BANG *for the* BUCK

Energy return on energy investment is a powerful metric for weighing which energy systems are worth pursuing.

BY FRANK KREITH

Engineers are still trying to understand how the concept of sustainability fits in with our profession. It's reasonable that engineers would have trouble with something like sustainability: There are no equations to solve that can optimize it and no widely agreed upon standards to which we can adhere. In fact, the concept is so nebulous that it fails the "know it when we see it" test.

In spite of this difficulty, no subject is more important to the engineering profession or the wider world that we live in. The first decades of this new century have presented us with four interlocking crises—a growing global population, depletion of natural resources, degradation of the environment, and economic instability—that cry out for a new way forward. This is especially true in the field of energy.

The global energy system is mostly based on fossil fuels—coal, petroleum, and natural gas—that are burned to power heat engines, to fuel automobiles, or to provide sensible heat. These fuels have been abundant enough to bring civilization to its present condition. Indeed, according to data from the Energy

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Information Administration, oil, coal, and gas account for around 84 percent of the world's primary energy consumption in 2011.

But it is becoming clear that, for a variety of reasons, it would be foolish to depend on them as we progress through this century. For one thing, the overwhelming scientific consensus is that emissions from burning fossil fuels are harming the environment: They are trapping atmospheric heat, changing the pH of the oceans, and altering rainfall patterns. What's more, even if there were not these harmful side effects, there is an even more compelling reason to begin developing alternatives: Fossil fuels will eventually become too depleted to use profitably.

ENERGY RETURN ON ENERGY INVESTMENT

$$\text{EROI} = \frac{\text{Energy return from system operations}}{\text{Energy to extract fuel and build plant and infrastructure}}$$

For energy systems, money isn't the only limiting factor. The amount of energy available is also limited, and it's critical to reduce the amount devoted to finding more energy.

A friend of mine once quipped that anyone who believes you can sustain exponential growth in a finite world is either a madman or an economist. And energy use has grown exponentially while fossil fuels are decidedly finite: They arise from the geologic processing of organic sediments over tens of millions of years. One can argue over just how much of those resources remain to be exploited, and some geologists contend that we are approaching the peak rate at which oil can be extracted. It is, however, obvious that the coal, oil, and natural gas supplies which were the easiest to extract have already been extracted, and that as time goes on, and deeper, more difficult, more remote fields are developed, it will become more expensive to produce these fuels. Even new technologies, such as the hydraulic fracturing of geologic deposits, cannot permanently alter that trend.

So in the face of the four major crises of sustainability, fossil fuels are intimately involved with three—resource depletion, economic instability, and environmental degradation. And as a consequence, fossil fuels cannot meet the demand of a growing global population nor can they ensure economic stability. A sustainable energy system, then, is going to be one that relies upon some other source of energy.

There are plenty of alternatives. Unfortunately, not every alternative is worth pursuing. What is needed is a metric by which to judge these alternatives in order to know which to invest in and which to ignore.

When planning for a future that is sustainable over the long term—that is, not a horizon that's defined by the next financial quarter or the next election year, but that extends a generation or more—it's important to judge energy systems by two metrics. One is traditional economics: how much it costs in dollars and cents. The other is more obscure but no less important: energy return on energy investment, also known as EROI.

EROI is the net energy produced during the life of a system divided by the total energy input to build and run the system.

Energy return on energy investment is a concept that's derived from the world of finance. For an investor who is only interested in a monetary return, there is a simple gauge for determining the viability of a business venture: Return on investment. That figure is calculated by dividing the net profit yielded by the total amount invested. By that measuring stick, a business venture that provides a $1,000 profit on a $2,000 investment (for an ROI of 50 percent) is better than one that yields $10,000 from a $100,000 investment (and ROI of 10 percent). Since none of us have access to unlimited funds, the return on investment is a useful metric for weighing the relative merit of competing choices for money.

For energy systems, however, money isn't the only limiting factor. The amount of energy available to run civilization at any given time, now and in the future, is also limited, and it's critical to reduce the amount of energy devoted to finding more energy.

One simple analogy is to think of a single organism that needs inputs of food to provide the nutrients to run its bodily functions and excess calories to enable growth. Ideally, access to food would be sufficient that little effort would be needed to get its fill and the organism would grow larger. But the conditions may change to require greater effort to get the same quantity food; the extra energy expended in that effort is energy that can't be devoted to growth. In the worst-case scenario, the effort required to get food is actually greater than the energy content of the food.

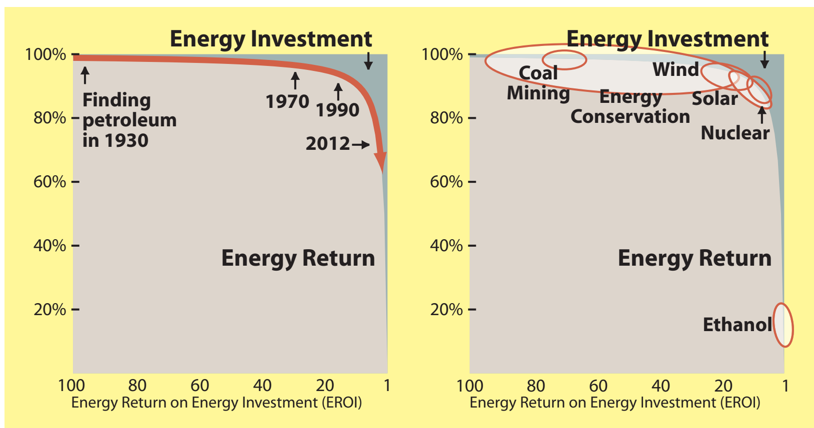
For a more concrete view of energy return on energy investment, you can devise a simple model of society's energy budget. In that model, the energy input streaming in from all sources—fossil fuels, hydropower, nuclear reactors, everything—is divided into four main uses: running the existing economy, maintaining of the infrastructure, replacing depleted energy supplies, and growing the economy or adding social amenities. Efficiency in the infrastructure and ease in replacing depleted fuel supplies enable growth. Conversely, the more energy devoted to replacing depleted fuel sources, the less that's available for amenities or growth.

To calculate EROI properly, it is necessary to be as inclusive as possible: take the total energy that is produced over the lifetime of the system and divide it by the cumulative energy required to build and sustain the energy system. Finding the numerator is straightforward—the energy produced over the life of a solar panel or a gas turbine or a nuclear power plant is readily calculated.

Finding the denominator, however, can be a headache. If the energy system consumes fuel, the energy content of that fuel must be accounted for. But so must the electricity that keeps the lights on in the power plant and the diesel that powers an oil drilling rig. And then one must expand the boundaries to account for the energy consumed elsewhere in the economy to produce the capital equipment needed to build the energy system, everything from the hydropower that runs aluminum smelting operations to the gasoline in the cars of factory workers. It's a complicated business, and when looking at individual processes, the results can vary depending on the assumptions you make in your analysis.

Fortunately, there is an alternative method that routes around the tedious accounting of every step in production. Prior economic analysis has been able to map out the flows of money and material from each sector of the national economy to every other sector. The result is a vast matrix known as an input-output table. Such tables are computed as *money* flows, but they can be converted to energy flows by looking at gross energy consumption in a sector of an economy and then assigning that energy proportionally to the economic output of that sector to find its energy intensity. So instead of trying to calculate the total energy needed to produce a power plant by tracing each material and labor input back to the soil itself, you can sum up the input from each sector of the national economy, multiply each dollar figure by that sector's energy intensity, and that sum should provide the total energy needed to construct the plant.

Tables exist of the computed energy intensity of various goods and services, and they are about as interesting as econometric tables can be. One will find, for example, that the services that have grown rapidly in the 21st century economy, such as real estate, banking, and medicine, require very little in the way of energy input. But the great industries of the last century—steelmaking and motor manufacturing and plastics—are all relatively energy intensive, as are the concrete, heavy machinery, and electrical hardware needed to build the national energy infrastructure.



When the EROI of a system falls below 10 or so, the net energy return begins to fall rapidly when compared to the amount of energy investment. Petroleum seems to be in terminal decline, while wind, solar and conservation look promising.

FOSSIL FUELS PROVIDED AN ENORMOUS energy return for the energy invested in finding them when they were first exploited. In the 1930s, for instance, petroleum exploration required the investment of the equivalent of just one barrel of oil to produce 100 barrels. Similarly coal had an EROI greater than 80. The comic premise of the old television show, *The Beverly Hillbillies*—that a stray bullet unleashed a gusher of oil—was an exaggeration, but not by much.

Such returns were revolutionary. For most of human history, energy returns of invested energy were abysmal, though accounting is made difficult because much of the energy input came in the form of human or animal labor. The old rule of thumb that about a third of a farm's acreage needed to be set aside to feed draft animals is suggestive of the EROI of that form of power.

Exploiting fossil fuels, however, provided an enormous energy surplus. With only a small percent of the energy extracted needing to be reinvested into energy development, society had the kind of windfall needed to make huge strides not only in raising the standard of living but also in increasing the population capable of receiving a high standard of living. No one who lived through the 20th century would call it a paradise, but more people were lifted out of subsistence peasantry during those 100 years than in any time in history.

But even before that century concluded, serious problems were becoming apparent. Some of these have received a great deal of attention—pollution and population overshoot especially—while others have been somewhat hidden. One such hidden problem is the decline in EROI from fossil fuel production.

It is only natural that when fossil fuels were first discovered, the most readily available and least expensive resources were developed first. But when the coal seams closest to the surface and the oil fields that were most accessible became depleted—as all fossil fuel deposits must—then mining and drilling operations had to go deeper and further afield to find new resources.

New technology made that feasible, just as a ladder makes picking the not-so-low-hanging fruit possible, but the added technology and infrastructure increased the amount of energy investment needed for production. What's more, the new fields and coal seams were often smaller or of inferior quality fuels than the earlier ones. The combination of a higher denominator of invested energy and a lower numerator of lifetime production led to a lower EROI over time.

For petroleum, the drop in EROI has been dramatic, according to researchers such as Cutler Cleveland at Boston University, Charles Hall at the State University of New York at Syracuse, and Carey King at the University of Texas at Austin. "The EROI for finding oil and gas has decreased from over 1000 in 1919 to 5 today," said Hall, "while the EROI for producing oil and gas has declined from about 30 in 1970 to 10 today." Oil derived from tar sands, such as those exploited in Alberta, can have EROIs as low as 3.

Conventional natural gas has had a similar decline. And the EROI for coal mining declined considerably by the 1980s, but the increasing use of surface mining, while producing environmental problems, has returned the figure to what it was in the 1950s, according to some calculations. It should be noted that when gas and coal are converted into electricity, their EROIs are reduced further by the inverse of the plant efficiency—as little as 35 percent for some coal-fired plants—and the energy embedded in the power plant itself.

SAMPLE EROI CALCULATION

In a 1998 study of wind farms in the Midwest, Scott W. White (now at the University of Kansas) and Gerald L. Kulcinski of the University of Wisconsin conducted an analysis of the net energy return for energy investment of the Buffalo Ridge Wind Farm in southwestern Minnesota. (White updated the study in 2007.) The energy investment data presented below is from their original paper; the energy return and EROI calculations have been updated.

BUFFALO RIDGE WIND FARM (PHASE I)

Energy investment to construct and maintain a 25 MW wind farm

	INITIAL ENERGY INVESTMENT (GJ)	ANNUAL ENERGY INVESTMENT (GJ/GWY)
Blades	6,363	4.76
Nacelles	17,499	13.08
Inverter	12,385	9.26
Wiring	696	0.52
Tower	49,431	36.94
Foundation	13,694	10.23
Materials total	100,068	74.79
Transportation to site	15,094	11
Construction	15,305	11
Operation/Maintenance	74,625	56
Decommissioning	7,652	6
TOTAL ENERGY INVESTMENT	212,744 GJ	plus 158.79 GJ/GWY

ENERGY RETURN FROM 25 MW WIND FARM (ESTIMATED)

Rated power output	25 MW
Capacity factor	25.6 percent (measured from 1994 to 1998)
Hours of operation	~153,000 (since 1994)
Conversion factor	3,600 J/Wh
TOTAL ENERGY RETURN	~3,500,000 GJ

ENERGY RETURN ON ENERGY INVESTMENT

Net energy	3,500,000 GJ
Energy investment	212,744 GJ
EROI since 1994	16.5
EROI over 25-year operation	23.5

DATA: S.W. White and G.L. Kulcinski, "Net Energy Payback and CO_2 Emissions from. Wind-Generated Electricity in the Midwest." December 1998 (UWFDM-1092); S.W. White. "Net Energy Payback and CO_2 Emissions from Three Midwestern Wind Farms: An Update." *Natural Resources Research/* 2007 DOI:10.1007/s11053-007.

New technologies such as horizontal drilling and hydraulic fracturing can increase oil and gas production in the short term, as it has in places such as the Bakken Formation of North Dakota and the Marcellus Shales of Appalachia. But they will not stem the decline in EROI. And because every incremental decline in EROI means less net energy available for new energy and economic growth, there is a point below which an energy source is not sustainable.

By some calculations, an EROI in the 3-to-5 range does not supply enough surplus energy to sustain modern civilization. Some oil production is already below that standard, and over time, it is expected that oil's EROI will only decline further as petroleum companies drill in deep oceans and the Arctic. Considering the central role that oil plays in the modern economy, finding alternative energy sources or reducing consumption must be a goal of supreme importance.

AS IMPORTANT AS IT IS to find an alternative to petroleum, it's vital that whatever new energy source we choose is itself sustainable over the long term. Fossil fuels such as coal and natural gas might be useful during the transition away from oil, but the finite nature of each resource and the inherent problems of continued environmental degradation and carbon emissions means that we shouldn't expect either coal or natural gas to be a sustainable energy solution.

Another issue is scalability. The amount of energy needed is enormous: the United States alone consumes around 100 quadrillion Btu each year, the energy equivalent of two-thirds of a cubic mile of oil. One alternative, biomass, is a generally low-cost energy source that is well understood and can provide both direct heat and fuel for transportation or electrical generation. But according to data from the U.S. Department of Agriculture, the maximum annual harvestable biomass yield for the U.S. is 1.3 billion tons, which represents only about 22 quadrillion Btu.

Just as important, however, is the EROI. Even on that score, biomass doesn't hold up as a sustainable option. Over the past 25 years, a number of research groups have looked at the issue of corn-based ethanol as a motor fuel. The results have been controversial, since the ethanol program in the U.S. is wrapped up in politics, but even the most optimistic studies have found that the energy return for corn-based ethanol is less than 2—too low to be considered sustainable. Other ethanol feedstocks, such as raw cellulose and sugarcane, may do somewhat better.

While biomass is problematic from an EROI standpoint, other renewable energy sources do much better. A study by Scott W. White of the University of Kansas and Gerard L. Kulcinski of the University of Wisconsin looked at the energy invested in the construction and maintenance of a wind farm built in Minnesota in 1994. White and Kulcinski found that the 25 MW wind farm requires an initial energy investment of nearly 212,744 GJ, or almost 60 million kWh. Nearly a quarter of that energy is tied up in the support tower alone. But in the more than 17 years since the first phase of that farm went online, it has generated an estimated 900 million kWh of electricity. That's an EROI greater than 16; by the time the turbines are decommissioned, the EROI should be 23 or higher.

Other recent studies of wind farms have found EROIs ranging from 14 to 25. And the technology keeps improving: while the average EROI for systems built in 1983 was a mere 2.5, by 1999 the average for new systems had increased to 23.

Solar power is another renewable technology that has kept improving. In some ways, solar power is a misleading term, since the principles and operation of solar thermal power systems are quite distinct from photovoltaics or passive solar heating. But each has followed a curve of greater efficiency and lower costs as material science and engineering has improved. Thermal applications—both for heat and for power—have improved, so that their EROIs are around 10 for active systems and between 20 and 40 for passive systems, depending on the system details and location.

Science is important, but it alone won't make any renewable energy system a success; it must be combined with sound engineering system analysis.

Photovoltaics are still rapidly improving, encompass a wide range of materials and approaches, and are dependent on a number of site-specific factors. Depending on the assumptions made in the calculation, present-day photovoltaic systems have EROIs ranging from 4 to as high as 20 for a utility-scale installation. Photovoltaic technologies that are more efficient in their use of energy-intensive materials, such as thin film PV, are expected to perform even better.

Other renewable energy technologies are difficult to assess in terms of sustainability. Hydropower can produce enormous returns—EROIs in the neighborhood of 100—but the number of optimal sites for new dams is small. And ocean thermal and wave energy systems have not been deployed widely enough to make an assessment.

Nuclear energy is a particularly problematic case. Its operation provides baseline power and doesn't produce greenhouse gases, and the marginal cost of electricity from a nuclear plant can be quite low after the initial investment has been repaid. But the amount of energy tied up in the construction and eventual decommissioning of the plants can be enormous, so much so that the EROI calculations can be surprisingly low. In the 1970s, for instance, Oak Ridge National Laboratory conducted an economic analysis of commercial nuclear power plants that determined their EROI to be about 6. More recently, Ceedata, a consultancy in the Netherlands, released a report on the total cost of nuclear power that concluded the EROI was only about 2.3 for an unrealisitcally short life of 30 years; that latter figure was hotly disputed by the World Nuclear Association and other groups.

A more optimistic assessment for nuclear's EROI is on the order of 10, but that does not include the final safe deposit of spent fuel and decommissioning. The number is also greatly influenced by the operating life of the plant: if a nuclear plant could be safely and reliably run for 60 years, that would increase the EROI, since the net energy return would accumulate while the energy investment would not grow substantially. Further study is warranted, but it does not appear that the EROI for nuclear power is clearly superior to wind, solar, or hydropower.

ENERGY RETURN ON ENERGY INVESTMENT should not be the sole metric by which we measure the sustainability of energy sources. Straight economics are important, as is the net energy gain and the scalability of the resource.

But EROI does provide something of an indicator of the most promising ways forward. Given the limits that the U.S. has placed on energy research and development, we ought not pursue R&D on energy conversion technologies, be it renewable or nonrenewable, that do not promise an EROI of 5 or greater. Government support, whether in the form of tax credits or direct subsidy, should be similarly limited to those best performing technologies. And an estimate of the expected EROI should be part of every grant proposal for energy R&D.

The direction of energy research ought to be toward material science that can extend the life and lower the cost of renewable energy systems, rather than toward highly theoretical analyses that have over-the-horizon payoffs. Science is important, but it alone won't make any renewable energy system a success; it must be combined with sound engineering system analysis.

Additionally, the planning for a smooth transition from fossil-based to sustainable energy must include a side-by-side analysis of the economics as well as the EROI of each potential system. The EROI analysis would ensure the long-term viability of the technology, and the commercial analysis would show how much the system will cost and, thereby, provide an estimate of the money required for the installation in the transition period.

There's one final suite of technologies that must be adopted as we move toward a sustainable future: Energy conservation. The payback on even the most mundane energy-saving steps, whether it's insulating water heaters or installing more efficient light bulbs, can create very large EROIs. Conservation measures in the U.S. have the potential to reduce energy consumption substantially—perhaps by as much as 50 percent—without negatively impacting our standard of living.

That level of energy reduction might seem impossible, but thanks to conservation measures taken in the aftermath of the Fukushima Daiichi nuclear plant accident, the Japanese economy adjusted to an immediate drop of nearly 30 percent in electricity supply because of the temporary shutdown of the nuclear power sector for safety inspections. Spreading the reduction in energy use over a number of years would lessen the hardship.

The transition from the oil- and coal-based economy we have now to a sustainably based future will not be easy. It must be started now, while our EROI is still relatively high, and it will require a change in lifestyle, sustained political support, and continuing technological improvements. But taking advantage of the low-hanging fruit of conservation and energy efficiency will make that transition easier and much less painful. ■