# Energy Return on Investment

Subjects: Energy & Fuels

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Energy Return on Energy Invested (EROEI) (also Energy Return on Investment (EROI)) is a dimensionless ratio that compares the output over the life of an energy generating system—such as a power plant—to the energy inputs to the system. EROEI thus has the potential to filter out unsuitable projects, and to rank surviving projects according to their energy return. EROEI is therefore an important adjunct to conventional monetary project assessments.

Ecosystem maintenance energy (ESME) costs | Energy Return on Energy Invested (EROEI) | energy payback time | fossil fuels | minimum EREOI | hydroelectricity | PV cells | renewable energy | solar energy | wind energy.

## 1. Introduction

Energy Return on Energy Invested (EROEI) (or Energy Return on Investment (EROI)) is a dimensionless ratio that compares the energy output over the life of an energy generating system—such as a power plant—to the energy inputs to the system.

In equation form EROI = $E_{out}/E_{in}$

Where

$E_{out}$ = the energy output over the plant's useful life

$E_{in}$ = the energy inputs over the plant's useful life.

Consider a wind turbine. The energy inputs ($E_{in}$) include the energy needed to mine and process the various materials needed for turbine construction and its connection to the grid; energy to both erect the turbine, and construct the access road; energy for operating the turbine over its lifetime, including any replacement parts needed such as replacing turbine blades; and finally, energy needed for decommissioning and removing the turbine and remediating the site after its useful life is over. This last energy cost may seem trivial for a wind turbine, but it is not for a large nuclear reactor and its spent fuel.

EROEI is analogous to cost-benefit analysis (CBA), a more general appraisal method for projects. CBA compares the expected benefits from the project to the costs of the project; the estimates for both benefits and costs are expressed in monetary terms and include estimates for non-monetary benefits and costs. (In contrast to EROEI calculations, however, CBA discounts future streams of benefits and costs by using an interest rate.) Also used in energy analysis is the energy payback time, which is the time in years the energy system must operate to repay the input energy costs, which is analogous to the payback time in economic appraisal of projects.

Clearly, the EREOI ratio must be >1.0 for an energy project to be viable; otherwise the project would be an *energy sink*, contributing no energy to the rest of the economy. The only exception is for proposed new energy sources—such as nuclear fusion energy or new types of photovoltaic (PV) cells—where it is accepted that during development, protypes may be temporarily energy sinks. Eventually however, they must pass the EREOI >1.0 test, or be discarded as an energy option.

But a number of researchers have argued that the EREOI must be much greater than unity for viability. Hall et al.[1] have argued that for the functioning of an industrial society, an EREOI value of at least 3 is needed for both corn-based ethanol and oil, measured at the farmgate/mine mouth. Weißbach et al.[2] found an ‘economic threshold’ for EREOI of 7, while Fizaine and Court[3] have even argued that for the US, an EREOI of 11 was needed for economic growth to continue. The value is important, since higher cut-off values will rule out many potential projects, particularly for renewable energy (RE).

Fossil fuels (FFs), nuclear fission and bioenergy sources differ from RE sources such as wind and photovoltaic (PV) electricity in that for the first energy group, the energy inputs accrue over the life of the energy conversion device. Coal, for instance, can be mined as required, so that the energy costs for mining and transportation represent an annual energy cost. It is different for the main two RE sources, wind and solar. Nearly all input energy costs must be paid upfront; the only ones that are deferred are the costs for decommissioning. This difference is very important if the output from these two sources must be rapidly increased as many researchers advocate in the light of the climate change emergency. If attempts are made to rapidly expand capacity, it is possible that the energy needed upfront for manufacture etc will be so great that energy inputs into the non-energy sectors will fall [4][5]—unless fossil fuel output is also increased (which, of course, would exacerbate $CO_2$ emissions).

## 2. Calculation of EROEI

It might be thought that the EREOI has a characteristic value for each energy type—certainly discrete EREOI values for each energy source are often reported in this way [see e.g. [6]]. However, the EREOI value for a given energy project, such as a wind or solar farm, will vary greatly, depending on:

- The year of installation—newer projects can take advantage of more efficient (probably larger) wind turbines or the latest PV cells
- The location of the farms—*ceteris paribus*, the EREOI will be higher for turbines installed in locations with strong, steady winds or PV arrays in high-insolation regions

- The distance to energy load centres—if the wind or solar farms are located in remote areas, the costs of power transmission will be higher
- Whether energy storage is needed because of surplus electricity generation—this will become an increasing problem as intermittent energy sources such as wind and solar increase their share of total primary energy, as seems very likely[7].

Given the above, it is not surprising that it is often very difficult to compare the numerical EREOI results of different researchers, particularly for RE electricity[8][9]. This problem arises, not only because of different conditions in the analyses (rated capacity, year of installation, insolation or wind speed levels, type of PV cells, etc.), but also because different researchers have used different approaches for calculation (process, input–output, or hybrid method) and different boundaries for their analyses. There is also a need to factor in changes in energy inputs as technology develops; EREOI can be time-dependent, based on the maturity of the technology.

The choice of *boundary* can make a great difference to the calculated value of EREOI for a given energy project. According to de Castro and Capellán-Pérez[10], the most-used EREOIs are: 'standard' (measured at the 'farm-gate'); final (at the consumer point-of-use); and 'extended' (which includes indirect investments as further inputs). They regarded the extended EREOI as being the most relevant.

## 3. Controversies in determining EREOI

A further reason why EROEI estimates are difficult to make is the challenge of estimating all input energy costs. All energy production methods—whether fossil, nuclear or renewable energy—generate externalities[7][8][11]. For fossil fuel power stations these include air pollution emissions, thermal pollution from coolant water, and release of $CO_2$ and other greenhouse gases. Increasingly, the costs of air pollution control, whether energy or monetary, are being internalised, through particulate filters and SOx scrubbers for exhaust stack gases. Although an increasing number of research papers have attempted estimation of the energy costs of $CO_2$ removal from FF power stations by capture of $CO_2$ from exhaust stacks, followed by compression, transport and subsequent deep burial in geological reservoirs, these high energy costs are presently not being incurred. The result is an over-estimation of the EROEI for fossil fuels.

But RE sources can also have significant environmental costs. The remediation of these damages—which we have elsewhere termed ecosystem maintenance energy (ESME) costs[7][11] can arise in a variety of ways. If, as can occur with hydro dams in the Amazon, trees are left to rot as the reservoir fills, for some years the GHG emissions from decaying vegetation can give hydropower the same level of GHGs as a natural gas plant of the same power output. For bioenergy plantations, the unpaid environmental costs can include biodiversity loss, as well as soil erosion and fertility loss if crop and forest wastes are used for fuel. Since the main justification for promoting RE is their environmental superiority to FFs, these ESME costs should be added to input energy, which will lower their EROEI values.

Even though compared with bioenergy or hydropower, wind and solar energy have fewer (uncounted) environmental costs, they are not negligible[7][11][12]. Although wind turbines cause bat and bird deaths, and PV cell production results in toxic wastes, the main environmental costs arise from mining input materials, as discussed below. Hadian and Madani[13] developed a 'relative aggregate footprint' for assessing the environmental sustainability of various energy sources. They found that PV solar energy was only marginally more environmentally sustainable than natural gas. Rehbein et al.[14] have further warned that future RE growth could have a big negative impact on many important locations for global biodiversity.

An increasingly important component of input energy will be that needed to mine and process the materials needed for energy conversion devices, especially for PV and wind turbine manufacture. As the global economy continues to expand as assumed in most forecasts, materials demand for the non-energy sectors of the economy will also expand. Wiedmann et al.[15] have shown the close correlation between global GDP and materials consumption. Mining already consumes some 8–10% of global energy[16]. In future, however, the most serious environmental costs will probably come from mining progressively lower-quality ores. If ore concentrations decrease by a factor of 10, wastes (and the environmental problems they create) can also be expected to rise by a factor of 10.

A final controversy concerns intermittent RE sources, mainly wind and solar energy. Conversion and storage will still be needed even if, as expected, the share of electricity in final energy demand is higher than today. However, this conversion need comes at a heavy energy cost. Energy can be stored in batteries, compressed air, or pumped hydro schemes, but then cannot be directly used for non-electric purposes. In contrast, hydrogen (H2) storage is more versatile, as it can be used in stationary fuel cells to produce combined heat and power. According to Ajanovic and Haas[17], using hydrolysis to produce H2 for direct use as a fuel is about 50–60% energy efficient for the full cycle. Direct H2 use would be far more efficient than re-conversion of the H2 to electricity, with only about 27-38% full-cycle efficiency. Conversion and storage equipment add to input energy costs, and the inevitable energy losses reduce output energy; both effects further reduce EROEI for intermittent RE sources.

## 4. Conclusions

Determining EROEI is a seemingly objective way of evaluating the feasibility of energy projects. But the EROEI values for all energy sources are hotly disputed, with large ranges for reported values for each energy type. Further, the values will change over time, because of the need to move to lower-quality energy sources (e.g. shale oil, lower-speed winds), lower-quality ores to construct the energy systems, and—for wind and solar energy—the need for energy conversion and storage.

NOTE: Much of this entry has drawn upon sections 4 and 5 of our paper:

Moriarty, P.; Honnery, D. Feasibility of a 100% global renewable energy system. *Energies* **2020**, 13, 5543.

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