulated energy in the past from an energy source no more accessible, and would waste this energy in that absurd technology.

For even higher intensities, the EROI falls below 0, which means that the energy (recursively) required to produce one unit of energy is infinite. Here, free energy coming from the past would not suffice to build the energy technology: one would also need to have free materials (i.e. materials requiring no energy to access them). Such a world is physically impossible.

2.2. A Simple Model With A Mix of Two Technologies

Now, let us consider two energy technologies, with the same energy intensity, but different materials intensities.

Even if this example is purely illustrative, let us call them PV (for solar photovoltaic) and gas (for gas power-plant electricity) to grasp the motivation for this paper. The numbers are completely made up, but they respect the fact that PV is more material intensive than gas [18]. Here is our new technology matrix, where p represents the share of PV in the energy (or electricity) mix.

$$A = \begin{pmatrix} 0 & 0 & 0 & p \\ 0 & 0 & 0 & 1-p \\ m_{PV} & m_g & m_m & 0 \\ E_{PV} & E_g & E_m & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & p \\ 0 & 0 & 0 & 1-p \\ 0.7 & 0.1 & 0.2 & 0 \\ 0.1 & 0.1 & 0.5 & 0 \end{pmatrix} \begin{matrix} \text{PV} \\ \text{gas} \\ \text{materials} \\ \text{energy} \end{matrix}$$

With some calculus, we obtain:

$$\text{EROI} = \frac{0.67 - 0.3p}{0.13 + 0.3p}$$

This corresponds to the system-wide EROI. But now that we have two technologies, we can compute the EROI of each of them:[4]

$$\text{EROI}_{PV} = 1.558 - 0.698p$$
$$\text{EROI}_{gas} = 5.154 - 2.308p$$

Logically, the EROI of PV is lower as compared to gas because of its higher material intensity. But it is worth noticing that both EROIs depend on the energy mix p: the EROI of a technology is not an intrinsic property. Indeed, it depends on the whole economic system, or more precisely, of all technologies used in their chain of production.[5] Here, the higher the share of PV in the mix, the more the lower EROI of PV contaminates each technology, and the lower the EROI of both technologies.

One can see on Figure 3 that for highest penetration of PV, the EROI falls below unity. In other words, a renewable energy mix with 100% PV is not sustainable in this example. Even more worryingly, if one computes the EROI of PV in an energy mix relying mostly on gas, one would find a high-enough EROI for PV (meaning, above 1). Hence, one cannot conclude that a technology is sufficiently efficient (or sustainable) just by computing its EROI in the current energy mix. Yet, EROIs computations have always been done from actual data of our economy, and could falsely represent the efficiencies of energy technologies in another energy mix, say, a 100% renewable one. This uncertainty concerning the sustainability of a decarbonized energy system motivates the core of this paper: the estimation of EROIs after a global energy transition.

[4] Similarly to the system-wide EROI, the EROI of a technology is the ratio between the energy delivered by one unit of this technology (over its lifetime), and the energy required to build, operate, maintain and dismantle it.

[5] *Chain of production*, *recursive* or *embodied inputs* are synonyms; their analysis is known as *structural path analysis* in the literature.

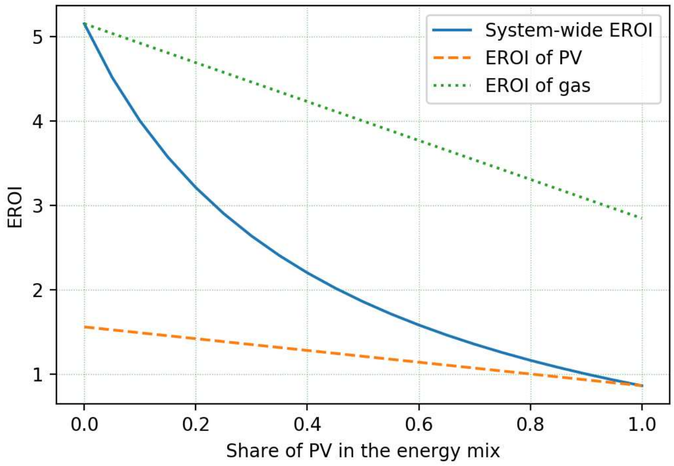

Figure 3: EROIs in the two-technology model in function of the share p of PV in the energy mix.

3. Estimation of Current and Future EROIs Using THEMIS

3.1. Setting and Data

Different notions of EROIs have been used in the literature, and some papers clarify them all (e.g. [5, 29]). The most relevant notion for this research is defined by Brandt & Dale [5] as the Gross Energy Ratio (GER) and called by King [22] the net external energy ratio.[6] The GER measures the ratio of energy delivered over energy embodied in inputs net of the energy of the fuels used in the process. Thus, for example, the denominator of the GER does not take into account the energy provided by gas in a gas powered plant. The term "gross" is used because all energy output is taken into account; on the contrary Net Energy Ratios subtract from the numerator all "self-use" output that is used in the pathway of production of the technology.[7] A related indicator that is sometimes used to compute EROI as it is already included in many input-output databases is the Cumulated Energy Demand (CED). I do not use it because Arvesen & Hertwich [1] have shown that it is erroneous to use the CED directly for EROI computations, without making adjustments.

In most cases, EROIs (or energy ratios) are defined using quantities of primary energy. However, I adopt a different approach in this paper, and use only secondary energies in my computations. Indeed, as Arvesen & Hertwich [1] put it, "EROI does not need to measure primary energy per se; the crucial point is to measure energy diverted from society in a unit of equivalence". Also, the choice of secondary energy carriers is consistent with an energy system relying on

[6] The terminologies of these two papers are not compatible. I follow Brandt & Dale [5], as their paper aims at harmonising the terminology.

[7] For King, 'gross' energy is the total energy diverted from Nature while 'net' is the output of energy from the technology, what Brandt and Dale call 'gross'. Furthermore, King would qualify 'external' any notion that subtract direct fuel inputs from the denominator (rather than just subtracting the output), while Brandt and Dale always take this as a base case, and employ 'external' when indirect self-use inputs are also subtracted: it mirrors their notion of 'net' for the denominator.

renewable electricity, while for such systems the definition of primary energy is not harmonized and this can lead to inconsistencies: Frischknecht et al. [12] spot for example a factor 6 between the cumulative (primary) energy demand for solar photovoltaic computed according to different methods. Although the sectors bringing energy are not the same in the two approaches (the primary approach uses crude oil when the secondary approaches uses gasoline, for example), both approaches are equally valid.

Furthermore, practitioners often use a factor of conversion (around 3) to account for the higher quality of electricity as compared to fossil fuels. I follow the recommendation of Murphy et al. [29] by undertaking my computations without and with a quality-adjustment factor of 2.6. However, I prefer not to bring to the fore the quality-adjusted computations, provided in Appendix C, and I focus instead on non-quality adjusted EROIs. The reason for this is that the factor of conversion is not well established: it represents the inverse of the yield of a thermal power station (about 38%), but this yield depends on the technology and on the fuel used. Moreover, for certain usage like heating, the yield of fossil fuels is close to that of electricity, and fossil fuels are disproportionately used for these applications for which they have a higher yield, therefore the difference in quality between fossils and electricity may be smaller than usually assumed.

To avoid the possible ambiguity of sentences, I reproduce below the formulas used to compute the EROI for a technology (or an energy system) t, which I denote GER_t^{2nd}. Let us recall that y is the vector of final demand, given by the scenario, and A is the technology matrix (or input-output table). E^S is the vector of unitary energy supply per sector, meaning that E_t^S is the energy supplied by one unit of sector t, hence $E^S \cdot y_t$ gives the energy supplied by the technology t:[8]

$$\text{supply}_t = E^S \cdot y_t$$

$\odot$ (resp. $\oslash$) denotes the Hadamard (or entrywise) product (resp. division), so that $E^S \odot \mathbb{1}_{\text{secondary}}$ is the vector of unitary *secondary* energy supply. The main term at the denominator of the *GER* is the secondary energy embodied in inputs, net of the energy supplied by the technology:

$$\text{net secondary embodied}_t = E^S \odot \mathbb{1}_{\text{secondary}} \cdot \left((I-A)^{-1} \cdot y_t - y_t\right)$$

To this term, we also need to subtract the energy supplied by the secondary fuels in the last step of the process[9] (logically, this term is nil for renewables). Indeed, such energy is not used to build or maintain the energy system; rather, it is an energy transformed and delivered by the energy technology.

$$\text{fuel input}_t = E^S \odot \mathbb{1}_{\text{secondary fuel}} \cdot A \cdot y_t$$

Finally, we have:

$$GER_t^{2nd} = \frac{\text{supply}_t}{\text{net secondary embodied}_t - \text{fuel input}_t}$$

I apply these formulas to the IOTs (i.e. technology matrices A) and the vectors of unitary energy supply E^S from THEMIS [13]. THEMIS contains hybrid input-output tables: precise data on electricity units (the *foreground*) is completed with data on other sectors that originates from life cycle inventories and national accounts (the *background*). Gibon et al. [13] have compiled various life cycle inventories into the 609 sectors of the foreground. The background contains data in physical units for 4,087 sectors from the life cycle inventory ecoinvent and data in monetary units for 203 sectors from the input-output database Exiobase 2 [36]. The 44 Exiobase regions are aggregated into 9 macro-regions that coincides with those of the International Energy Agency (IEA), so that the number of rows and columns in each IOT is 9 times the number of sectors: 44,046. Starting from data of the 2010 IOT, the 2030 and 2050 IOTs of THEMIS embed expected technological efficiency improvements of key sectors. Furthermore, it is worth noting that THEMIS IOTs are constructed as if the whole economy were at a steady-state, contrarily to national accounts, which give the flows between sectors for a given year. This matches perfectly our purpose, because there is no need to adjust the EROI computations for the growth of some sector or for the lifetimes of some technologies.

The two scenarios native in THEMIS are the baseline (BL) and the Blue Map (BM) scenarios of the IEA [20]. While the former posits an almost constant electricity mix, the latter is compatible with a 50% probability to contain the global mean temperature anomaly to +2°C in 2100. As Blue Map still relies at 30% on fossil fuels based electricity in 2050 —including 17% with Carbon Capture and Storage (CCS); it does not allow to assess more decarbonized scenarios. Hence, I combined with THEMIS the scenarios from Greenpeace's Energy [R]evolution report [33]. Greenpeace proposes a business as usual scenario (REF) close to baseline, as well as two scenarios compatible with the 2°C target. Both exclude CCS and phase out from nuclear between 2012 and 2050.[10] The first Greenpeace scenario, Energy [R]evolution (ER), comprises 93%

[8] In practice, y is obtained from the scenario of energy demand from the IEA:

$$y_t = \left(\text{demand}_t \oslash E_S\right) \odot \mathbb{1}_t.$$

[9] Technically, we would need to subtract secondary fuels to all similar steps in the embodied inputs, for each embodied input that uses a thermal power plant. However, I neglect these terms, as this would complicate the presentation for no significant difference in the result: a variation in the value of *fuel input* below 0.1% for all technologies considered.

[10] The study funded by Greenpeace was in fact conducted by researchers at the Institute of Engineering Thermodynamics of the German Aerospace Center (DLR), who applied their model REMix. Using the same model, Berrill et al. [3] minimize the cost of European electricity generation under different carbon prices. Interestingly, an outcome of the model was to phase nuclear out, but to select coal with CCS. This indicates that the choices of Greenpeace were not solely motivated by a minimization of costs, but also by expert judgment and ethical considerations.

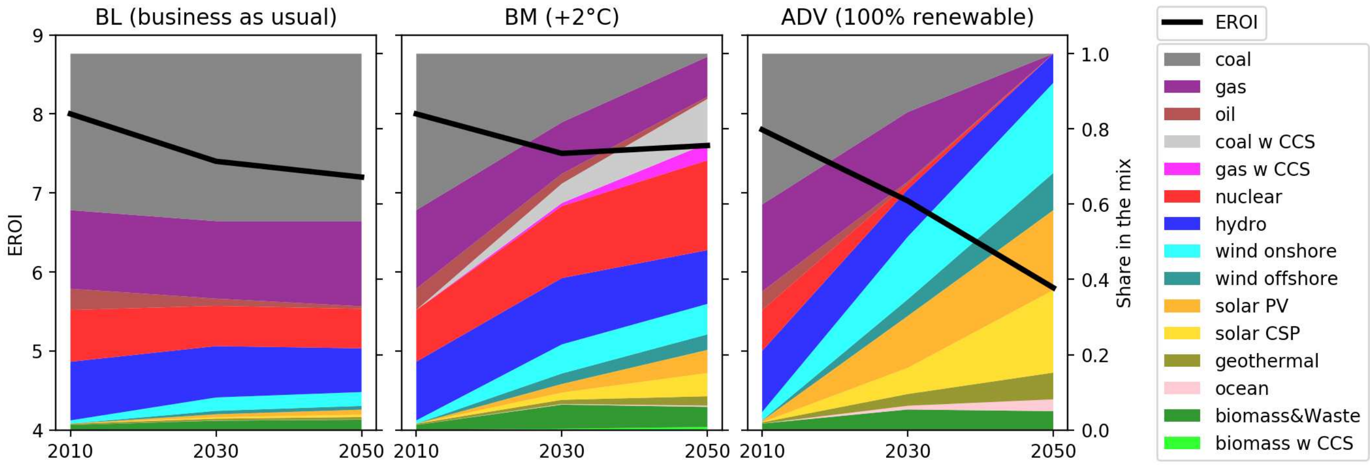

Figure 4: Evolution of global EROIs and mixes of electricity for different scenarios.

of electricity from renewable sources in 2050, while the second one, Advanced Energy [R]evolution (ADV), attains 100% renewable. As the difference is small between these two scenarios, I focus on the 100% renewable one. I describe my methodology for embedding the regional electricity mixes of Greenpeace's scenarios into THEMIS in Appendix A.

In the literature, most EROIs estimations follow a bottom-up approach that use data from life cycle inventories. Bottom-up studies describe in details the power facilities and the most direct inputs to the energy technologies —the *foreground*, but they do not cover the *background*: indirect inputs such as clerical work or R&D. On the contrary, the input-output method allows to encompass all embodied inputs exhaustively. As a consequence of this more comprehensive account of embodied energy than usual, we expect estimates of EROIs lower than the average of the literature. That being said, it is not a concern if our estimates are not directly comparable to those of the literature, as we are mainly interested in comparing them internally, among the different years and scenarios, and to scrutinize whether they vary substantially or not.

Because renewable sources are intermittent and dispersed, the capacity, grid extension and storage they require do not increase linearly with the electricity delivered. Hence, as Greenpeace scenarios are not native in THEMIS, they need further adjustments to account for these non-linearities. I explain in Appendix A how the need for surcapacity is addressed. Concerning transmission and storage, however, the requirements are not given by the Greenpeace report [33], so they have not been taken into account. Even if the report does not precise any plan relative to storage, hydrogen produced from renewables seems to play a substantial role in Greenpeace scenarios, as its share in the electricity mix is 5% in ADV 2050. However, as the sector 'Electricity from hydrogen' is absent from THEMIS, hydrogen has been excluded from this analysis. These limitations should be addressed in future work, together with the study of an energy transition in the transportation sector (which also relies on hydrogen). Meanwhile, other references can provide information on orders of magnitude of storage and transmission [3, 24, 32]. Applying the same optimization model that is used in the report, Scholz et al. [32] show that the cost of storage and transmission combined is 4.6% of total cost in a business-as-usual scenario and 10.6% in a 100% renewable one. The adjustment needed for the cost, around 6%, gives a rough estimate of the upward bias of unadjusted EROI estimates (see section 4.2 on the relation between price and EROI).

Finally, data for Concentrated Solar Panels (CSP) had to be adjusted, because the original data mistakenly contained an energy supplied by unit of solar CSP of 0 (leading to abnormally low EROIs, around 2). Backed by Thomas Gibon, core developer of THEMIS, I corrected this error by setting the unitary energy supplied for solar CSP in all regions to its value in *OECD North America* (still letting the value depend on the scenario and the year).

3.2. *Main Results*

Main results are shown in Figure 4 and in Table 1, while complementary results can be found in Appendix C, notably for quality-adjusted EROIs. Some EROIs are missing, because not all technologies already existed on an industrial scale in 2010, and some technologies are discarded in the future by some scenarios. One can notice that, as expected, PV and wind panels have a lower EROI than electricity from fossil fuels. The EROIs of renewables decrease, as anticipated in the previous section. However, they remain largely above 1, suggesting that renewables are truly sustainable energetically. The system-wide EROI for the entire electricity sector is given at the bottom line. It is currently 8.0; it decreases slightly until 7.4±0.2 in 2030 and 2050 in both IEA/THEMIS scenarios. Unsurprisingly, the decrease is a little more pronounced in the scenario with 100% renewable electricity: at 6.9 in 2030 and 5.8 in 2050.

While EROIs of renewable technologies are lower in scenarios with higher shares of renewable, which was expected, one may be surprised that global EROI is slightly lower in the Baseline scenario (7.2 in 2050) than in Blue Map (7.6), driven

Table 1: EROIs and share in electricity mix of electric technologies in the model THEMIS for different scenarios and years. The bottom line in columns *mix* gives the total secondary energy demand, in PWh/a.

Scenario	Baseline (BL)						Blue Map (BM, +2°)				ADV (100% renewable)			
Year	2010		2030		2050		2030		2050		2030		2050	
Variable	EROI	mix	EROI	mix	EROI	mix	EROI	mix	EROI	mix	EROI	mix	EROI	mix
biomass w CCS	–	0	–	0	–	0	4.6	0	4	0.01	–	0	–	0
biomass&Waste	11.3	0.01	6.2	0.02	5.8	0.03	5.5	0.06	5.2	0.05	5.2	0.05	4.6	0.05
ocean	5.5	0	2.4	0	2.9	0	3.7	0	5.8	0	4.8	0.01	4.9	0.03
geothermal	5.3	0	5.1	0.01	5	0.01	5.2	0.01	5.4	0.02	3.8	0.03	3.9	0.07
solar CSP	21.5	0	8.8	0	9.1	0.01	8.2	0.02	7.9	0.06	9.2	0.07	7.8	0.22
solar PV	9.2	0	7.4	0.01	7.1	0.01	6.3	0.02	6	0.06	5.4	0.14	4.7	0.21
wind offshore	9.3	0	10.9	0.01	10.5	0.01	7.6	0.03	6.2	0.04	6.5	0.04	6.4	0.1
wind onshore	9.4	0.01	9.2	0.04	8	0.04	7	0.08	7.3	0.08	7.1	0.17	5.8	0.24
hydro	13.1	0.16	11.8	0.14	11.8	0.12	12.7	0.18	13.1	0.14	11	0.13	10.9	0.08
nuclear	10.4	0.14	7.2	0.11	7	0.1	7.3	0.19	7.4	0.24	8.3	0.02	–	0
gas w CCS	–	0	–	0	7.4	0	7.9	0.01	9.1	0.05	–	0	–	0
coal w CCS	–	0	–	0	6.1	0	7.1	0.05	7.1	0.12	–	0	–	0
oil	8.2	0.06	9.5	0.02	9.6	0.01	9.4	0.03	7.3	0.01	9.9	0.01	–	0
gas	13.7	0.21	14.8	0.21	14.6	0.23	17.1	0.14	19.6	0.11	16.4	0.18	–	0
coal	12.6	0.42	11.3	0.45	11.3	0.45	11.4	0.18	12.4	0.01	10.3	0.16	11.5	0
Total (PWh/a)	8	19.76	7.4	34.29	7.2	45.97	7.5	28.01	7.6	40.22	6.9	36.74	5.8	64.04

by lower EROIs for gas (14.6 in BL 2050 vs. 19.6 in BM 2050) and coal (11.3 vs. 12.4). Although available in the on-line code (or on demand), regional estimates are not reported here. They show that EROIs of renewables, gas and coal are lower in BM as compared to BL in *OECD Europe* and *OECD Pacific*, but are almost all higher in the other regions. Unsurprisingly, the sign of the difference between both scenarios is the same for renewables and hydrocarbon in almost all cases, suggesting that the EROIs of gas and coal drive those of renewables. Hence, the higher EROIs of BM are probably due to the early shutdown of the least efficient thermal power plant in this scenario. Another unexpected result is the slight decrease of EROIs in the BL scenario, from 8 in 2010 to 7.2 in 2050. The examination of regional estimates reveals that this decrease is driven by the increasing share of regions with lower EROIs in the global mix, the EROIs in each region remaining quite stable.

4. Implications of a Decreasing EROI on Prices and GDP

The forecast of declining EROIs made in the previous section calls for an assessment of its economic implications. The main channel through which a decrease in EROI could affect the economy is arguably a rise in energy price (and correlatively, in energy expenditures). In this section, I review the literature on the relation between EROI and the price of energy, estimate it empirically, and extend a result from Herendeen [17] to characterize this relation. Although an inverse relation holds in special cases and has some explanatory power on observations, the theoretical analysis shows that "anything can happen". This theoretical result contrasts with the view that decreasing a EROI necessarily leads to a recession.

4.1. *Inverse Relation Proposed in First Studies*

King & Hall [23] point both theoretically and empirically that the price of a unit of energy p_t and the EROI of a technology t are inversely related. Defining the monetary return on investment MROI (i.e. the financial yield $\frac{\$_{\text{out}}}{\$_{\text{investment}}}$), they derive the formula:

$$p_t = \frac{\$_{\text{out}}}{E_{\text{out}}} = \frac{\text{MROI}_t}{\text{EROI}_t} \cdot \frac{\$_{investment}}{E_{\text{in}}} \qquad (1)$$

Heun & de Wit [19] find an equivalent formula. They designate MROI as the mark-up m_t, consider production costs per gross output $c_t = \frac{\$_{\text{investment}}}{E_{\text{out}}+E_{\text{in}}}$ and use their own notion of EROI:
$\text{EROI}_t^H = \frac{E_{\text{out}}+E_{\text{in}}}{E_{\text{in}}} = \text{EROI}_t + 1$, so that equation (1) rewrites

$$p_t = \frac{m_t}{\text{EROI}_t^H - 1} \cdot \frac{\$_{\text{investment}}}{E_{\text{out}}+E_{\text{in}}} \cdot \frac{E_{\text{out}}+E_{\text{in}}}{E_{\text{in}}} = \frac{m_t \cdot c_t}{1 - 1/\text{EROI}_t^H}$$

The problem with these formulas is that all variables move together: when EROI varies, so does the cost of production, so that we cannot predict the future price taking this cost as fixed. Heun & de Wit [19] acknowledge this; and thus study the empirical link between EROI and price.

4.2. *Empirical Relation Between EROI and Price*

Using US data on oil and EROI from [6], Heun & de Wit [19] regress p_t on the EROI.[11] They obtain a good fit even in their simplest regression ($R^2 = 0.8$), and find

[11] Although they claim that their explained and explanatory variables are respectively the cost of production and their notion of EROI, EROI^H, the former is indeed the producer price and the latter our more standard notion of EROI, according to the source of their data: Cleveland [6].

Table 2: Predicted average global price of electricity (in €/MWh)

year	2010	2030			2050		
scenario	all	BL	BM	ADV	BL	BM	ADV
price	27	28	30	30	28	30	32

$p_{\text{oil}} = \beta_0 \cdot \text{EROI}_{\text{oil}}^{-1.4}$.

This result is interesting, and documents a negative relationship between price and EROI, which is close to an inverse one. As the authors do not regress price on the inverse of EROI, one cannot compare such "inverse fit" with their "log-log fit". To undertake this comparison, I run these two regressions using all estimates of EROI computed using THEMIS, one for each combination of scenario, year, region and sector. To obtain the price corresponding to each EROI, I use the vector v of value-added per unit of each sector provided by THEMIS. Indeed, prices can be seen as emerging from value-added according to

$$p = v \cdot (I - A)^{-1}$$

because the price of s, p_s, is the sum of the value-added of inputs embodied in s: $v \cdot (I - A)^{-1} \cdot \mathbb{1}_s$. To the extent that the physical constituents and processes of a given technology will not change in an unexpected way, and as THEMIS models technical progress but not behaviors nor general equilibrium effects, the prices forecast using the above formula seem less reliable than the EROI estimates. For this reason, I report only the global average electricity prices of the main scenarios (see Table 2), but I do not detail the substantial variations between regions or sectors.[12]

Table 3 reports the results of both the log-log and the inverse fits. I ran each model twice: first, on all 2079 positive observations available, and then on the 104 observations for year 2010. To make the R^2 of the log-log fit comparable to that of the inverse fit, I compute it as the sum of squared errors between "observed" prices and predicted prices (instead of their respective logarithms). As all R^2 are between 0.53 and 0.57, the inverse fit is almost as accurate than the log-log fit. Moreover, although the elasticity of price on EROI estimated here is different from that found by Heun & de Wit [19] for oil (around −0.5 as compared to −1.4), both figures are close to 1. At first sight, empirical findings appear to confirm an inverse relation between price and EROI. However, Figure 5 shows that a high share of the variance in price remains unexplained by EROI, even more so for values of EROI around the global averages of 6-8, where the fit is almost flat and the errors substantial. In addition, theoretical analysis rejects the existence of a mapping between price and EROI.

4.3. *The Case Against Any Simple Relation*

Herendeen [17] shed new light on the theoretical relation by treating the question from its matrix form and introducing the concept of value-added. Herendeen showed how to

[12] The results are on-line and available on demand.

Table 3: Regressions of price on EROI (both estimated using THEMIS). All coefficients are significant at the 1‰ level.

Obs.	**N**	**Specification**	**Coefficients** *a*	*b*	R^{2a}
All	2079	$p = \frac{a}{EROI} + b$	85	18	0.54
2010	104		71	20	0.53
All	2079	$\log(p) = a \cdot \log(\text{EROI}) + b$	−0.57	2.0	0.57
2010	104		−0.44	1.9	0.57

[a] The R^2 given for log-log fits is not the original one, cf. text.

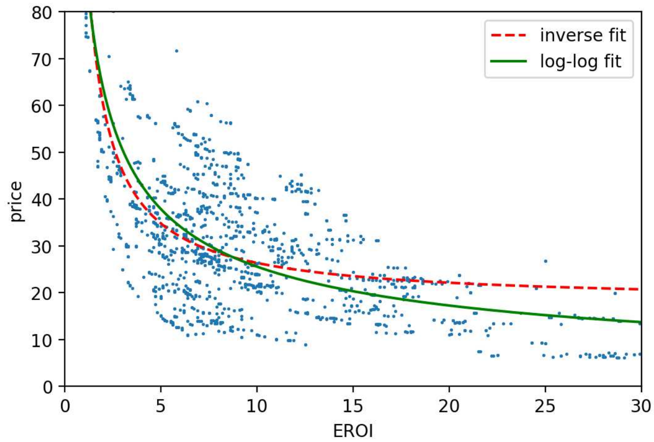

Figure 5: Regressions of price on EROI (all observations, from THEMIS).

express rigorously the price in function of the EROI when the economy is constituted of two sectors (energy and materials), and explained the limits of such exercise. Hereafter, I extend the results of Herendeen to an arbitrary number of sectors, n. First, I need to introduce one concept he uses: energy intensity.

To deliver one unit of energy technology t, the production mobilized is $(I - A)^{-1} \cdot \mathbb{1}_t$, while the energy mobilized, called the energy intensity of t, writes $\varepsilon_t = \mathbb{1}_E^T \cdot (I - A)^{-1} \cdot \mathbb{1}_t$, where E is the set of all energies.[13] ε_t is in fact the gross energy embodied in t, i.e. the sum of the delivered and the net embodied energy. Hence, the EROI of t is a simple function of ε_t: $\text{EROI}_t = \frac{\mathbb{1}_E^T \cdot \mathbb{1}_t}{\mathbb{1}_E^T \cdot ((I-A)^{-1} - I) \cdot \mathbb{1}_t} = \frac{1}{\varepsilon_t - 1}$.

In the following, I show that the price a technology t is a certain function of the coefficients of A,[14] and that each coefficient of A can be expressed as a function of EROI. Composing two such functions, we obtain that the price is inversely related to EROI. However, the relation is not unique (as it depends on the coefficient of A chosen to make the connection), and the other parameters in the relation are not constant. The demonstration starts with a lemma:

[13] I assume here that the unit of an output of an energy sector $e \in E$, hence of $\mathbb{1}_E^T$, is an energy unit, like TWh.

[14] More precisely, a function field of a certain algebraic variety.

Lemma 1. *Let A be an invertible matrix and let x be a coefficient of A. Then,*

(i) the determinant of A is a linear function of x, denoted D^A*;*

(ii) each coefficient (i,j) of the adjugate of A is a linear function of x, denoted $P^A_{i,j}$*;*

(iii) each coefficient (i,j) of A^{-1} *is a rational function in x of degree 1, which writes:* $\left(A^{-1}\right)_{i,j} = \frac{P^A_{i,j}(x)}{D^A(x)}$.

Proof. Let $A = \left(a_{i,j}\right)_{1\leq i,j\leq n} \in GL_n(\mathbb{R})$ and let $\left(i_0, j_0\right) \in [\![1;n]\!]^2$ so that, without loss of generality, $x = a_{i_0,j_0}$. (i) From its definition by the Leibniz formula, the determinant of A writes $\det(A) = \sum_{\sigma\in S_n} \operatorname{sgn}(\sigma) \prod_{i=1}^n a_{i,\sigma(i)}$. In this linear combination, each term is a product containing x at most once, it is thus a linear function of x. (ii) A minor being the determinant of a submatrix of A, we know from (i) that it is a linear function of x (which reduces to a constant for submatrices that do not contain x). Each coefficient of the adjugate of A is (plus or minus) a minor of A, hence a linear function of x. (iii) Using (i) and (ii) and the Laplace expansion of A: $A^{-1} = \frac{\operatorname{adj}(A)}{\det(A)}$, we reckon $\left(A^{-1}\right)_{i,j} = \frac{P^A_{i,j}(x)}{D^A(x)}$. □

Proposition 1. *(Generalization of [17]) Assuming that all coefficients of the transformation matrix A are constant except one, noted* $x = a_{i_0,j_0}$*, and that EROI varies with x; the price of t can be expressed as a linear function of its energy intensity* $\varepsilon_t = 1 + \frac{1}{EROI_t}$*, so that:*

$$\exists!\left(\alpha,\beta\right) \in \mathbb{R}^2,\ p_t = \frac{\alpha}{EROI_t} + \beta$$

Remark. With the terminology of Heun & de Wit [19] or Herendeen [17], the relation above would write: $p_t = \alpha \frac{\text{EROI}^H_t}{\text{EROI}^H_t - 1} + \gamma$, with $\gamma = \beta - \alpha$. This is because in their definition of EROI, the numerator is ε_t instead of 1.

Proof. From lemma 1, for all $(e,t) \in [\![1;n]\!]^2$, there is a unique linear function $P^{I-A}_{e,t}$ such that $\left((I-A)^{-1}\right)_{e,t} = \frac{P^{I-A}_{e,t}(\delta_{i_0,j_0} - x)}{D^{I-A}(\delta_{i_0,j_0} - x)}$, where $\delta_{i,j}$ is the Kronecker delta. As a linear combination of compositions of linear functions, the functions $Q(x) := \sum_{e\in E} P^{I-A}_{e,t}\left(\delta_{i_0,j_0} - x\right)$ and $P(x) := \sum_{i=1}^n v_i P^{I-A}_{i,t}\left(\delta_{i_0,j_0} - x\right)$ are themselves linear. By definition, we have $\varepsilon_t = \sum_{e\in E}\left((I-A)^{-1}\right)_{e,t}$, so that $Q(x) = \varepsilon_t D^{I-A}\left(\delta_{i_0,j_0} - x\right)$. As P, Q and $x \mapsto D^{I-A}\left(\delta_{i_0,j_0} - x\right)$ are linear, and as ε_t varies with x, it is easy to show that there are unique real numbers α and γ such that $P(x) = \alpha Q(x) + \gamma D^{I-A}\left(\delta_{i_0,j_0} - x\right)$. Finally, observing that $p_t = \sum_{i=1}^n v_i \left((I-A)^{-1}\right)_{i,t} = \frac{P(x)}{D^{I-A}(\delta_{i_0,j_0} - x)}$, we have: $p_t = \frac{\alpha Q(x) + \gamma D^{I-A}(\delta_{i_0,j_0} - x)}{D^{I-A}(\delta_{i_0,j_0} - x)} = \alpha\varepsilon_t + \gamma$. □

In the general case, we cannot obtain a *better* result, i.e. a formula that still holds when letting more than one coefficient vary. Indeed, denoting $\omega_{i,t}$ the coefficient (i,t) of $(I-A)^{-1}$, the Laplace expansion of $I - A$ gives us $\omega_{i,t} = \frac{(-1)^{i+j}}{\det(I-A)} \det\left(\left((I-A)_{j,k}\right)_{\substack{j\in[\![1;n]\!]\setminus i \\ k\in[\![1;n]\!]\setminus t}}\right)$. Hence, we have $\varepsilon_t = \sum_{e\in E}\left((I-A)^{-1}\right)_{e,t} = \sum_{e\in E}\omega_{e,t}$ and $p_t = \sum_{i=1}^n v_i\left((I-A)^{-1}\right)_{i,t} = \sum_{i=1}^n v_i\omega_{i,t} = \sum_{e\in E} v_e\omega_{e,t} + \sum_{i\notin E} v_i\omega_{i,t}$. Denoting $\tilde{v} = \frac{\sum_{e\in E} v_e\omega_{e,t}}{\sum_{e\in E}\omega_{e,t}}$ and $r = \tilde{v} + \sum_{i\notin E} v_i\omega_{i,t}$, we obtain

$$p_t = \tilde{v}\varepsilon_t + \sum_{i\notin E} v_i\omega_{i,t} = \frac{\tilde{v}}{\text{EROI}_t} + r$$

However, one has to keep in my mind that r, $\tilde{v}$ and EROI_t all depend on the coefficients of A, and vary together when A changes. If there is only one type of energy ($E = \{e\}$) or if value-added is equal for all types of energy ($\forall e \in E,\ v_e = \tilde{v}$), $\tilde{v}$ does not depend on the coefficients of A anymore, and we obtain a formula close to that of King & Hall [23]: $p_t = \frac{v_e}{\text{EROI}_t} + r$. Still, when the EROI varies because more than one coefficient of A changes, r varies concomitantly, and the EROI cannot be used as a sufficient statistic to infer the price. For this reason, one cannot identify empirically a linear relation between price and the inverse of EROI without strong assumption on the steadiness of A.

Actually, the theoretical relation between EROI and price is so fragile that one cannot even conclude that it is a decreasing relation: I provide in Appendix B a numerical example showing that EROI and price can both increase at the same time when more than one coefficient varies. Such acknowledgment dissuades from predicting long run prices by simply looking at estimations of future EROIs.

Does this mean that EROI is unrelated to any economic concept? Fizaine & Court [11] argue that there is a minimum EROI below which the US economy enters a recession. They first show that energy expenditure Granger causes growth in the US, then determine a threshold of energy expenditure above which the US enters in a recession, and finally use a modified version of equation (1) to relate this to a minimum non-recessionary EROI. However, they misleadingly replace the inverse of the energy intensity of investment $\frac{\$_{investment}}{E_{\text{in}}}$ by that of the whole economy, $\frac{GDP}{E_{\text{out}}}$. This prevents them from noticing that cost reductions in the energy production could compensate the effect of a decreasing EROI on prices. As we have seen, EROI, price and energy expenditure can all decrease at the same time, which undermines the idea that a recession caused by a surge in energy expenditure is ineluctable as soon as EROI goes below some threshold. In addition, an energy price increase should have an expansionary effect on net exporters of energy, at odds with the mechanism extrapolated by Fizaine and Court from the case of the United States, which is historically a net energy importer. Overall, the analysis of this section tempers the idea that EROI is relevant in economic issues and suggests that this notion is best suited for the physical study of energy systems.

5. Concluding Remarks

This work includes a first attempt at estimating future EROIs in a decarbonized electricity system. By examining a broad range of scenarios, it concludes that the system-wide EROI of the power sector should slightly decrease until 2050, from 8 to 7.2 in a business-as-usual scenario, or 5.8 in a scenario with 100% renewable electricity. As the EROI of each technologies is expected to remain well above 1, our results restore confidence about the energetic sustainability of renewable electricity, which was questioned theoretically.

Even though an inverse relationship between EROIs and energy prices was found empirically, a large share of price variability remains unexplained. Furthermore, a theoretical analysis of this relation showed that a declining EROI does not automatically imply increasing energy prices, and does not necessarily lead to a recession.

Finally, this paper assessed scenarios of transition in the electricity sector, but further research is still needed to estimate future EROIs in complete energy transitions, which include a mutation of the transportation system, agriculture and industry.

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Appendix A. Updating a Matrix A To a New Given Mix

The technology matrices A for the IEA scenarios are readily available in THEMIS, but these matrices have to be updated to the new electricity mix for the Greenpeace scenarios. To do this, I exploit the fact that both THEMIS and Greenpeace use the world regions of the IEA, and I modify the electricity input of each sector by the regional mix given by Greenpeace. The most accurate algorithm to update an input-output matrix is known as GRAS [21]. Although I implemented this algorithm in pymrio, I could not use it, because this algorithm uses the new sums of rows and columns to balance the matrix, and the vector of final demand y or the vector of production x is necessary to know them. As THEMIS doesn't include such vectors, I had to use a simpler method, which relies on the assumption that the electricity mix of inputs is the same across sectors for a given region. Given the perfect substitutability between electricity produced by different technologies and the uniqueness of electric grids, this assumption seems justified.

There are two different updates to make. First, I modify the vector of second energy demand (used to infer the final demand of technology t, y_t) so that it perfectly matches the demand of the scenario. Second, I modify the submatrix D of A containing the rows of electricity sectors. To convert D in energy units, I multiply each row t of D by the corresponding energy supplied per unit of technology t, E^S_t. I call the result E: the coefficient E_{is} of E gives the electricity from sector i required to make one unit of sector s' output, where $i = i(t,r)$ corresponds to technology t in region r. Then, I premultiply E by a block diagonal matrix with R blocks of size $T * T$ containing only ones (where $R = 9$ and $T = 15$ are the number of THEMIS regions and electricity sectors, respectively) to obtain a matrix B. Each row of B gives the total electricity from a given region r required to produced each output, E^{tot}_r, and each row E^{tot}_r is replicated T times:

$$B = \begin{pmatrix} B_1 \\ \vdots \\ B_R \end{pmatrix}, \quad B_r = \begin{pmatrix} E^{\text{tot}}_r \\ \vdots \\ E^{\text{tot}}_r \end{pmatrix}$$

Next, each row of B is multiplied by the share of a technology t in the mix of the corresponding region, which defines a matrix $\tilde{E}$. Each coefficient $\tilde{E}_{i,s}$ of $\tilde{E}$ gives the electricity from sector i required to make one unit of sector s' output, according to the new mix (by construction, for all electricity sector $j = i(t,r)$, the share of technology j in the regional mix, $\frac{\tilde{E}_{j,s}}{\sum_t \tilde{E}_{i(t,r),s}}$, is the same across all sectors s). Eventually, I obtain the new submatrix $\tilde{D}$ by converting each row of $\tilde{E}$ to the original units of A (by dividing each row by the appropriate unitary energy supplied E^S_t).

A last update is needed for Greenpeace scenarios, to account for the extra capacity needed when intermittent sources fail to deliver energy: the ratio of capacity (in GW) over production (in TWh) is somewhat higher in Greenpeace scenarios than in IEA/THEMIS ones. Thus, I multiply each column of an energy sector (representing all inputs required for one unit of output of this sector) by the ratio of the capacity-over-production ratios of Greenpeace and IEA/THEMIS. Doing so relies on the fact that the energy required to operate a power plant is negligible in front of the energy required to build it (see e.g. Arvesen et al. [2]).

Appendix B. Example of Non-Decreasing Relation Between EROI and Price

Herendeen [17] proposes a calibration on US energy data of his toy model with 2 sectors (materials and energy), which yields as realistic results as a two-by-two model can yield. I start from a slightly modified version of his calibration (called *base*), in the sense that the figures are rounded, and I show how a deviation of two coefficients (in the *new* calibration) leads to an increase of both EROI and price of energy. This proves that in general, nothing can be said of the relation between EROI and price, not even that it is a decreasing relation.

For this, I use the formulas for EROI and price given by Herendeen [17] (where I convert the price to \$/gal using the conversion factor 1 Btu = 114,000 gal):

$$\text{EROI} = \frac{1}{A_{ee} + \frac{A_{em}A_{me}}{1-A_{mm}}}$$

$$p = \frac{v_e(1-A_{mm}) + v_m A_{me}}{(1-A_{ee})(1-A_{mm}) - A_{em}A_{me}} \cdot 114{,}000$$

Table B.4: Example of sets of coefficients exhibiting a non-decreasing relation between EROI and price in a two sectors model.

	base	**new**
v_m	0.5	
v_e	$5 \cdot 10^{-6}$	
A_{em}	1700	
A_{me}	$4 \cdot 10^{-6}$	
A_{mm}	0.5	0.6
A_{ee}	0.3	0.25
EROI	3.2	3.7
price	1.5	1.6

Appendix C. Complete Results

Results without quality adjustment for IEA/THEMIS scenarios are provided in section 3.2; those for Greenpeace's scenarios are in Table C.5. Quality-adjusted results follows in Table C.6 (IEA/THEMIS) and C.7 (Greenpeace). The quality adjustment consists in separating each energy in the formula of the EROI according to its origin (electric or thermal), and to weight electricity by a factor 2.6. For example, the quality-adjusted (gross) embodied energy for a unit of technology t writes

$$\text{embodied}_t^{\text{qual. adj.}} = E^S \odot (2.6 \cdot \mathbb{1}_{\text{electric}} + \mathbb{1}_{\text{thermal}}) \cdot (I - A)^{-1} \cdot \mathbb{1}_{\text{t}}$$

Table C.5: EROIs and share in electricity mix of electric technologies in the model THEMIS for the Greenpeace scenarios. The bottom line in columns *mix* gives the total secondary energy demand, in PWh/a.

Scenario	**all**		**REF**				**ER** (+2°C, no CCS, no nuclear)				**ADV** (100% renewable)			
Year	**2012**		**2030**		**2050**		**2030**		**2050**		**2030**		**2050**	
Variable	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**
biomass w CCS	–	0	–	0	–	0	–	0	–	0	–	0	–	0
biomass&Waste	8.4	0.02	6.4	0.03	5	0.03	5.3	0.06	4.7	0.06	5.2	0.05	4.6	0.05
ocean	4.6	0	2	0	2.5	0	4.2	0.01	4.5	0.03	4.8	0.01	4.9	0.03
geothermal	5.6	0	3.8	0.01	2.5	0.01	3.6	0.03	3.7	0.07	3.8	0.03	3.9	0.07
solar CSP	35.2	0	9.2	0	7.9	0.01	8.5	0.05	7.7	0.17	9.2	0.07	7.8	0.22
solar PV	13.6	0	6.9	0.02	5.2	0.02	5.5	0.11	4.4	0.2	5.4	0.14	4.7	0.21
wind offshore	9	0	8.6	0.01	7.7	0.01	5.6	0.03	5.9	0.08	6.5	0.04	6.4	0.1
wind onshore	9.6	0.02	9.1	0.05	7.1	0.05	7.2	0.15	6	0.22	7.1	0.17	5.8	0.24
hydro	12.1	0.16	11.3	0.14	11.1	0.13	11	0.14	11	0.1	11	0.13	10.9	0.08
nuclear	12	0.11	7.2	0.1	7	0.08	8.3	0.02	–	0	8.3	0.02	–	0
gas w CCS	–	0	–	0	–	0	–	0	–	0	–	0	–	0
coal w CCS	–	0	–	0	–	0	–	0	–	0	–	0	–	0
oil	8.1	0.05	10.8	0.02	11.1	0.01	9.9	0.01	9.2	0	9.9	0.01	–	0
gas	14.6	0.23	15	0.23	15.4	0.25	16.4	0.21	17.2	0.06	16.4	0.18	–	0
coal	11.6	0.4	11.1	0.4	11.1	0.39	10.6	0.19	10.8	0.01	10.3	0.16	11.5	0
Total (PWh/a)	7.8	22.6	7.4	36.26	7.1	50.11	6.9	33.6	5.7	49.2	6.9	36.74	5.8	64.04

Table C.6: Quality-adjusted EROIs (with a factor of 2.6 for electricity) and share in electricity mix of electric technologies for IEA/THEMIS scenarios. The bottom line in columns *mix* gives the total secondary energy demand, in PWh/a.

Scenario	**Baseline (BL)**						**Blue Map (BM, +2°)**			
Year	**2010**		**2030**		**2050**		**2030**		**2050**	
Variable	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**
biomass w CCS	–	0.00	–	0.00	–	0.00	9.5	0.00	8.5	0.01
biomass&Waste	20.6	0.01	12.5	0.02	11.7	0.03	11.5	0.06	11.0	0.05
ocean	9.1	0.00	4.4	0.00	5.5	0.00	7.0	0.00	11.3	0.00
geothermal	11.4	0.00	10.2	0.01	10.1	0.01	10.5	0.01	11.3	0.02
solar CSP	44.5	0.00	17.6	0.00	18.1	0.01	17.2	0.02	16.9	0.06
solar PV	17.4	0.00	14.7	0.01	14.4	0.01	13.2	0.02	12.8	0.06
wind offshore	19.5	0.00	21.1	0.01	20.3	0.01	15.3	0.03	13.0	0.04
wind onshore	18.3	0.01	18	0.04	15.6	0.04	14.5	0.08	15.3	0.08
hydro	25.4	0.16	22.9	0.14	22.8	0.12	25.1	0.18	26.3	0.14
nuclear	19.1	0.14	13.3	0.11	12.9	0.10	13.5	0.19	13.9	0.24
gas w CCS	–	0.00	–	0.00	14.3	0.00	16.1	0.01	18.8	0.05
coal w CCS	–	0.00	–	0.00	11.6	0.00	13.7	0.05	14.2	0.12
oil	12.7	0.06	15.4	0.02	15.8	0.01	15.4	0.03	11.8	0.01
gas	22.3	0.21	24.4	0.21	24.1	0.23	28.9	0.14	33.4	0.11
coal	20	0.42	18	0.45	18	0.45	18.3	0.18	19.6	0.01
Total (PWh/a)	15.2	19.76	14.2	34.29	14	45.97	14.8	28.01	15.3	40.22

Table C.7: Quality-adjusted EROIs (with a factor of 2.6 for electricity) and share in electricity mix of electric technologies for Greenpeace scenarios. The bottom line in columns *mix* gives the total secondary energy demand, in PWh/a.

Scenario	**all**		**REF**				**ER** (+2°C, no CCS, no nuclear)				**ADV** (100% renewable)			
Year	**2012**		**2030**		**2050**		**2030**		**2050**		**2030**		**2050**	
Variable	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**	**EROI**	**mix**
biomass w CCS	–	0	–	0	–	0	–	0	–	0	–	0	–	0
biomass&Waste	15.6	0.02	12.5	0.03	9.8	0.03	10.4	0.06	9.2	0.06	10.2	0.05	9.1	0.05
ocean	7.7	0	3.6	0	4.5	0	8.4	0.01	9.1	0.03	9.3	0.01	9.7	0.03
geothermal	12	0	7.5	0.01	5	0.01	7.2	0.03	7.3	0.07	7.5	0.03	7.7	0.07
solar CSP	72.7	0	18.9	0	16	0.01	17.6	0.05	16.1	0.17	18.9	0.07	16.2	0.22
solar PV	25.6	0	13.6	0.02	10.5	0.02	11.5	0.11	9.2	0.2	11.2	0.14	9.9	0.21
wind offshore	17.2	0	15.9	0.01	15	0.01	11.5	0.03	12.2	0.08	13.2	0.04	13.2	0.1
wind onshore	18.5	0.02	17.5	0.05	14	0.05	14.8	0.15	12.4	0.22	14.7	0.17	12.1	0.24
hydro	23.3	0.16	21.9	0.14	21.7	0.13	21.3	0.14	21.3	0.1	21.3	0.13	21.1	0.08
nuclear	22.6	0.11	13.5	0.1	13.2	0.08	16.3	0.02	–	0	16.4	0.02	–	0
gas w CCS	–	0	–	0	–	0	–	0	–	0	–	0	–	0
coal w CCS	–	0	–	0	–	0	–	0	–	0	–	0	–	0
oil	12.5	0.05	17.5	0.02	17.9	0.01	15.7	0.01	13.3	0	15.7	0.01	–	0
gas	23.4	0.23	24.8	0.23	25.5	0.25	27	0.21	28.2	0.06	27	0.18	–	0
coal	18.3	0.4	17.6	0.4	17.8	0.39	16.5	0.19	16.5	0.01	16.1	0.16	15.3	0
Total (PWh/a)	14.9	22.6	14.3	36.26	13.7	50.11	13.8	33.6	11.8	49.2	13.7	36.74	11.9	64.04

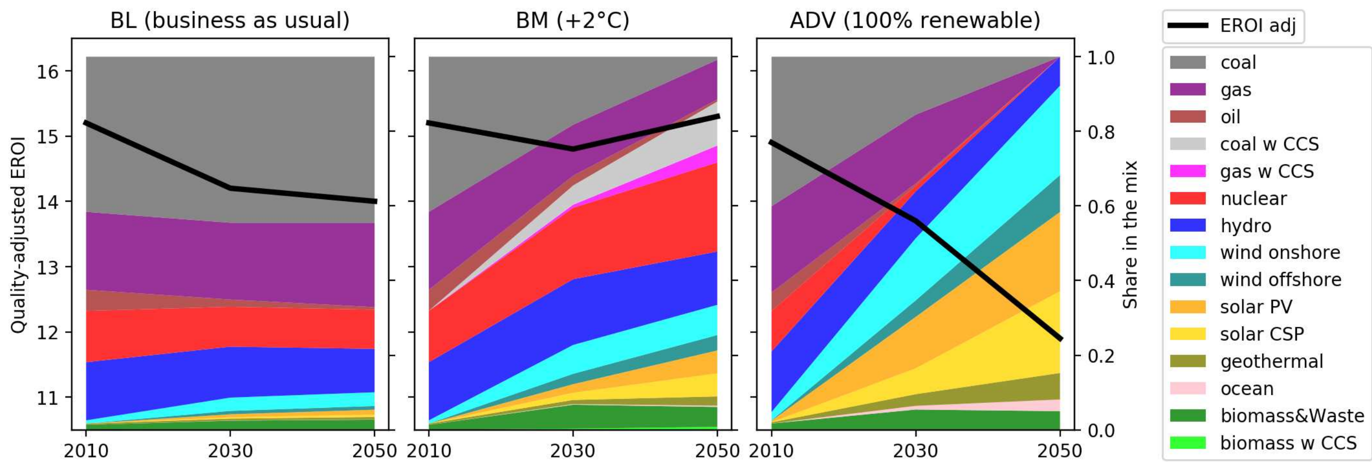

Figure C.6: Evolution of global quality-adjusted EROIs (with a factor 2.6 for electricity) and mixes of electricity for different scenarios.