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Ideal EROI (energy return on investment) deepens the understanding of energy systems

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ABSTRACT

This article presents a new EROI (energy return on investment) factor named the ideal EROI, or EROI_{ide}, that provides the theoretical upper boundary of the EROI of a given system. The EROI_{ide} is the ratio between the inputs within the EROI_{stnd} boundaries and the theoretical maximum output from a given system; i.e, all losses are omitted and the maximum theoretical energy output of the system is used. EROI_{ide} resembles the concept of the idealised Carnot heat engine. Although the EROI of a given system can never be equal to EROI_{ide}, the EROI_{ide} can be used to estimate the potential for improvement; e.g., if the difference between the EROI_{ide} and EROI_{stnd} is small then little improvement can be expected from further research funding. Calculations using EROI_{ide} can add a valuable depth to the overall results of an EROI study, benefitting policy makers involved in energy policy planning. Three application examples of EROI_{ide} are provided, one for a hydroelectric power plant, one for a geothermal power plant and one example for a hypothetical wind farm. The calculations show that the hydro power plant could improve approximately 3 fold, whereas the geothermal plant had a potential of 27 fold improvement over its lifetime.

1. Introduction

When power plants are constructed, it is expected that the plant will eventually return more energy to society than the original construction, maintenance and daily operations consume over its lifetime. The output from the power plants is often only considered, but a more holistic view is needed to study the viability of the construction of such plants. It has a previously been stated that efficiency improvements play a major part in the global sustainable development [1]. Such mechanism as we provide in this article should prove helpful when comparing the viability of energy conversion systems and subsequently assist in the journey towards sustainability in the energy sector.

If an energy conversion system provides a high output, it may seem viable, but the construction, access and refinement of the source, maintenance of equipment, daily energy use and even the transport of the product used for electricity production (such as oil from the wells) may also be energy consuming. EROI (energy return on investment) is in essence the ratio between the energy outputs, that is the usable energy output from the power plant, and inputs from a system under study [2,3]. Inputs are regarded as the energy that is used to produce, maintain and operate the power plant under study, rather than the energy input that is used in the energy conversion process (such as falling water, hot steam etc.). This ratio is then calculated as a function of time as the power plant under study is constantly producing output and therefore increasing its EROI. The output is then calculated as the delivered electricity or any other energy containing product such as gases, oil or hot water. When a power plant is studied, it can be generally assumed that the inputs increase gradually during its operational lifetime and the major part of the input energy is used in the construction process. There are, however, know exceptions; e.g., geothermal power plants consume (input) large portion of their output energy for cooling water pumps. EROI has for the most part been used to study the viability of fossil fuels. However, EROI calculations have also been used to show efficiency in agriculture [4], aquaculture [5] and in the fishing industry [6]. Results are often used to assess the viability of the energy sources under study. It has been claimed that for electricity producing systems, the EROI must exceed 3 to be sustainable for modern society [7]. This is usually not the case for systems that are not directly in electricity production, such as farms and fisheries which usually have an EROI well below 1. In general, EROI calculations do not include monetary values, which is evident

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in farming. For example, a farmer might produce a high quality product, which he only produces a small amount of. His EROI would be relatively low, but he could still be maintaining good financial income. Some systems, such as biofuel might have an EROI around 3 [7], which under current circumstances is not considered high compared to oil and coal who have an EROI of around 20 and 80 respectively [8]. The question for such systems is however what is the theoretical maximum EROI they can allow for and will they ever be viable. EROI calculations have been rather chaotic in terms of standard methodology [9]. Until recently no standard was evident for researchers to follow. This was however changed in 2011 when a proposed standard was put forward. The proposed standard included various boundaries, where different factors are included. This allows researchers to state which EROI they are referring to in their calculations [9]. EROI results are good to compare different energy systems in regards to how much energy they return to society against the energy they consume. Also, with todays increasing demand on high efficiency in power production, EROI can show how efficient the systems are. The authors have noticed that by calculating the theoretical maximum ideal output from a system, valuable results can be seen that are likely to be a tool for policy makers, private and public but also research funds and corporations looking to promote research in the field. Supporting research in a field where the room for improvement is great is more likely to return results that are of significance rather than funding research where little or no possibility is for any improvement. EROI_{ide} describes the EROI of an energy conversion system if losses are omitted, it has unlimited access to energy, its operation is uninterrupted and it does not consume any power for operation. EROI_{ide} will in essence show policy makers how much improvement is possible within the energy producing system under study.

2. Methodology

It is suggested by the authors that the standard put forward by Murphy et al. should be used for general EROI calculations. By doing so it is ensured that EROI results can be compared. The EROI equation can be described as follows [10]:

$$\mathrm{EROI} = \frac{\mathrm{ED}_{\mathrm{out}} + \sum \nu_j O_j}{\mathrm{ED}_{\mathrm{in}} + \sum \gamma_\kappa I_\kappa} \tag{1}$$

where $\mathrm{ED}_{\mathrm{out}}$ is the energy content of all products produced and leave the power plants ν_j, represents all co-products, such as brine which may be used for other industries O_j, is the energy content of any co-product that is produced at the power plant $\mathrm{ED}_{\mathrm{in}}$, is the energy content of all products entering the plant γ_κ, is the amount of co-efficient (input) products, such as the energy used for producing the material used for maintenance I_κ, is the energy content of the co-efficient products.

Equation 1 is, however, general and does only provide the basic concept for EROI calculations, where there are some indirect inputs and outputs with the direct inputs and outputs. Murphy et al. clarified this in more detail as can be seen in Table 1. The further right, or down, in Table 1 expands the boundaries of the system under study. For example, If one is only to include output of energy after extraction one would refer to the first column. If one would however also have data about the energy usage in the energy processing (such as refinery of oil) one would use the EROI factors in the second column. If one also has the data of how much energy is then delivered to the end user, the EROI factors in the last column are used. With regards to the inputs, one refers to the rows in Table 1. For example, if one has the data for all indirect energy and material inputs, it would be correct to refer to the row number 2. So, if one has the data about all indirect energy and material inputs, including all direct energy and material inputs, as well as the data about how much energy is delivered to the end user one would refer to the $\mathrm{EROI}_{3,i}$ in the calculations.

Table 1
System boundaries provided by Murphy et al. [9].

Boundary for energy inputs	1. Extraction	2. Processing	3. end use
1. Direct energy and material inputs	$\mathrm{EROI}_{1,d}$	$\mathrm{EROI}_{2,d}$	$\mathrm{EROI}_{3,d}$
2. Indirect energy and material inputs	EROI_{stnd}	$\mathrm{EROI}_{2,i}$	$\mathrm{EROI}_{3,i}$
3. Indirect labor consumption	$\mathrm{EROI}_{1,lab}$	$\mathrm{EROI}_{2,lab}$	$\mathrm{EROI}_{3,lab}$
4. Auxiliary services consumption	$\mathrm{EROI}_{1,aux}$	$\mathrm{EROI}_{2,aux}$	$\mathrm{EROI}_{3,aux}$
5. Evironmental	$\mathrm{EROI}_{1,env}$	$\mathrm{EROI}_{2,env}$	$\mathrm{EROI}_{3,env}$

The EROI_{stnd} results provide a baseline for the EROI_{ide} calculations where only the output (numerator) has to be modified. That is, omitting all losses in the system to provide a theoretical maximum output, a limit which can never be reached with regards to EROI. To account for the theoretical maximum output, Equation (1) is modified to be as follows:

$$\mathrm{EROI}_{ide} = \frac{\sum \beta}{\mathrm{ED}_{\mathrm{in}} + \sum \gamma_\kappa I_\kappa} \tag{2}$$

where $\sum \beta$ accounts for the theoretical maximum output from a given system omitting all losses. Since raw inputs to systems vary greatly (such as wind, solar, hydro etc.), the $\sum \beta$ has to be modified for different systems. For example, if a hydro power plant is studied, the $\sum \beta$ would be substituted with the output from the designed capacity from the plant omitting all losses.

For geothermal power plants, it is suggested that the energy available, or exergy, from all wells is used as the ideal output. For wind turbines, the theoretical maximum output can be represented as [11]:

$$P = \mathrm{d}(KE)/\mathrm{d}t = \left(1/2\mathrm{mU}^2\right)\Big/\mathrm{d}t = 1/2\mathrm{U}^2\mathrm{d}m/\mathrm{d}t = 1/2ApU^3 \tag{3}$$

where an area A with mass of air $\mathrm{d}m$ is flowing through. In the time $\mathrm{d}t$ the flow will travel the distance $U\ \mathrm{d}t$, where the cylinder of volume $A\ U\ \mathrm{d}t$ containing mass $\mathrm{d}m = A\ p\ U\ \mathrm{d}t$, where p is the air density [12], which under normal pressure is approximately 1.2 kg/m^3. There are however certain laws of physics that can not be overlooked. Accounting for the total energy available in the wind, does prove a theoretical maximum, but as Betz has previously claimed, this would create a problem. If the wind would be harvested 100%, it would then subsequently stop directly behind the turbine, which would then in essence stop further air to flow through the area. Accounting for Betz law, one can see that only 59.3% (16/27) of the air can theoretically be harvested from any wind turbine design, which should be taken into consideration when EROI_{ide} calculations are made for wind turbines.

As Murphy et al. suggest, EROI_{stnd} should always be calculated when energy systems are studied with regards to their EROI, which is the reason why they authors recommend that the inputs from the EROI_{stnd} are always used in the EROI_{ide} calculations.

3. Results

This section demonstrates how EROI_{ide} can be used to provide a deeper understanding of an energy producing system in conjunction with EROI_{stnd}. Three cases are put forward to provide understanding of expected results. The first case is from a study by Atlason & Unnthorsson [13] where the EROI for Fljotsdalsstod hydroelectric power plant was estimated, the second is a the