Energy efficiency and energy prices: A general mathematical framework

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Abstract
Mankind’s prosperity has been dependent on availability of affordable energy in the recent centuries. Today, the need of sustainability requires precise energy efficiency evaluation. Unfortunately, the traditional metrics like energy return on investment (EROI) suffer from the system boundaries and from the inability to describe labor and physical capital in terms of energy. Therefore, they tend to omit up to 50% of input energy consumption. The price of energy model (PERM) and cost of energy model (CERM), derived via matrix description of production process, show that the ratio of the average energy input cost to the average useable energy output cost describes energy efficiency completely. The same holds for the ratio of energy prices, if shares of aggregate rents, taxes and subsidies in the input and output prices are similar. The above price (cost) ratio can serve as an EROI check and eliminate the need for a lengthy process analysis. The results enable the extension of energy efficiency metrics by social and environmental effects, measurable mostly in monetary terms.

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1. Introduction
Energy availability determines the economic growth [3]. The increasing role of renewables in the energy mix is inevitable with the ongoing depletion of fossil fuels. Gupta and Hall [21], p. 1796 sound the alarming bells in this matter. Similarly, Hall, Lambert and Balogh [22] draw attention to decreasing EROI in fossil fuel extraction and increasing importance of energy efficiency (EE). The renewable energy dominated during the ancient and medieval period due to the lack of large-scale fossil fuel extraction technology. Let us not discuss how renewable and sustainable that period actually was with respect to the deforestation (cp.[28]). However, it is unclear whether our future energy needs will be satisfied with energy from solar cells, fusion [36], cellulose-based ethanol [62], fission, tidal, current or wave plants, windfarms or other sources. First-generation liquid biofuels seem to be more expensive than fossil fuels ([62], p. 193, Fig. 4). Electricity from photovoltaic (PV) farms is subsidized in the most European geographical latitudes in order to be competitive. Contrary to that, biodiesel, corn-based ethanol and PV farms are reported to have energy return on investment >1 [46,58]. Those contradicting results require an explanation.

Therefore, there is a need for precise estimation of energy production efficiency, as the mankind’s future depends heavily on the energy availability [32] and the biomass probably will not be a sufficient source [16]. There has been an ongoing discussion about the usefulness of economic metrics. The latest attempts to link economics and EE have not been successful. Murphy, Hall, Dale and Cleveland [42] relate monetary return on investment to EROI, but derive tautological results. Herendeen [24] provides partial solution to the linkage of EE to prices in a two-sector input-output framework. Unfortunately, he meets the same limitations that the typical EROI calculation does: system boundaries and aggregation/classification issues [42,7]. Let us briefly explain them. The calculable energy inputs, which are the primary energy inputs and eventually the buildings and machinery, are usually within those system boundaries. Thus, the boundaries limit the calculation of indirect energy expenses, however important they could be. As the EROI is frequently calculated ex-ante, there could have to be assumptions on inputs energy intensity, and calculation input data have to be taken from I/O databases. However, the local conditions (including transportation or specific building design and technology) could significantly differ from those available in aggregated form in I/O databases.

This paper proves mathematically that economics can provide simple and effective tool for EE assessment without a need for process analysis. We utilize the hypothesis that ultimate
production factor behind all others (labor, capital) is energy ([3,20], p. 181 [47], [54], or [55]). Without system boundaries, the ratio of energy input and output costs (energy cost ratio = ECR) approximates the energy return on investment (EROI). With those boundaries, ECR is superior to EROI. As the costs are not always observable, input/output energy price ratio (EPR) could be used instead. However, that would require the rent\(^1\) shares in the input and output energy prices to be similar.

This paper aims to show the concept of mathematical relation between energy prices and energy efficiency, generally applicable without unnecessary technical and economic complications. The solution elaborated here needs both extensions and independent empirical examination.

The rest of this paper consists of presentation of the contradiction between EROI and energy prices, discussion of the recent energy evaluation methodology advancements, development of the model, and discussion and conclusions.

2. The puzzling EROI

It is almost impossible to identify all the basic inputs, due to complexity of the modern production process. However, EROI requires that in order to express all input energy.

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\text{EROI} = \frac{\text{useful output energy}}{\text{input energy}}. \quad (1a)
\]

Does EROI account for the energy spent by the people employed in energy production in house heating, commutation, etc.? Probably, it does not. Therefore, the quantity of inputs tends to be underestimated in the traditional EROI calculation, whereas the quantity of outputs is well known. That could overrate measures of this kind.

Murphy and Hall ([41], p. 115) show in the case of both, oil/diesel and corn-based ethanol, that the traditional EROI is significantly higher than the one adjusted for additional non-obvious cost like “construction and maintenance costs of roads and vehicles” ([41], p. 114), or in turn they consider minimum EROI to provide transportation service is approx. 3:1 and use it to counter the corn-based ethanol EROI at cited 1.3. Naturally, Murphy and Hall [41] conclude that there are no relevant governmental or nongovernmental subjects, that would comprehensively try to “understand and calculate EROI and its effects” (p. 114).

Chu and Majumdar [13] provide comprehensive review of contemporary levelized cost of energy (LCOE). The striking observation is that among the renewable energy sources, only hydro, wind, waste, and geothermal seem to be cost-competitive to the fossil fuels (p. 300 ibid). Thus, the most of the “sustainable” or “green” energy is actually more costly than the traditional one, although many studies mention the renewable energy EROI above 1.

Pickard ([46], p. 1121) cites several sources of current photovoltaics (PV) EROI estimates ranging from 2.4 to 5.9. However, Chu and Majumdar's ([13], p. 300) energy pricing estimates tell a different story: PVs' LCOE is twice the LCOE of nuclear power, coal-fired plants or natural gas CC GT. Most European countries have to subsidize PV electricity (stipulate the obligation of distribution and transmission companies to buy out the PV electricity at rigid prices or subsidize the PV energy producers with “green bonuses”). Indeed, comprehensive calculation, which accounts for energy content of labor and capital, derives extended EROI (EROE) of PV in Switzerland approx. 1 [14], similarly to the ratio of non-renewable energy investment to energy delivered (NEIED) in the first Chinese PV tower = 0.95 [11].

Tao et al. [58] state that the second-generation biofuels could provide energy return on investment (EROI as measured in MJ/MJ) up to 2.7 considering energy displacement credits and up to 1.5 without such credits in the best case scenario. The ratio of 1.5 MJ gain per 1 MJ spent (or 50% net gain) is quite poor efficiency, although possibly sustainable. Firrisa, van Duren, and Voinov [17] calculate the energy inputs quite comprehensively (see the complicated Fig. 1, ibid), yet they report EROEI (in fact EROI) at least 1.7 for rapeseed biodiesel production.

However, the economist's point of view could be quite different. The EIA reported all grades conventional retail gasoline prices between $2 and $3/gallon in 2010/2011. The ethanol-gasoline blend E85 has been more expensive than gasoline, and biodiesel B99/B100 has been more expensive than diesel in the U.S. since 2000 through 2014 [1], see Fig. 1. The cheapest vehicle propulsion fuel has recently been electricity [1], which was more than 4 times cheaper than E85 or B99/ B100 during 2011–2014 period, especially due to 3.4 times higher efficiency of electric engines compared to Otto-cycle internal combustion engines. Despite all of the inputs to liquid biofuel production being mostly cheaper than liquid biofuels, many studies report EROI of biodiesel [see review at [50], tab. 4] and of corn-based ethanol [43] up to 2. However, it is worth noting, that some of the studies reviewed by Russi [50], resp. Murphy, Hall & Powers [43] report EROI of liquid biofuels below 1. Some other papers (e.g. Solomon [53]) clearly indicate that the traditional liquid biofuels are unsustainable too.

Even the best case for liquid biofuels [58], with gasoline prices between $3 and $4/gallon in 2012–2014 shows that the producer price of the second-generation bioethanol or isobutanol GGE at $3.27, resp. $3.62 (ibid) could be economically unsustainable without special taxes on fossil fuel energy and without obligatory blending of liquid biofuels. Thus, the crucial questions are:

1) Why is the isobutanol or the second-generation bioethanol at the factory doorstep at least as expensive as gasoline at the gas station, if these biofuels' EROI is 1.5 at worst?
2) How costly would the biofuel production be in the post-fossil fuel world?

The answer to the first question can be based on the accounting for total energy consumed due to the biofuel generation. The answer to the second question requires complete description of production process both in terms of quantities and prices. That is tedious and tricky work, as it is difficult to avoid omissions and errors. Did Tao et al. [58] account for the energy tied in the factory machinery and buildings and consumed by labor force? We do not know.

In the age of energy, when even people's relaxation is so energy-demanding, such an omission can significantly distort the results. Yang et al. [64] present results totally opposite to Tao et al. [58] and show that if accounted for net cumulative energy consumption during the preparation of every non-renewable input in the corn-ethanol producing process, the corn-based ethanol production in China is strongly unsustainable.

Either the traditional energy efficiency metrics need innovations and extensions or they need an accuracy and completeness check, possibly from economics.

3. Energy efficiency measures’ innovations and recent literature review

3.1. Energy efficiency measures’ innovations

Some newest papers use EROI computation that encompasses

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\(^1\) Rents are the net economic benefits, i.e. economic profits.

\(^2\) Biodiesel fuels with 99% or 100% share of biodiesel.
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