Energy Return On Energy Invested (EROI): A Quintessential but Possibly Inadequate Metric for Sustainability in a Solar-Powered World?

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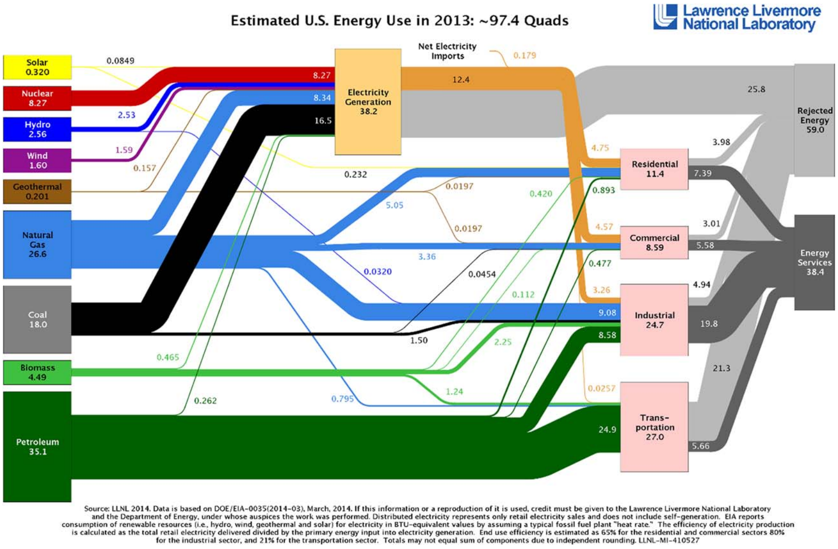

Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Fig. 1. ***Sankey diagram of energy flows in the United States. Courtesy of Lawrence Livermore National Laboratory (DOE): https://flowcharts.llnl.gov/content/energy/energy_archive/energy_flow_2013/2013USEnergy.png.***

> [An existence in which there is] "no culture of the earth; no navigation, nor the use of the commodities that may be imported by sea; no commodious building, no instruments of moving and removing such things as require much force; no knowledge of the face of the earth; no account of time; no arts; no letters; no society; and which is worst of all, continual fear and danger of violent death; and the life of man, solitary, poor, nasty, brutish, and short."
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> —Thomas Hobbes, Leviathan, 1651 [1, ch. XIII].

The objective of this Point of View is to explore the open question of whether mankind, having run through its dowry of fossil fuels, will be able to maintain its advanced global society. Given our present knowledge base, no definite answer can be reached.

It seems only common sense to believe that, to survive, a band of hunter gatherers must arrange its activities to acquire at least as much energy as it expends—both directly in hunting and gathering and indirectly in essential ancillary activities, such as basal metabolism, which support the hunting and gathering. For the band to renew itself by reproduction, rather

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more energy than that is required. For it to develop civilization, still more energy must be captured.

Leaving aside the energetically minor energy fluxes associated with sensation and perception, the band's survival hangs upon its success in providing: 1) the food needed to support the band's basal metabolism; and 2) the additional food needed to execute mechanical work, which compensates for environmental conditions and enables procurement of the band's nourishment. In the developed world, mankind is far removed from hunting and gathering. But we should never forget that it is only 200 years since over 80% of the energy used by the United Kingdom for power purposes was provided by fodder for animals and food for laborers [2, Fig. 2].

Understanding the energy flows is far from simple, even within a community of hunter gathers. They collect biomass, the caloric content of which can be precisely determined by controlled combustion. But this biomass is composed of many components. First, there is hair and skin, which humans find difficult to digest but various fish and reptiles can utilize more completely. However, humans can convert hair and skin into clothing that aids in thermoregulation and sandals that may expedite the process of collecting. Second, there are woody plant materials, which humans find difficult to digest but various mammals and insects can utilize rather better. However, such materials when dried can be used as adjuvants of thermoregulation and survival (shelter and fuel); and as fuel they make possible cooking, which enhances the digestion of food [3]. Third, there are nonwoody plant materials, which humans can digest raw, but which are more effectively digested when comminuted, tenderized, and cooked; moreover, cooking inhibits the dispersal of various infections.

A lone hunter may return with an antelope, the consumption of which nourishes the entire band. But the hunter is part of a system that, for example, provided him with a water skin and sandals for the hunt, collected the wood for cooking, and maintained the band's infrastructure. If the band flourishes, it is not just the lone hunter but the system as a whole that is to be congratulated.

If the band's best efforts fail to collect a viable mix of materials, the band must either move or disintegrate.

I. ENERGY RETURN ON ENERGY INVESTED

The concept of energy return on energy invested (EROI) is related to the familiar economic observation that a wise investor does not expend more money on a project than, in aggregate, he expects to get back. Therefore, it is commonly defined as EROI = (energy output)/(energy input) = (energy returned)/(energy invested); and one desires it to be greater than one: much greater. This definition is simple, direct, and satisfying. It is also ambiguous and/or misleading because of the following.

1) There are many different kinds of energy, all of which are measured in joules. Yet energy is always conserved and never destroyed: instead it is transformed. The unifying thread is that a joule of any sort of energy can, in principle, always be converted to a joule of thermal energy at ambient temperature, in which state it can perform no useful mechanical work. The other forms of energy can be transformed into successor forms which can perform mechanical work, but not necessarily on a one-joule-to-one-joule basis. In short, it is complicated. But the basic idea is that mankind must: a) capture the sorts and quantities of energy that societal functionality requires; and b) do so with an input considerably smaller than the captured output—because that output provides the surplus energy resources needed to evolve from a pack living hand-to-mouth into a complexly organized society with material wealth and copious knowledge. Fortunately, fluxing through our environment, there is plentiful solar energy to support our civilization, if only it can be captured on the cheap.

2) By many orders of magnitude, the leading source of the energy powering human life and society is solar radiation [4], itself the product of stellar nuclear fusion. It is responsible not only for the planetary biomass man exploits but also for the fossil fuels that have powered the Industrial Revolution of the past three centuries.

3) Unfortunately, the fossil fuels, upon which mankind today depends, were formed over hundreds of millions of years by fortuitous geological processes [5]: think of them as a rich dowry which, like the former hardwood forests of America's Midwest, just happened to be there—waiting to be exploited and easy to exploit. When, later this century, the resources of fossil fuels run low, there is no guarantee that the Earth's copious solar resources will be as easy to capture, turn into electrical or mechanical energy, and exploit.

4) In 2013, some 316 million Americans consumed in aggregate approximately 97.4 quads of primary energy, equivalent to[1] $\sim 2100 \times 10^{2}\ \mathrm{kcal\ d^{-1}\ p^{-1}} \sim 11\ \mathrm{kW\ p^{-1}}$, roughly hundredfold an active human's daily nutritional requirement of ~ 2100 kcal; this hundredfold ratio is the energetic equivalent of many score faithful servants

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[1] In the expanded International System (SI) units of this paper, "day" is abbreviated as "d," and "person" is abbreviated as "p."

> working very hard to improve the material well being of each of us. It is no wonder that, the world over, societies are choosing paths of development.

When, later this century, the world's population approaches ten billion, each of whom might well like to enjoy the gross domestic product of a developed economy, providing such affluence will require a net flux of captured energy on the order of 100 TW. Assuming a modestly optimistic harvested solar flux of 11 W m^{-2} [6], this implies a solar collecting system of area $\sim 9 \times 10^6$ km^2. As this is a bit less than the net area of the world's subtropical deserts, the task might even be doable; but it will be achievable only if the EROI is large enough.

Conceptually, EROI is simple to quantify if measurement of the quantities defined is momentarily neglected. Let ${}_pE_{\text{out}}$ (in joules) represent the total usable energy shipped by a particular energy-gathering scheme in the pth year of its existence ($p = 1, 2, \ldots, P$); and let ${}_pE_{\text{in}}$ (in joules) be the total energy expended during the pth year for: 1) the ancillary activities essential to the scheme plus 2) the direct process of scheme operation. Further, let $E_<$ (in joules) be the energy input required to create the scheme and $E_>$ (in joules) the energy needed to remediate the scheme's site at the end of the scheme's life. Finally, define EROI as the dimensionless ratio H, where

$$H = \frac{\sum_{p=1}^{P} {}_pE_{\text{out}}}{\left\{E_< + \sum_{p=1}^{P} {}_pE_{\text{in}} + E_>\right\}}. \quad \text{(1a)}$$

This ratio is EROI.

Simplification: If for all p, ${}_pE_{\text{out}} = \langle {}_pE_{\text{out}} \rangle$ and ${}_pE_{\text{in}} = \langle {}_pE_{\text{in}} \rangle$, then

$$H = \frac{\langle {}_pE_{\text{out}} \rangle}{\left\{\langle {}_pE_{\text{in}} \rangle + \frac{1}{P}[E_< + E_>]\right\}}. \quad \text{(1b)}$$

Equation (1b) makes obvious the desirability of energy capture schemes having intrinsically long lifetimes plus, insofar as possible, reusable infrastructure. For sufficiently large P, $[E_< + E_>]$ becomes irrelevant; and the nominal yearly surplus $\langle \mathrm{E}_{\text{surplus}} \rangle = \langle {}_pE_{\text{out}} \rangle - \langle {}_pE_{\text{in}} \rangle$.

This formalism has three critical weaknesses. First, it is not the only formalism. In energetics as in economics, there are different schools of thought. In this essay, four will be mentioned prominently. Second, the energy embodied in building, maintaining, and operating an energy collection scheme is hard to evaluate. What is the energy embodied in a day's work of a laborer at the facility? What is the energy embodied in a simple aluminum reflector at a concentrated-solar-power facility, especially if the reflector contains a high fraction of aluminum scrap? One may have to fall back upon crude surrogate measures such as: in 2013, America's gross domestic product was ~\$16.8 trillion, while its primary energy consumption was ~103 EJ (overwhelmingly fossil fueled); therefore, each dollar of GDP is the "equivalent" of ~6.01 MJ$_{\text{th}}$. Except that, third, most massive renewable energy schemes of the future are expected to output electricity for the grid, and that energy can be converted to mechanical work with very high efficiency, whereas, it normally takes around three thermal joules to accomplish one joule of mechanical work. Therefore, one should probably establish a nominal "exchange rate" of 3 J$_{\text{th}}$ for 1 J$_{\text{elec}}$, and perform all comparisons in terms of electrical joules.

For the case of a band of hunter gatherers, the dominant energy scheme is its group activity: if its overall $H < 1$, then the band will starve. On the other hand, if $H \gg 1$, then the band might even flourish. Concretely, human basal metabolism is commonly reckoned to be ~1.5 W kg^{-1} [7], which for 50-kg hunter gatherers works out to be about 1500 nutritional calories a day each. If the food gathered brings in no more than this, the band can be expected to disappear: a life of hunting and gathering requires rather more energy than basic basal metabolism.

For a more complex society with many energy inputs, an individual scheme whose EROI turns out to be < 1 could be merely a costly and embarrassing learning experience, while supporting a high standard of living might require a societal EROI $H_{\text{soc}} \gg 1$. These notions are qualitatively illustrated by the "pyramid of energetic needs" proposed by Lambert *et al.*, [8, Fig. 12], and the minimum EROI required to sustain, just barely, an organized society has been estimated roughly by Hall *et al.*, [9] to be $H_{\text{soc}} \sim 3$. Obviously, $H_{\text{soc}} > 1$ is essential. Clearly, $H_{\text{soc}} \gg 3$ is highly desirable. Even so, the linchpin issues would seem to be as follows.

1) Does the aggregate system of many energy collecting schemes yield a large enough surplus of energy [9], over and above the demands of the collecting schemes, to operate the society? In energy as in business, it is not the magnitude of the operation that counts: it is the magnitude of the profits.
2) If the surplus energy is meager, can a buildout of the collecting schemes even be arranged? Probably so, as discussed by Murphy in his brilliant essay "The Energy Trap" [10]. But it may not be easy.
3) Is as large a return of surplus energy return needed as demanding a high EROI would suggest? Fig. 1 shows that only 40% of the primary energy absorbed by the United States actually goes to performing the desired energy services. Presumably, much of this wastage reflects Carnot inefficiencies inherent to converting heat energy into useful work.

Prospectively, therefore, an energy future in which the primary input is overwhelmingly electric could avoid Carnot inefficiencies and thereby nearly eliminate the rejected energy; this could easily halve the primary energy needed.

II. ESTIMATES OF EROI FOR PHOTOVOLTAICS

The group most prolifically disseminating EROI statistics is that associated with Charles A. S. Hall of the State University of New York at Syracuse, which has also discussed the extant data and the methodology (e.g., [11–13]). They note, disquietingly, that "values from different regions and different times for the same fuels . . . can give quite different results" [13, p. 143]. Estimates specifically relevant to photovoltaic (PV) generation have been provided by at least four collaborations.

1) The group associated with Vasilis Fthenakis at Brookhaven National Laboratory (Upton, NY, USA) has evaluated the prospective EROI of rooftop installations of moncrystalline silicon solar cells and reckons it to be about 5.9 [14, Table 1].
2) The group associated with Pedro Prieto of the Asociación para el Estudio de los Recursos Energéticos (Madrid, Spain) has studied three years of data from approximately 4 GW of installed PV capacity and reckons its EROI to be about 2.4 [15, Ch. 7].
3) The group associated with Daniel Weißbach of the Institute für Festköper-Kernphysik (Berlin, Germany) has estimated the prospective EROI of rooftop installations of polycrystalline silicon solar cells in Germany and, using several different EROI definitions, reckons it to be about 4.0 [16, Table 3].
4) The group associated with Adam Brandt of Stanford University (Stanford, CA, USA) has estimated various different EROI-related energy ratios for PVs, and has suggested an EROI in the neighborhood of 5.8 [17, Table 2].

Additionally, other authors, taking more qualitative paths, have even raised doubts as to whether the energy supplies needed to support complex advanced societies can be sustained by renewables alone (e.g., [18] and [19]).

The four quantitative estimates yield an arithmetic mean EROI of 4.5 and a geometric mean EROI of 4.3. Both means invite the reader to be cautiously optimistic about the sustainability of a potential carbon-neutral future powered by renewables. To be conservative, suppose them to be correct to within a factor of two (i.e., mean ±3 dB). This leads to a projected societal EROI somewhere in the range $[2.2 < H_{\mathrm{soc}} < 8.8]$.

III. LOW EROIS MERIT PRUDENT POLICIES

In such complex circumstances, with rapidly changing technological underpinnings, and with a plethora of conflicting viewpoints, an obvious but costly strategy would be as follows.

1) To remember that reliable and comprehensible experimental data are the gold standard of scientific decision making.
2) To gather the four analytical groups for an extended Summer Workshop to revisit the three years of Spanish solar data, only sketched out in the Prieto and Hall monograph [15].[2] The goal would be to achieve step-by-step group agreement on a consensus analytical pathway to be followed, with a minutely detailed description of the provenance of each input datum and its transformation into an output datum.
3) To launch, based on this consensus pathway, a dozen or more meticulously audited 1-GW solar PV demonstration projects, whose auditing protocols effectively followed the energy as well as the money. Such procedures should provide markedly better data with rather less scatter.

Because there are disturbingly many recent predictions that peak fossil fuel is rapidly approaching and could be well past in only 30 ± 60 years [20], decision makers have a critical need to know precisely what EROIs can be attained using collecting schemes for renewable energy: too low a value could presage a serious regression in the global human development index.

Such information would not, however, totally resolve the complete systemic EROI problem because of the energetically demanding needs for: 1) a radically strengthened long-distance transmission backbone that serves to average generation over continent-sized areas; and 2) an ancillary infrastructure of massive electricity storage to finesse the remaining supply fluctuations inherent to solar-derived electricity. While transmission is often recognized as an issue, it was covered in detail by none of the four groups cited for EROI estimates. However, the Weißbach group did predict storage-related EROI reductions of as much as 40% [16]. That could pose serious difficulties.

In summation, as the Age of Fossil Fuels draws to a close, it appears that mankind may be facing an obligatory change to renewable fuel sources—without having done due diligence to learn whether, as envisioned, those renewable sources can possibly suffice. ■

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[2] This accumulation of data covers the construction and operation during 2009–2011 of the what was at the time the world's largest PV generating effort.

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