Energy Return On Investment – setting the record straight.

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EROI is a key metric of the viability of energy resources. Many studies have focused on EROI at point of extraction, resulting in deceptively high numbers for fossil fuels, and inconsistent comparisons to renewables. In a recent *Nature Energy* paper, Brockway *et al.* (2019) set the record straight.

Net Energy Analysis (NEA) is a scientific discipline borne out of an 'energy theory of value'[1], and its principal metric, Energy Return On Investment (EROI)[2] measures how much energy is 'returned' (to human societies) as a usable energy carrier, per unit of energy 'invested' in the chain of processes that are required to make that energy carrier available:

$\mathrm{EROI} = E_{out} / \Sigma\, (E_{inv})$, where:

E_{out} = energy output ('return'); $\Sigma\, (E_{inv})$ = sum of all energy 'investments'.

Despite its seeming simplicity, however, the devil is in the details, and a wide range of different EROI values may be calculated for even the very same energy resource, depending on the adopted system boundary, and especially on the stage along its supply chain at which the 'returned' energy carrier is sampled. More specifically, the EROI of an energy resource may be calculated at point of extraction from the geo-biosphere – also referred to as EROI_{st} ('standard'; e.g., crude oil at the wellhead), or at the point where, and in the form in which, it is supplied to the end user – also referred to as EROI_{pou} ('at point of use'; e.g., refined petrol at the pump, or electricity produced by burning heavy fuel oil)[3].

Historically, most of the EROI literature focused on the EROI_{st} of fossil fuels, and its change over time as reserves gradually become depleted and require more energy investment to exploit[4]. One of the first studies in which a methodologically consistent analysis of the oil supply chain at different stages of its supply chain was performed, was based on historical production data for California[5], and it documented a dramatic drop in EROI when expanding the boundary and shifting the analysis from point of extraction to point of use (Figure 8). More recently, the declining EROI along the supply chains of a range of primary energy resources, respectively as currently supplied to the UK and Chile, was documented in Raugei and Leccisi[6] (Figure 3) and Raugei *et al.*[7] (Figure 6).

A lack of standardisation in system boundaries and the ensuing superficial 'apples-to-oranges' comparisons[8] of EROI values referring to different energy carriers (e.g., raw fuels at point of extraction, and refined thermal fuels and electricity at point of use) are especially

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problematic – and potentially conducive to misguided interpretation – when conventional energy resources (like fossil fuels) are pitched against renewables (like wind and photovoltaics), since the latter directly produce electricity 'at point of extraction', and hence for them EROI_{pou} is much closer to EROI_{st}.

In their recent *Nature Energy* paper, Brockway *et al.*[9] broke new ground by performing a systematic, world-wide analysis of the EROI of all fossil fuels based on International Energy Agency (IEA) data and a multi-regional input-output (MRIO) approach, and calculated final aggregate values for EROI_{st} (which they refer to as $\text{EROI}_{\text{PRIM}}$, or 'primary') and EROI_{pou} (therein referred to as EROI_{FIN}, or 'final').

Their findings point to a number of very important take-home messages, namely:

(i) The aggregate $\text{EROI}_{\text{PRIM}}$ of all fossil fuels at point of extraction (Figure 3) has been slowly declining over time (due to the progressive depletion of the most easily accessible reserves, and consistently with previous literature findings), and is currently at around 30:1.

(ii) The aggregate EROI_{FIN} of all fossil fuels-derived energy carriers at point of use (Figure 4) is characterised by a much 'flatter' trend over time (due to the fact that the largest investments are those required for refining and transportation, and not for extraction), and is much lower at around 7.5:1 for refined thermal fuels, and 3:1 for fossil fuel-derived electricity.

(iii) The values of EROI_{FIN} are much more relevant to society than $\text{EROI}_{\text{PRIM}}$ (since final energy carriers are much closer to actual end services), and EROI_{FIN} enables a more consistent and "fairer" comparison between fossil fuels and renewables like wind and photovoltaics.

(iv) When compared consistently and referring to the same energy carrier (i.e., electricity), the EROI_{FIN} of fossil fuels is not only much lower than often previously assumed, but in fact often lower than that of renewables.

The authors then conclude that such low EROI_{FIN} values for fossil fuels point to a hitherto underestimated risk in terms of reduced future global availability of net energy, and resulting potential impending constraints to our economies.

However, at the same time, these same results also hint at a more encouraging outlook in that, contrary to previously wide-spread perceptions, they prove that renewable electricity generation actually does represent a viable alternative to fossil fuel-derived electricity, since the former's EROI_{FIN} is now typically higher than the latter's has ever been.

Either way, these are sobering results that cannot be ignored but demand attention from all involved actors, within and beyond academia. Future research is arguably still needed, though, to address two important lingering points.

Firstly, it is time to move beyond EROI analyses of individual energy resources (or even 'families' of energy resources, such as all fossil fuels) taken in isolation, and focus instead on comprehensive scenario analyses of the entire mixes of energy technologies that are used to provide societies with the two main types of energy carriers that they need, i.e., on the one hand thermal fuels, and on the other hand electricity. Such a holistic analytical approach is especially called for now that the world is on the verge on a major energy transition, and it must incorporate all elements of the system, including e.g., distribution networks, and, in the case of electricity, projections of the required energy storage capacity (once again, taken at the whole grid mix level, and not arbitrarily assigned to any individual technology).

Secondly, and potentially even more importantly, analyses must start taking into account that any 'minimum' EROI supposedly required to support our societies is not a value fixed in stone, but is in fact a moving target, dependent on the efficiency at which the final energy carrier(s) are used in the mix of end services. As illustrated in Brown *et al.*[10] (Figure 1), a massive cross-sector electrification and a concomitant shift away from thermal processes – the efficiency of all of which is severely constrained by the Carnot ratio ($\eta_{max} = 1 - T_C/T_H$) – may open the door to achieving the required services with much lower demand for primary energy, which in turn entails that a significantly lower EROI than previously assumed may suffice[8].

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