Behind the Numbers on Energy Return on Investment

A full listing of the sources and references behind the calculations in this EROI infographic

Credit: Oliver Munday

When I proposed an article to *Scientific American* on energy return-on-investment, also known as EROI, I didn't realize how much legwork would be involved in gathering the numbers needed for an infographic to accompany the story.

On the surface, the measurement of EROI seems simple. It is just the energy output divided by the energy input. (For gasoline, for example, the output would be the energy in a gallon of gasoline, and the input would be all the energy required to make the gasoline—including oil exploration, drilling and refining.)

Despite the simple equation for EROI, however, there is a lot of complexity under the hood. One issue is that there is a range of EROIs in the literature for each energy source. In part this is because various researchers use different methods for calculating the number. The differences often reflect disagreements about how energy intensive various steps are in the process. To get numbers that I thought were reasonable, I consulted dozens of studies to get a sense of the range of EROI figures for each energy source, then figured out which ones seemed middle-of-the-road as well as computed in a way consistent with all the other EROI figures that I used.

Also, there's no single accepted way of calculating EROI, because it depends in part on what you count as an input. Two of the main types of EROI that researchers calculate are also known as the “net energy ratio” and the “external energy ratio.” For sources such as tar sands, there can be a large difference between these two measures because some methods of getting tar sands out of the ground derive a lot of the energy required for the processes from the tar sands themselves (see the paper cited by Adam Brandt below). The “net energy ratio” counts all inputs—whether diesel fuel for a truck or the tar sands themselves. The external energy ratio, on the other hand, only counts the energy that society puts in, and doesn't count what comes from the resource itself. This means the external energy ratio is always higher than the net energy ratio. Whenever possible, I used the external energy ratio because it is most relevant to the question of how much energy we get out, for the energy we put in. (For calculating greenhouse gas emissions, on the other hand, you would want to consider all energy inputs, and the total emissions from them.)

For biofuels, the EROI reported is usually the external energy ratio, and it doesn't include energy derived from, say, burning the stalks of sugarcane to help power the process of refining sugarcane juice into ethanol. So studies of biofuels will sometimes cite the “fossil energy ratio,” which is similar to the “external energy ratio.”

The external energy ratio number was not available for every energy source.

For example, with conventional oil only the net energy ratio was available. The difference between these two types of EROIs, however, would likely be relatively small for conventional oil (personal communication, Charles Hall).

There are uncertainties in any EROI estimate, in part because energy companies usually don't report detailed information on their energy consumption. To calculate the energy input, researchers have to make an estimate based on the dollars spent on various processes and goods—such as the cost of steel to line an oil well. To keep the infographic as simple as possible, we did not attempt to show error bars or ranges on the estimates, and generally rounded them off to a single digit. This was meant to reflect the uncertainty in any single estimate as well as the fact that there is not a single, precise EROI for any energy source.

To get EROI figures that I thought were representative, I reviewed as many studies as I could find on each energy source, going over at least several dozen studies. Then I chose a recent EROI estimate for each energy source that appeared typical or average, and appeared to be calculated in a way roughly comparable with the estimates for other energy sources. Here are the studies from which I chose to draw for the EROI values:

- Conventional oil: M. C. Guilford et al., "A New Long Term Assessment of Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production," in *Sustainability* (2011) (link).
- Ethanol from sugarcane: I. C. Macedo et al., "Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020," *Biomass and Bioenergy* (2008) (link).
- Biodiesel from soybeans: A. Pradhan et al.: "Energy Life-Cycle Assessment of Soybean Biodiesel Revisited," *Transactions of the*

American Society of Agricultural and Biological Engineers (2011) (pdf).

- Tar sands: There are no peer-reviewed, published estimates of the EROI for tar sands, as far as I could tell. So I drew on an unpublished paper sent by Adam Brandt of Stanford University (Adam Brandt et al., "The energy efficiency of oil sands extraction: Energy return ratios from 1970 to 2010," under review by *Energy*). The paper reports various types of EROIs for tar sands, and I used the number for the external energy ratio for refined fuels.
- Heavy oil from California: Adam Brandt, "Oil Depletion and the Energy Efficiency of Oil Production: The Case of California," *Sustainability* (2011)(link). Note that this is for California only; there is no accepted definition of "heavy oil," and the value may be different for other countries (such as Venezuela), which may use different technologies for extraction and refining.
- Corn ethanol: There have been heated arguments over what the EROI is for corn ethanol, such as a 2006 exchange in *Science*. But all seem to agree that its EROI is less than 2—which puts it at the bottom of the heap for liquid fuels. I drew on a meta-analysis that averaged six different estimates, giving an EROI of 1.4. Hammerschlag, "Ethanol's Energy Return on Investment: A Survey of the Literature 1990–Present," *Environmental Science & Technology* (2006) (link).

For sources of electricity, I used EROI values that are for electricity produced by a particular source, rather than the EROI for the production of the raw fuel that can be used to make electricity. So in the case of coal, for example, the EROI for the coal itself would be roughly three times higher than the EROI for electricity from coal (because the typical efficiency of a coal-fired power plant is around 33 percent).

- Hydroelectric: There are a wide range of EROI values reported for hydroelectric dams, from around 40 to more than 250. To reflect this range, I reported the value as “40+”. See, for example, Gagnon et al., “Life-cycle assessment of electricity generation options: The status of research in year 2001,” *Energy Policy* (2002) (link).

- Wind: I used a meta-analysis of 50 studies, including 119 different wind farms or turbines. Kubiszewski et al., “Meta-analysis of net energy return for wind power systems,” *Renewable Energy* (2010) (link).
- Coal: Most studies on the EROI of coal report the value at the “minemouth,” for all the energy content in the coal. To make it comparable with other electricity sources, especially renewables, I used the EROI for electricity from coal. I drew on one particular study that had as its main focus solar power, but which compared it with fossil fuels: Raugei et al.,“The energy return on energy investment (EROI) of photovoltaics,” *Energy Policy* (2012) (link). The EROI figure there was consistent with what you would get from a back-of-the-envelope calculation, dividing the minemouth EROI for coal by three, to account for the losses of energy in a power plant (personal communication, Charles Hall of S.U.N.Y. Environmental Science and Forestry).
- Solar (PV): There are a wide variety of estimates of solar PV's EROI as well—in part because the technologies and production techniques are improving fast, a major reason for the large price reductions over the past decade. I used the most recent peer-reviewed study I could find (Raugei et al., 2012, cited above). Solar PV's EROI is almost certainly rising (Raugei et al., 2012; personal communication, Michael Dale of Stanford University). The latest data in Raugei's study was at least a couple of years old, so the EROI today is most likely higher than 6, the number cited in my article.
- Natural gas: It was difficult to find an EROI estimate for natural gas because data for natural gas is typically reported along with that of oil. For the EROI figure of 7, I used an alternative measure devised by Carey King of the University of Texas at Austin that he calls the “energy

intensity ratio," and which is comparable with the EROI. King's value for the energy intensity ratio of electricity from natural gas is also consistent with what a back-of-the-envelope calculation would give, using an EROI of oil and natural gas of 20 at the wellhead, and adjusted to take into account the typical efficiency of a natural gas power plant (around 40 percent to 45 percent). King, "Energy intensity ratios as net energy measures of United States energy production and expenditures," *Environmental Research Letters* (2010) (link).

- Nuclear: As with hydroelectricity, the EROI estimates for nuclear power span a very large range. Some claim that the EROI is actually less than 1—which would mean that the whole process is not a source of energy, but rather a sink—whereas others (such as the World Nuclear Association, an industry group) estimate that the EROI is much higher than perhaps any other source of energy, around 40 to 60 when using centrifuge enrichment. I drew on a paper that reviewed many studies, and estimated the EROI to be 5. Lenzen, "Life cycle energy and greenhouse gas emissions of nuclear energy: A review," *Energy Conversion and Management* (2008) (link).

For the graph "Oil's Advantage Drops," which shows EROIs over time, the data was from papers cited above. Conventional oil: Guilford et al., 2011. California heavy oil: Brandt, 2011. Soybean biodiesel: Pradhan et al., 2011.

The numbers in the graphic "Mileage Return on Investment," are based (for all the liquid fuels) on a fairly simple equation from unpublished work by Carey King of the University of Texas at Austin. Multiplying the EROI by the car's mileage (in miles per gallon), then divided by the energy density of the fuel (in gigajoules per gallon) gives the miles you can travel, for one gigajoule of input into making the fuels. I used an average mileage of 30 miles per gallon for new gasoline cars and 33 miles per gallon for diesel cars based on EPA fuel economy estimates. (Note that King's calculations used somewhat different EROI values than I did, so the numbers for "mileage return on investment" differ somewhat from his results.)

For electric cars, I also used EPA estimates of the miles they can go per kilowatt-hour of electricity input, multiplied by the EROI for average U.S. electricity—a weighted average of all the sources of electricity in the U.S., based on EIA statistics for electricity generation. This estimate for electric cars does not include the energy required to manufacture the cars and their batteries—nor does the estimate for conventional cars include the energy required to make them. There is a good reason to think that electric cars require more energy to create, because the battery production process does require some additional energy to build. Life cycle analyses, however, such as Notter et al., "Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles," *Environmental Science & Technology,* (2010), estimate that part of the energy required to make the battery is offset because electric cars have a simpler drive train, which requires less energy to build. Overall, the energy required to make an electric car is around 20 percent greater than that needed to make a conventional car, Notter et al. estimated. I hope that researchers will publish results of more comprehensive estimates for "mileage return on investment," or some similar measure for transportation services that factors in the EROI of different energy sources.

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