The Changing Meaning of Energy Return on Investment and the Implications for the Prospects of Post-fossil Civilization

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Energy return on investment (EROI) is a useful physical metric to compare the utility of energy production processes and their development over time. The concept has been extended from its physical, process-based origin to one that describes the societal metabolism. As such, EROI has been used to speculate about the prospects of humanity in a late-fossil and post-fossil civilization. Often, the narrative to emerge around EROI is that in the (near) future, prosperity will be compromised. Here, we take a fresh look at EROI, with a distinction between a physical EROI, which is useful at energy project level, and a societal, or economic, EROI—appropriate at the level of the whole economy. This distinction leads us to conclude that a renewable future is possible. Such a future is essentially unconstrained by the physical EROI and will have an acceptable economic EROI—not much different from that of the past century.

Introduction

Any living entity—whether an organism or a human society—must appropriate more energy than it consumes in order to survive, reproduce, and grow.[1] The importance of this surplus has been recognized for many decades from ecological[2,3] and anthropological perspectives.[4] Net energy analysis is used to determine the surplus, with energy return on (energy) investment (EROI) emerging as the most popular indicator. Proposed by Charles Hall and colleagues in the 1980s,[5] it quantifies the energy surplus (energy return) as a fraction of the effort required to generate the surplus (the investment) for a given activity. Renewed interest since the mid-2000s has once again propelled EROI to be a popular although ambiguous and at times controversial[6–8] indicator of progress and regress of society's ability to provide itself with energy.[9] EROI can be considered a measure of productivity,[10] with a high EROI value being indicative of a process or a society that makes net energy available with little effort or (energy) investment. A low value is indicative of an inefficient process, a low-quality resource (as in the case of fossil fuels), or—at the level of society—an expensive energy system.

Where the primary EROI literature is concerned with the neutral reporting of trends, a significant body of secondary literature has developed that makes bold generalizations and inferences. It is viewed as a "critical parameter for understanding and ranking different fuels"[11] or "the most important parameter" of energy production,[12] leading to calls that "net energy analysis should become a critical policy tool."[9] We concur that energy return assessment has been useful for the analysis of modern and pre-modern societies, and it will be useful going forward in guiding the development toward a sustainable energy system. But at the same time, we must be cognizant of the evolving nature of energy provision over time, of changes in the energy economy, and of technological change. Taken together, this implies that how, why, and to what extent EROI limits societal development changes with time. In this paper, we analyze these changes.

High EROIs are associated with prosperity and a higher standard of living,[13] with many highlighting that declining EROIs can disrupt modern prosperous lifestyles.[10,14] Conventional use of EROI leads, however, to pessimistic prognostications. A few quotes illustrate this point. In a paper rich on data, Hall et al. conclude that "[d]eclining EROI is probably already having a large impact on the world economy" and that as we move to deploy a greater share of renewables, such a shift "would result in declines in both the quantity and EROI values of the principle energies used for economic activity," leaving no other conclusion than that if humanity is to solve its problem, "an adjustment of society's aspirations for increased material affluence" is vital,[13] with other authors reaching similar conclusions.[14–16] This gloomy outlook is based on the view that transitioning toward a renewable-energy-powered society "seems to necessarily imply a shift from a higher to a lower EROI supply energy mix".[17]

At the heart of what is a pessimistic outlook lies an ultimately speculative conjecture of what physical, project-level energy returns mean for a society as a whole using inappropriate extrapolations of simplistic models of how the economy functions. In this paper, we will be very explicit about the differences between simple physical EROIs and systemic economic EROIs, taking a different approach than previous authors. This allows us to be more appreciative of the fundamental change in energy provision as the energy system transitions from being fossil based to (largely) renewables based and leads to a positive outlook for a post-fossil society of similar or even greater complexity than that of today.

EROI Definitions

Traditionally, EROIs have been calculated using a range of different boundaries to produce assessments at point of extraction, $EROI_{st}$ ("standard"), and at the point of use, $EROI_{pou}$ ("at point of use"), of energy carriers. While there has been some attempts to categorise and standardize these approaches,[18] wide ranges of EROI values, using different boundaries, which have often been used interchangeably to compare and contrast energy carriers, giving "apples to oranges" comparisons.[8] This has been particularly problematic when comparing fossil fuels such as oil and gas to technologies that directly produce renewable electricity, leading to inappropriate comparisons. The majority of published EROI values represent a physical assessment using

$$\mathrm{EROI}_p = E_{out}/E_{inv},$$

where E_{out} is the energy output (i.e., energy delivered to society) and E_{inv} the sum of all the primary energy investments. The boundary used can vary depending on whether the assessment is conducted at the point of extraction, e.g., oil well, or at the point of use, e.g., electricity. As others have shown,[8,19] the difference between these two interpretations is significant, with only the point of use being considered an indication of the actual net energy return being made available to society. Point of extraction assessments, such as those usually conducted for fossil fuel resources like crude oil, are only meaningful when comparing against similar energy sources, e.g., comparing crude oil production from different sites. Due to the different boundaries used, this has traditionally made comparisons between different energy sources problematic. For example, comparing the electricity generated from solar photovoltaics with that from fossil fuels[19,20] has often used inconsistent boundaries generating misleading results.

The other forms of EROI that have emerged are systemic economic EROIs, typically expressed as energy expenditures as a fraction of GDP.[21,22]

$$\mathrm{EROI}_e = \mathrm{GDP}/C_{e,inv},$$

where GDP is the global (or national) gross domestic product and $C_{e,inv}$ is the total amount of money spent in that economy for procuring energy. (Below, we will come back in more detail on how to calculate energy expenditure.)

Energy Return in Natural Systems

EROI is both a simple and a generic ratio, with its initial ecological applications concerning the use of scarce calories in animal populations. For biological organisms, strategies are employed that appear to maximize their own EROI.[1,23,24] Decline occurs when food availability and quality is reduced, requiring them to expend more effort to achieve the same return.[23] Similarly, in early human societies, just as in nature, useful energy has historically been scarce, with EROI being used to better understand the prosperity of early hunter-gatherer existence and assess the energy-capturing activities of modern industrial society.

When looking at the majority of literature on modern energy systems, published EROI values represent physical EROI (EROI_p), which is in effect the energy return derived from fossil fuel investments. We acknowledge that many of the EROI_p values reported in the literature often refer to functionally non-equivalent energy carriers sampled at different stages of their respective supply chains, which has generated misleading comparisons. However, regardless of the boundaries employed, these assessments best evaluate the most effective strategies to generate energy carriers while minimizing investment of precious (and scarce) fossil fuels. The fundamental attractiveness of this physical EROI_p is that it circumvents the problems associated with monetary assessment of energy's net benefit to society that may be obscured by subsidies, externalities, etc.[9] EROI_p is a critical measure when energy is scarce. But it is obvious that the scarcity of calories in hunter-gatherer societies is different from fossil fuel scarcity in modern society and different yet again from energy scarcity in a future renewable-energy-based society. Assessments in these simpler systems, using the physical energy return ratio, at the project-by-project and technology-by-technology level makes the assessment of the economy-wide averages difficult.

Energy Return in Complex Societies

The other form that EROI can take is a societal or monetary-based EROI (EROI_e), variations of which have been employed previously.[21,22] This societal EROI is the summation of all types of energy flows (returns) that the economy is getting and is expressed as energy expenditures as a fraction of GDP (i.e., the inverse of GDP fraction of energy expenditure). While no longer a "physical" metric per se, it seeks to aggregate economy-wide monetary flows associated with energy production. This is a natural extension of the physical EROI, where, rather than looking at the flow of calories, one looks at the economic surplus (as embodied in income) that results from investment in energy production, assumed to be the driving force, animating spirit, and *sine qua non* for the economic production process.

As with animal populations that decline due to too much effort finding food, human society prospers only by accessing large collective energy returns with little societal investment (as measured by GDP). The greater the share of GDP that goes to energy, the less is available as surplus for discretionary investment and consumption, and the less society prospers. As such, energy expenditure can be considered a major limit to growth, with maximum "tolerable" prices being determined for the United States at 11% of GDP.[22] In other global assessments, it has been determined that the developed world was in recession during both instances of energy cost rising above 8% GDP.[21]

The GDP share spent on energy is actually an imperfect guide to determining the effort invested in the production of energy. It includes rent that is the income derived from the ownership of land and other free "gifts of nature" (such as fossil fuel resources). Thus, rent ("unearned income") is not work, not a proper effort. This explains that EROI_e fluctuates over the course of business and investment cycles and spikes in times of energy crises. These variations obviously do not represent fluctuations related to the physical process of energy extraction either at the project-level or in aggregate. To make the distinction, we introduce EROI_e^{real}, which is the economic EROI at society level based solely on productive economic effort, with rent stripped off. What we previously introduced EROI_e as (the inverse of GDP fraction of energy expenditure) is not properly scaled to an energy-economic investment, so it is better termed an apparent economic EROI—denoted as EROI_e^{app}.

Physical and economic EROIs are useful but are not the same, even though their numeric values may not have been too

Table 1. The Historic Epochs Distinguished and Discussed in This Paper with Their Energy Use, Their Typical EROI Values, the Short-Term Regulating Factor of EROI, and the Nature of Long-Term Limits to Societal Development

Historic Era	Energy/Capita (GJ/cap)	$\langle EROI_p \rangle$ (range)	$\langle EROI_e \rangle$ (range)	Short-Term Variability	Long-Term Limit
Hunter-gatherer	6	∼10[1]	∼3[29]	food availability	carrying capacity; population density
Pre-modern agricultural	30	2[22] (2–3)	1.5 (1–2.5)	agricultural productivity	total population (Malthusian)
Modern, fossil-industrial	100–300	20[13] (2–100)	10–20	energy access	$EROI_p$
Future, renewable	>100	–	>10	capital availability	material resources; technology cost ($EROI_e$)

different in recent times. After all, not all economic activity is equally energy intensive: within the economy, the GDP output per MJ input can vary significantly. Moreover, technology changes over time, and the energy intensity of GDP steadily decreases over time. Applying these distinctions to historic patterns of energy use, we come out with a clear, new, and more positive outlook on the coming renewable energy era based on recent work that takes stock of recent advances in renewable energy technology and extrapolations thereof to the future.[25–28] We look at four different energy-use epochs: the prehistoric hunter-gatherer, the pre-modern agricultural, the modern fossil-industrial, and a future renewable epoch.

The Changing Nature of Energy Return over Time

The chief characteristics of the energetic metabolism of society in the four human epochs relevant to our narrative are given in Table 1, along with the limits to growth encountered in each of them. Starting with the hunter-gatherer, anthropology has provided us with a reasonable assessment of the time and energy expenditures in these societies. In their economy, calories were the scarce resource of concern. Life may have been—in Hobbes's famous words—nasty, brutish, and short; it had also a leisurely quality. On average, some 2.5 days per week were used to obtain all the food they needed.[29] If we equate time with money and compare that (anachronistically) to an eight-hour work day, the economic EROI was—for what it's worth—about three. Others have found even higher values for specific hunting techniques.[30]

When hunter-gatherers gradually gave way to farmers, this was not due to superior diet, longevity, or lifestyle (to use yet another anachronistic term). Quite the contrary—life got worse. This led Jared Diamond famously to suggest that agriculture was humanity's worst mistake.[31] But farmers outbred the hunter-gatherers, compounding the mistake. While hunter-gatherers appear to be limited to densities well below one person per square kilometer, farming allows hundred-fold higher population densities.

In the agricultural epoch, food and feed (animal fodder) were still dominating the energy economy, as well as the monetary economy. Fouquet's data indicate that in the agricultural United Kingdom of 1800, 40% of primary energy came from food for labor and 30% from animal feed.[32,33] Likewise, as Figure 1 shows, around that same time, half of GDP was spent on food-for-labor, feed, and wood (and increasingly on coal). From this realization of how food and feed were part of the energy economy and the historic pattern of GDP expenditure in Figure 1, we infer that $EROI_e^{app}$ was on average less than two, with significant variation from year to year, depending on the bounty of the harvest.

Fluctuations in the harvest represent a variation in both the physical EROI of the agrarian economy and the real economic EROI. The same efforts and the same inputs would return a different output every year. Even though we do not have the data, we can reasonably assume that both $EROI_p$ and $EROI_e^{real}$ varied from year to year and that both would have been higher than $EROI_e^{app}$ because of speculation.

These data highlight the historical fall in prices of energy services. During the last great energy transition (shift from biomass to fossil fuels), the energy cost share of the economy declined significantly, with preindustrial societies spending, as a proportion of GDP, four times as much on energy than we do today. In the fossil industrial era, this trend continued with the turn of 21st century, by some estimates representing the cheapest energy in history.[33]

Due to need to conserve the scarce fossil resources, $EROI_p$ emerged as the measurable quantity when evaluating fossil and now renewable energy sources. While there is an enormous scatter in the data, reflecting the variability between projects and technologies, in addition to a range of boundaries being used for the assessments, a more or less complete picture of the physical energy return for the main forms of energy supply has now emerged, these being primarily energy return on fossil fuel investment analyses. Fossil fuel EROIs (coal, oil, and gas), typically measured at the wellhead, have deteriorated over time, inherent in the finite nature of fossil resources and the natural propensity of humans to use "the best" first. The aggregate EROIs of all fossil fuels at the point of extraction have been slowly declining over time since the days of "easy oil."[38] The aggregate $EROI_p$ of all fossil fuels at point of extraction has been slowly declining over time and is currently at around 30:1.[19] Today, many oil and gas energy projects in the United States have an $EROI_p$ of only 10:1,[38] with some even lower for unconventional oil production,[39,40] feeding concerns about the future. When looking at the final stage, the EROI of the actual energy carriers delivered to society ($EROI_{fin}$), the ratios are on average around 6:1, declining by 10% over the last 25 years.[19] The EROI of electricity generated from wind and solar on the other hand, which produce electricity and thus "final-stage energy," have typically been estimated between 5–20:1.

As Figure 2 illustrates, its average, $\langle EROI_p \rangle$, is the weighted average of the individual $EROI_p$ values of the main energy resources. The resource mix varies over time, as does the quality of the resource. In recent years, renewables have been added to the mix, with low but rising $EROI_p$. In spite of Hall's reasonable

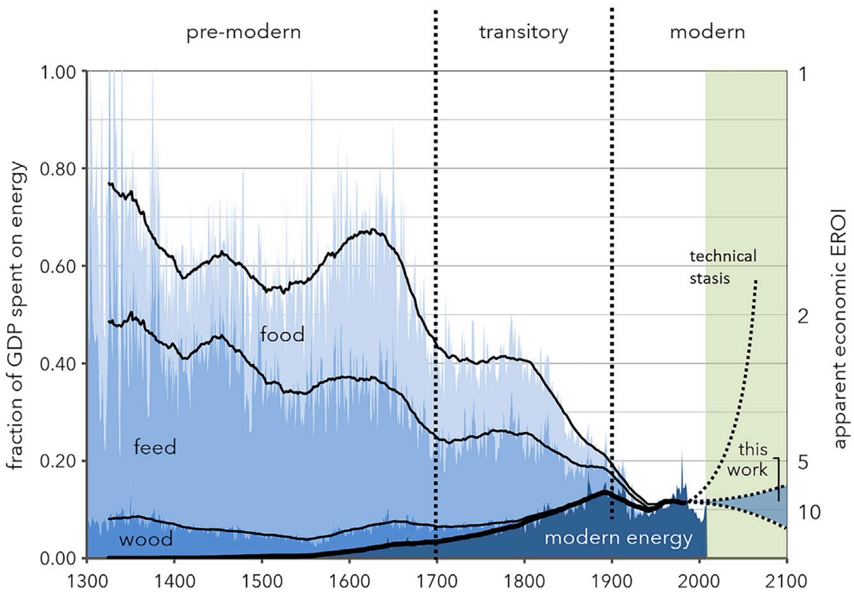

Figure 1. The Historic Development of Energy Expenditure in the United Kingdom
The historic data are from Fizaine and Court,[22] based on Fouquet.[32,34–36] The forward projections is inferred from the analysis of Hall,[37] which is effectively a world with no or little technological progress (technical stasis). It is contrasted with the inferred EROI development on the basis of this work, which relies on bold technical progress, especially concerning solar fuels.

and plausible inference that <$EROI_p$> has declined over the course of the latter half of the 20th century, the fraction of GDP spent on energy (the inverse of $EROI_e^{app}$) has fluctuated but does not show a systematic downward trend. Rather than having a physical origin, the fluctuations must be attributed to a combination of business cycles and geopolitical disturbances. These at times lead to scarcity, with high prices not reflecting higher economic inputs into the energy sector but rather the consequence of rent taking in a supplier's market.

We may reasonably infer that $EROI_e^{real}$ (for which data are lacking) has been fairly smooth during the 20th century and presumably more or less constant, plotting naturally just above the peaks and plateaus of the $EROI_e^{app}$ curve, that is, the times when energy prices were low and supply plentiful. (More work and mode data analysis would be needed to further substantiate this claim as fact, but we believe that it is sufficiently plausible to complete the present narrative.)

If we accept the conventional view that <$EROI_p$> has declined over the latter parts of the 20th century[19] while $EROI_e^{real}$ remained constant, this is manifestation of technical progress. One could even turn the argument around: since technical progress in oil and gas production and in the energy sector generally is amply documented, it must be so that the gap between <$EROI_p$> and $EROI_e^{real}$ has narrowed.

Energy Return in a Future, Renewables-Based Epoch

The conventional view of the future in the EROI literature—as indeed elsewhere—has been to consider that the intermittent renewables, such as solar and wind, will displace fossil-based power generation and for biofuels to substitute for oil-based fuels. The inference from this is that the inevitable downward trend of $EROI_p$ of the fossil era—due to stocks depletion—looks to be exacerbated by the energy transition, as solar and wind have lower $EROI_p$ values than coal, and biofuels have lower values than oil-derived gasoline and diesel.[13] Noting further that photovoltaics (PV) and wind need backup to compensate for their intermittent nature, the scene is set for a world of perilously low EROI—possibly too low to sustain the affluence of a complex civilization.[1,10,12,14,15,41,42] When correcting for boundary inconsistencies in the physical assessments, it has already been shown that at the point of use stage, that fossil fuel EROI ratios may be much closer to those of renewables than previously expected.[19]

The problem with this framing, however, is that a reality of the long-term threat, based on an ultimately arbitrary minimum EROI value, is implied from the extrapolation of the short-term transitional trends in the energy transition (PV and wind replacing coal, biofuels replacing oil). Since, as this paper highlights, the value of EROI analysis at a societal level is to shed light on the long-term, society-wide implications of energy supply for society, we offer an analysis of the future societal-level EROI for what can be considered a plausible aspirational endpoint of the transition to renewable energy, namely an energy system based on massive deployment of cheap PV and wind power, part of which is used to provide the energy input for synthetic fuels production. Indeed, this future image has only in recent years become plausible and conceivable, based on the great advances in the commercialization of PV solar and wind over the last decade.

The commercialization of wind and solar technologies have brought their cost down to respectively \$30–60/kWh and \$40–50/MWh,[43] with costs for solar likely to drop by two-thirds by 2040, according to some analysts.[44] Given these cost levels and outlook and given the realistic worldwide potential of solar and wind electricity generation, easily in excess of 1,000 EJ/year, it is natural to see solar and wind as the backbone of a future energy system. The much-touted problem of intermittency requiring fossil backup can be turned around by significantly overbuilding PV and wind and converting the intermittent electric oversupply into fuels.[25]

The idea of excess power conversion to a synthetic fuel has recently become popular under the heading Power-to-Gas, where "gas" can be either hydrogen or methane.[45,46] Taking the idea to its extreme, all the world's fuel will in a future, renewables world be synthetic "Power-to-X," where X can be hydrogen, natural gas, or liquid hydrocarbons. To the extent that hydrogen can be used, it should be used, as the conversion efficiency is highest and closing the material loop through water is trivial. However, its distribution and use might not be universally viable. That is why, to prove our point on the EROI viability of a true, fully renewable energy system, we assume that X is hydrocarbons, synthesized from renewable hydrogen

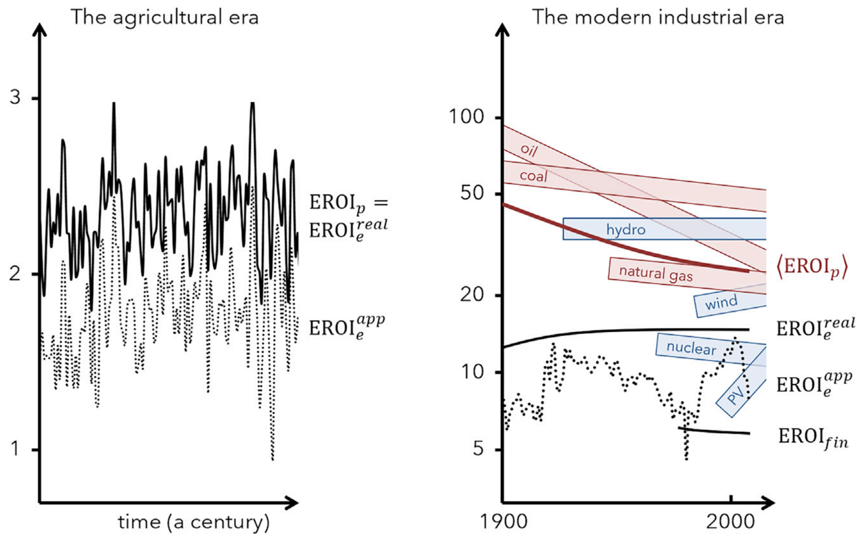

Figure 2. Indicative Representations of the Fluctuations and Trends over Time of EROI in the Agricultural Age and in the Modern Industrial Age

Values for $EROI_e^{app}$ are for the United Kingdom taken from Fizaine.[22] The estimates for $EROI_p$ are estimates discussed and referenced in the text. Color is used to distinguish between fossil hydrocarbons and non-fossil electricity. Finally, global, economy-wide estimates for final-stage energy return, $EROI_{fin}$, based on input-output analysis is taken from Brockway et al.[19] Both time axes span roughly a century. For the agricultural age, the actual data used are 1400–1500, but it is representative of any century. For the industrial age, we have plotted the 20th century (1900–2008) using Fizaine's UK data for $EROI_e^{app}$ and an approximate rendering of Hall's 20th century development for $EROI_p$, both its downward overall trend, and the specific values of energies as they come into the mix. Note the difference in vertical scale and the logarithmic axis for the right-hand graph.

and air-captured CO_2. Kraan and colleagues outline an all renewable pathway that provides further context, data, and calculations to show that based on where technology stands today, and with reasonably assumptions on technology progress, the future price of 24/7 electricity delivery can be around \$100/MWh, and Power-to-X synthetic hydrocarbons can be produced for \$200/bbl (where bbl is barrel, the standard measure of oil, 159 litre).[45,46] This equates to \$30–35/GJ for both electricity and fuel. A 50/50 split between electricity and fuel in end use is a reasonable estimate of what is plausibly achievable. It corresponds to very significant further, but by no means complete, electrification of the energy system (50% should be compared with 20% today).

Such an energy system might at the very earliest be realized by the middle of this century. Using the standard assumption of continued economic growth at 3% per year, and a continued increase in the energy productivity across the economy, improving 1.5% per year as it has done for the past decades. By the middle of the century, this results in a \$250 trillion global economy having a total final consumption (TFC) of 600 EJ/year, numbers that are in tune with the reference scenarios of the International Energy Agency (IEA) but markedly higher than more sustainable scenarios such as the IEA's sustainable development scenario or scenarios by environmental non-governmental organizations (NGOs), which put mid-century TFC more somewhere between 300 and 500 EJ/year.[47]

Even so, $EROI_e$ in this future fully sustainable energy economy would be around 10—based on energy costing \$30–35/GJ and an energy productivity close to \$400/GJ. This means that $EROI_e$ would have a value just above 10, not too different from that of today's fossil-dominated energy system, in marked contrast with earlier predictions based on energy returns (see Figure 1).

Finally, we also consider $\langle EROI_p \rangle$ in this all-renewable energy system. The straightforward answer is that it will be between 10 and 20, which is where PV and wind are today,[48,49] again not too different from today's average. One may point to complications with this, as a significant fraction of primary electric energy is lost in conversion to fuel. But the same is true today with the conversion of fossil fuels to electricity. These conversions and what to count as energy delivered to society make EROI assessments tricky. But the situation is no different for the renewable energy system we have outlined here, as it is for the largely fossil-based system of today. The difference is that today, energy conversion losses (and the prime difference between total Primary Energy Supply (TPES) and TFC) comes from fuel-to-power losses, whereas in the future, it will come from power-to-fuel losses.

Energy Return Will Not Constrain Future Development

Unlike in any previous epoch, energy in the future will not be scarce. This is fundamentally a technological achievement: sun and wind have always been plentiful resources, but solar photovoltaic panels and wind turbines have recently become practical, affordable devices to convert the resource into useful energy, notably electricity. In the energy-scarce world of both the distant and recent past, running out of energy was a key concern and energy resource management a priority. Thus, $EROI_p$ was a key parameter for evaluating new energy technologies.

However, in the energy-abundant future that PV and wind energy technologies are about to open up for humanity, the limit to prosperity will be not energy scarcity but the economic cost of accessing energy. It has been widely recognized that industrial society stagnates when the cost of energy rises dramatically,[15,21,22,50] with maximum tolerable prices being estimated for United States energy expenditure,[22] this being entirely obvious, since spending more on energy leaves less in the societal budget for discretionary spending. Future prosperity will be constrained not by energy scarcity but by getting prices high enough to make energy economic to produce without making it unaffordable for consumers. $EROI_p$ assessments have traditionally focused on the investments that are required to produce energy, which we argue are no longer scarce, making this indicator less relevant for a renewable powered epoch. The selling price of energy, which may include rent taking, ultimately determines the demand for energy products, which are captured more effectively in $EROI_e$ assessments.

In an energy-abundant renewable epoch, the constraint on energy production will shift from energy resource scarcity to capital scarcity for investments in renewable energy conversion technologies. Our analysis has highlighted that future renewable technologies can provide a 50/50 mix of electricity and synthetic fuel to society at an affordable price, as evidenced by $EROI_e$ levels similar to todays. This should provide us with a sense of purpose and long-term comfort as we take on the daunting task of converting the energy system toward this long-term "end state."

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