State of the World 2013

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CHAPTER 7

Energy as Master Resource

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On a spring morning in 1890, the German chemist Wilhelm Ostwald arose early in a Berlin hotel room, preoccupied by a conversation of the previous evening. He had come to Berlin to meet with physicists to discuss his work developing a new theoretical foundation for chemistry, one consistent with the first and second laws of thermodynamics. The first law holds that matter and energy can be neither created nor destroyed, only transformed. The second law states that in any such transformation, the capacity of the energy to do useful work is diminished. The energy does not disappear—the first law—but some of it has become "bound" energy, energy incapable of being useful. In 1865, Rudolf Clausius coined the term *entropy* as a label for this degraded energy, and it allowed him to state the law succinctly: within any thermodynamically closed system, energy is conserved but entropy must increase.[1]

Ostwald was finding these laws enormously useful in developing a rigorous understanding of chemical transformations—work that would eventually win him a Nobel Prize. He had come to the conclusion that the science of energy was not merely a subfield within physics but its very foundation. While in Berlin, he told the physicists that their discipline, too, needed to undergo a "radical reorientation" to accommodate these fundamental truths. Because matter is indestructible and energy degrades, energy must be the key: "From now on . . . the whole of physics had to be represented as a theory of energies."[2]

The group did not give him a warm reception. Ostwald wrote later that they found his idea "so absurd that they refused to take it seriously at all" and instead offered just "ridicule and abuse." He spent a fitful, nearly sleepless night and arose early to walk the still-dark streets, mulling over how best to proceed. Sunrise found him in the *Tiergarten*, surrounded by the budding life of a spring morning in the park. And there he had an insight that he later described in religious terms, calling it a "personal Pentecost" that came to him

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with a force and clarity he had never experienced: "All," he saw, "is energy." And if energy cannot be created and cannot be recycled, then the energy budget of the planet, and of the human economy on the planet, must be finite.[3]

Energy and the Transformation of Science

Ostwald developed this epiphany into his doctrine of energetics, which he thought should revolutionize all human understanding: natural and earth sciences, of course, but also history, economics, sociology, politics, even ethics and moral philosophy. (This, because to Ostwald the laws of thermodynamics implied a new categorical imperative: "Waste no energy!")[4]

Thermodynamics did indeed begin to reshape many disciplines. Solutions to three of the outstanding thermodynamic problems in the Newtonian physics of the day—the photoelectric effect, Brownian motion, and black-box radiation—led a young Swiss patent clerk, Albert Einstein, to his overthrow of the discipline's mechanistic foundations with his general and special theories of relativity. Biology was reconstructed on thermodynamic grounds in the 1920s through the work of A. G. Tansley, Edgar Transeau, Max Kleiber, and others who began conceiving of organisms as energy fixers or consumers and of natural systems as complex webs of energy flows and transformations, thereby developing the modern science of ecology. Alfred Lotka and Howard Odum extended the approach, pointing to the role that energy appropriation plays in evolution: individuals and species that have the largest net energy surplus can dedicate more of their life energy to reproduction, outcompeting their rivals.[5]

At the turn of the nineteenth century, the American historian Henry Adams, having read Ostwald and others on the subject of energy, toyed with a thermodynamic interpretation of history, perhaps merely as metaphor, perhaps as a parodic dissent from the scientific progressivism of the day, perhaps as a literal modeling based on the figures for coal consumption in which he briefly immersed himself. In the mid-1950s William Frederick Cottrell, an American sociologist, linked social and economic change to changes in energy sources and the technologies they power. And in his 1970 *Pentagon of Power*, historian Lewis Mumford took up the theme.[6]

Increased interest in ecological and environmental history late in the twentieth century led to sustained inquiries that focused on the energy history of the human economy, such as Alfred Crosby's *Children of the Sun: A History of Humanity's Unappeasable Appetite for Energy* in 2006. Seen through the thermodynamic lens, what has been called the Industrial Revolution is, more properly, the Hydrocarbon Revolution, a once-in-planetary-history drawdown of stored sunlight to do work and make wealth in the present. The petroleum era will most likely depart as suddenly as it came; in the grand sweep of geologic time, our use of petroleum is just an instant, a brief burst of frantic activity that has produced exponential growth in wealth and human population—and in humanity's impact on planetary ecosystems. (See Figure 15–1 in Chapter 15.)[7]

Economics: The Failed Revolution

Alone among disciplines that aspire to the status of rigorous science, economics remains relatively unaffected by the reconstructive impulse of thermodynamics. Most of the discipline retains its roots in the Newtonian mechanism, in which every action has an equal and opposite reaction and there are no irreversible flows. Nowhere is this clearer than in the circular flow model of production and consumption that lies at the heart of standard economics modeling, in which the economy is seen as a closed system of exchange between households (which supply factors of production and buy goods and services) and firms (which use factors of production to make goods and services for sale to households). As Lester Thurow and Robert Heilbroner describe it in *The Economic Problem*, "the flow of output is circular, self-renewing and self-feeding," because "outputs of the system are returned as fresh inputs." This is patent nonsense. Anything that can take as input what it excretes as output is a perpetual motion machine, a violation of the second law of thermodynamics.[8]


USAFHRA

The flow of output: a B-29 assembly line in 1944.

In reality, an economy—like any living thing or any machine—sucks low entropy from its environment and excretes a high-entropy wake of degraded matter and energy. Matter can be recycled; once extracted from the planet, much of it could be kept within the circular flow of the monetary economy instead of being discarded back into the environment. But recycling matter takes energy, which cannot be recycled. Thus energy is ultimately the limiting factor on the generative side of the human economy. (There are also limits on the waste side, in the finite capacity of the planet to absorb our effluents.) This is why Romanian-born American economist Nicholas Georgescu-Roegen described the entropy process as "the taproot of economic scarcity"—and why energy is the master resource.[9]

Over the years, conventional economics has been critiqued several times in light of thermodynamics. One critique came from another Nobel-laureate chemist, the Englishman Frederick Soddy. In the 1920s and 1930s he produced a series of books developing the idea that an economy is, at bottom, a system of energy use. The chief mechanism by which the economy denies this physical truth, Soddy believed, was its monetary system.[10]

Soddy drew distinctions between wealth, virtual wealth, and debt. Wealth is the stock of physically useful objects the economy has produced; it has an origin in low entropy and is subject to entropic decline. Money is virtual wealth; it symbolizes the bearer's claim on real wealth and resists entropic decay. Debt, held as an asset by those who lend money, is a claim on the future production of real wealth.

Soddy's fundamental insight was that when money is lent at compound interest, claims on the future production of real wealth increase exponentially—but real wealth can only grow incrementally, through an expansion of the economy's matter-and-energy throughput or through achieving greater efficiency. As the monetary system encourages public and private debt to grow faster than the economy can grow the means of paying it back, the system develops an irresistible need for some form of debt repudiation. This comes as inflation, bankruptcy, foreclosure, bond defaults, stock market crashes, bank failure, pension fund wipeouts, collapse of pyramid schemes, and loss of paper assets and expected investment income of any form.

Aggressive expansion of the economy's matter-and-energy throughput raises hopes and expectations along with output of real wealth. Those hopes and expectations make growth-through-debt seem normal, which can stave off the inevitable financial reconciliation for a time. Eventually, however, expansion of throughput hits a local or absolute limit, confidence falters, and the system rapidly "de-leverages" into collapse. Staving off debt repudiation simply ensures that when it comes it will come hard and fast, as a crisis—as it did in the Great Depression, as it has in every other downturn the global economy has experienced since then.[11]

A few economists gave Soddy's ideas serious attention and found merit in them. The discipline as a whole, however, closed ranks against him, ignoring his ideas and dismissing him as a crank, a scientist who had overstepped his expertise—much as the physicists in Berlin had responded to Ostwald.[12]

Another thermodynamics-based critique of economics was offered in the 1970s by Georgescu-Roegen and his student, Herman Daly. Georgescu-Roegen's masterwork, *The Entropy Law and the Economic Process*, serves as the foundation of ecological economics—an emergent school that combines an appreciation of the laws of thermodynamics with a recognition that humans receive economically valuable but generally nonmarket, unpriced ecosystem services from nature.[13]

In purely physical terms, Georgescu-Roegen noted, an economy consists of nothing more than a set of institutions and processes by which we turn valuable low-entropy inputs into valueless, high-entropy waste. Production of waste is, of course, hardly the point. What we seek is psychological: the "augmentation of an immaterial flux, the enjoyment of life." If that is the ultimate purpose, then it is foolish and ultimately dysfunctional to judge the economy by any other measure. Appreciation of energy as a master resource thus leads directly to use of alternative economic indicators, metrics that assess the economy's capacity to provide sustainable well-being, happiness, or life satisfaction to its participants. (See Chapter 11.)[14]

The thermodynamic revolution in economics also suggests a different conceptual slicing of human productive activity, an alternative to the triumvirate of land, labor, and capital that is offered by neoclassical theory. All economic value is produced by intelligence operating on matter using energy. Capital—the tools and equipment we use to increase labor productivity—is matter embodying both energy (the energy used to extract, refine, shape, and assemble the materials from which it is made) and intelligence (the accumulated inventions and innovations that have gone into its design). Labor is discretionary intelligent energy that participates in production. Land—nature—is the source of all matter and energy, and its systems also embody billions of years of trial-and-error design intelligence encoded into genes, evolution's information storage system. Energy as master resource thus offers a continuity of explanation and understanding between economics and ecology, a necessary step in establishing our economies on an ecologically sound foundation.[15]

In this model, it is easier to see that under conditions of maximum sustainable uptake of matter and energy from the environment, any further increase in the sum total of human well-being has to come from the development of intelligence—from innovation, from intelligent distribution of the products of the economy to achieve maximum well-being, from the application of what we know and can learn about wringing greater efficiency from matter and energy throughput. However inventive humans turn out to be, they will never invent their way around the laws of thermodynamics. That fundamental truth is denied by standard infinite-growth theory, which blithely projects productivity gains from technological innovation indefinitely into the future.

We can continue to seek and enjoy greater life satisfaction while maintaining a constant, steady-state, sustainable throughput of matter and energy in the economy. Our ability to raise our standard of living in a steady-state economy is limited only by our intelligence and our imagination—and the laws of thermodynamics.[16]

Net Energy Analysis and Energy Return on Energy Invested

An appreciation of energy as master resource leads directly to an appreciation of a key economic indicator that is more fundamental than the monetary price of energy or even an economy's gross energy throughput: its net energy uptake, the energy available to an economy after the energy costs of obtaining that energy are paid. Crucial to this figure is the energy return on energy invested, or EROI, of energy sources, a calculation pioneered by researchers Cutler Cleveland, Charles Hall, Robert Herendeen, and Randall Plant. It takes energy to acquire energy: to make economic use of a barrel of oil requires not only drilling the well but also transporting the oil to a refinery, converting it to a variety of petroleum products, and shipping them to end users—as well as expending energy to make the drilling rig, the steel in the refinery equipment, the tank trucks that take gasoline to service stations, the automobiles that burn the fuel, and so on. Only the net that is left after all this energy expense has been paid is available to augment that "immaterial flux, the enjoyment of life," as Georgescu-Roegen put it.[17]

The EROI of fuels can rise with technical efficiencies but tends to decline over time. For instance, according to a 1981 paper exploring this idea, the petroleum energy obtained per foot of drilling effort declined from about 50 barrels of oil equivalent in 1946 to about 15 in 1978. While the authors did not calculate EROI specifically, a figure can easily be inferred: the energy return on energy invested in drilling declined from about 50:1 to 8:1 in that period. Direct calculations of EROI for the U.S. oil industry show that it dropped from roughly 24:1 in 1954 to 11:1 in 2007.[18]


Joint Pipeline Office

An oil and gas drilling installation on an artificial island built for the purpose in the Beaufort Sea north of Alaska.

The reason is simple: other things being equal, rational beings will seek the largest increment of benefit for the smallest outlay—the biggest bang for the buck (or calorie). Naturally, high EROI sources were exploited first. Worldwide, and despite aggressive development of more-efficient extraction techniques, the average EROI of petroleum is falling, from a high of 100:1 in the 1920s to about 20:1 today.[19]

In calculating EROI, the boundaries of the analysis are crucial to the result and are the subject of much debate and discussion. If the exploitation of an energy source requires infrastructure (like roads, vehicles, a steel industry) that has other uses, how much of the energy embodied in that infrastructure should be assigned on a per unit basis to the energy source that flows through it? How far should the boundaries of analysis be extended? The answers are by no means clear-cut, and this accounts for some of the confusion, cross talk, and variety of result in this field of study.[20]

An agreed-upon standard for the boundaries of EROI analysis would allow for economically rational decisionmaking between different energy systems. Even without that standard, EROI analysis reveals the irrationality of making those choices according to current market price, which is a human construct, dependent on current demand, subsidies, taxes, and the rates at which a flow of energy is extracted from its global stock. At the macroeconomic level, rational policymakers should be trying to maximize total sustainable delivered well-being, which (other things being equal—which they often are not) would mean maximizing the EROI of a sustainable energy system for the economy. The effort to use price signals to find and promote that outcome requires that the relative monetary prices of different kinds of energy reflect their relative social costs and benefits—a project that must begin with their relative EROIs. (See Table 7–1.)[21]

If we continue to disregard the climate consequences of burning carbon-based fuels, the EROI of oil will decline further, as we drill deeper, transport farther, and bring energetically expensive oil from tar sands and shales (which have EROIs as low as 5:1) online. Is there some minimum EROI

Table 7–1. Energy Return on Energy Invested, Average and High and Low Estimates, Different Energy Sources

Energy Type	Average	High Estimate	Low Estimate
Oil	19:1		5:1
Coal		85:1	50:1
Natural gas	10:1		
Hydroelectric		267:1	11:1
Nuclear		15:1	1.1:1
Wind	18:1		
Solar photovoltaic		10:1	3.7:1
Geothermal electricity		13:1	2:1
Geothermal heat pump		5:1	3:1
U.S. corn ethanol		1.8:1	< 1:1
Brazilian sugar cane ethanol		10:1	8:1
Soy biodiesel		3.5:1	1.9:1
Palm oil biodiesel	9:1		
Tar sands oil	5:1		
Oil shale		4:1	1.5:1
Wave	15:1		
Tidal	6:1		

Source: See endnote 21.

that an economy or civilization needs in order to be successful? One study postulates that an EROI of 3:1 is "a bare minimum for civilization. It would allow only for energy to run transportation or related systems, but would leave little discretionary surplus for all the things we value about civilization: art, medicine, education and so on." The authors estimate that "we would need something like a 5:1 EROI from our main fuels to maintain anything like what we call civilization."[22]

But a civilization with a 5:1 average EROI cannot support the kind of military investment that can be made by a civilization with a 6:1 or 7:1 EROI—and if military force is useful in securing access to resources, then the minimum EROI a civilization needs to survive is probably some close correlate of the average EROI of its potential enemies and competitors.

If we bracket off such concerns, then the minimum EROI for any particular civilization will depend on a variety of internal factors, some of which are not easily quantified. Appropriation of energy has social, political, and ecological costs and benefits that will depend on factors like the resilience of the host ecosystems, the resilience of the civilization's social systems and social capital, and the expectations its members have for the future, including their expectation of material comfort for themselves and their progeny. It is likely that any definitive answer to the question of a minimum EROI for our civilization can only be derived experimentally—history will reveal it to us when our civilization falls below it.

Can renewables be built out and exploited rapidly enough to avoid making that experimental determination? Perhaps. (See Chapter 8.) If educated guesswork puts the EROI floor at 5:1, a figure that is approached by current petroleum technologies, apparently we can breathe easier knowing that renewables generally do significantly better: photovoltaics (PV) are conservatively estimated at 10:1 and wind at 20:1 or perhaps 50:1.[23]

But some EROI analysts worry that as society is forced to make do with less oil, it will fall into an EROI or Energy Trap. This, according to physicist Tom Murphy, comes about because the energy it takes to build the infrastructure necessary for a sustainable, renewable energy economy must come from current energy consumption. Unlike monetary investments, which can be made on credit and then amortized out of the income stream they produce, the energy investment in energy infrastructure must be made upfront out of a portion of the energy used today: "Nature does not provide an energy financing scheme. You can't build a windmill on *promised* energy."[24]

The arithmetic is daunting. To avoid, for example, a 2-percent annual decline in net energy use, replacing that loss with solar photovoltaic (with an EROI pegged at 10:1) will require giving up 8 percent of the net energy available for the economy. (This is because the EROI of solar PV is calculated over the life of the equipment: a 10:1 return over 40 years means that the break-even point is four years out, and until then most of the energy invested in PV construction is a sunken cost, an incompletely compensated energy expense.) “We cannot,” writes Murphy, “build our way out of the problem. If we tried to outsmart the trap by building an eight-unit replacement in year one, it would require 32 units to produce and only dig a deeper hole. The essential point is that up-front infrastructure energy costs mean that one step forward results in four steps back.”[25]

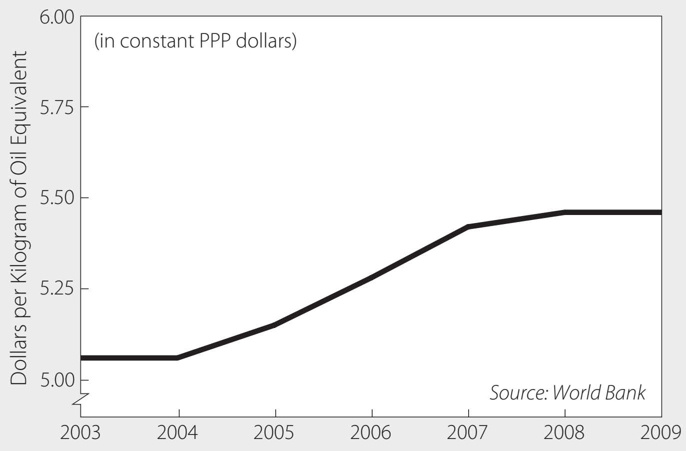
The grim truth, Murphy warns, is that on a sheer energetic basis it seems to make more sense to continue to develop oil, even with a 5:1 EROI, than to build wind or solar PV capacity with higher EROIs. While there are plenty of reasons to move to solar and away from oil (climate change prominent among them), EROI, according to Murphy, is not one of them. The problem is rooted in the sunken energy costs of petroleum infrastructure (which makes the continued use of petroleum energetically cheap) and the non-negotiable reality of the energy economy.[26]

The goal of a renewable energy economy is clear, but the path to it seems blocked. The paradox is reminiscent of the one proposed by Zeno, whose logic denied the possibility of all motion: you can never get from point A to point B because first you must go halfway to point B, then halfway again, then halfway again, and so on, never arriving. Legend has it that Diogenes of Sinope refuted Zeno by standing up and walking about. The paradox of the Energy Trap may not be so easily resolved. Refraining from energy expenditure on consumption today in order to use that energy to invest in the infrastructure we need to ensure energy consumption 10, 20, and 50 years into the future, Murphy warns, will require a kind of sacrifice and political will that does not come easily to representative democracies and for which there is scant historical precedent. Politically, the most acceptable path is to finance the energetic investment not by decreasing energy use for consumption today but by maintaining energy use for consumption while increasing the total energy appropriation of the economy—an aggressive expansion of the economy’s footprint in paradoxical service to the goal of achieving sustainability.[27]

Eventually, solar and renewables will hit a takeoff point: they will capture enough energy to support the construction of additional solar and renewable infrastructure without requiring us to reallocate energy use away from maintaining the living standards we then enjoy. Achieving this at a high level of energy consumption becomes increasingly difficult as the average EROI of our energy sources declines. If the net energy captured by the economy begins to decline as the peak of fossil fuel production passes, the Energy Trap seems unavoidable.

Can conservation and efficiency save us from the Energy Trap? Maybe. The United States could significantly reduce gasoline use with the simple expedient of carpooling, for instance. Four vehicle occupants instead of one

Figure 7–1. GDP per Unit of Energy Use, 2003–09



represents a 75 percent savings, and if the savings were dedicated to building renewable infrastructure (a big "if," but still), this would go a long way toward solving the problem. According to calculations of energy use per constant gross domestic product dollar (see Figure 7–1), current efficiency efforts achieve an annual savings of 1.39 percent, which could be dedicated to building renewable infrastructure with no decrease in the amount of energy going to consumer satisfactions.[28]

But these savings are not sustainable. The low-hanging fruit can be plucked only once, and marginal returns from future conservation and efficiency efforts will necessarily decrease. And whatever savings we achieve, there will be pressure to use them to increase or simply maintain current consumption instead of building solar infrastructure. Yielding to that pressure will condemn future humans to a poorer, stingier, less commodious life.

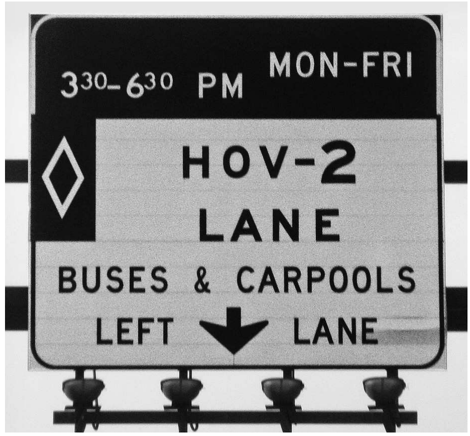
Sometimes a problem that seems irreducible at the macro scale can, like Zeno's paradox, be solved at the level of individual behavior. Would a rational consumer postpone for a few years some of his or her energy-intensive consumption in order to invest in insulating a house or installing solar panels? Yes—given the right market signals and realistic assumptions about the cost of energy tomorrow. Consumers decide to make this sort of investment every day—and those decisions could cumulate into the macro result that the Energy Trap tells us would be politically difficult to achieve.

This much is clear: sooner or later we will have an economy that runs on its current solar income. The amount of energy that economy will have at its disposal depends on the choices we make today.

Toward a New Worldview

Reality, economic reality included, is sufficiently complex that diametrically opposed idea systems can serve as lenses through which to interpret it, with both systems claiming to be confirmed by what is seen. When an economy is founded on an EROI of 100:1, you can hold almost any economic theory you want and still see an enormous generation of wealth. The decline in average EROI of the world economy brings political challenges—including pressure for austerity in government budgeting—and a kind of evolutionary pressure to get our economic theories right. The incorporation of thermodynamics into economics as a foundational idea system would bring the most influential social science into congruence with physical reality.[29]

It would also return economics to its roots in political economy. A steady-state economy will have to face issues of fairness and justice in distribution that were more easily addressed (or postponed to the future) in a high-EROI, supposedly infinite-growth economy. And economically rational, benefit-maximizing choices about energy use will turn on such "externalities" as the social and political costs and benefits of different energy systems, which fall outside of the discipline of economics as currently practiced. Economics will either admit these issues into the discipline or confess its abject impotence to illuminate the most pressing economic issues of our era.



Mario Roberto Duran Ortiz

Carpool sign on a Maryland Interstate highway.

Ultimately, economics will have to recognize that we live on a finite planet and that the laws of thermodynamics apply to economic life as to all other life. This observation from the British physicist Arthur Eddington remains as apt today as when it was written nearly a century ago: "The second law that entropy always increases holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations—then so much the worse for Maxwell's equations. If it is found to be contradicted by observation—well, these experimentalists do bungle things sometimes. But if it is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation."[30]

Had economists collapsed in deepest humiliation on being shown in the 1930s or again in the 1970s that their theories fell against the second law, we would have made a great deal more progress toward the goal of establishing our economy and civilization on a sustainable flow of matter-and-energy throughput. Foresters have a saying that is appropriate here. The very best time to plant a tree, like the best time to admit that energy is the master resource, is decades ago. The second best time is today.

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