The Oil Drum: Net Energy

Discussions about Energy and Our Future

What is the Minimum EROI that a Sustainable Society Must Have? Part 1: Surplus Energy and Biological Evolution

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The following multi-part series is taken from a paper that my colleagues and I published last year in the free, on-line journal ***Energies****. You may access the entire PDF here. All references can be found in the pdf.*

EROI theory is rooted in the biological principle that in order to survive each species on earth must procure more energy from its food than it expends attaining that food. From this basic principle the importance of energy surplus became evident, as food sources needed to "pay" not only for metabolism but also for reproduction and storage for leaner times. Part 1 of this three part series presents a brief history of the concept of surplus energy and how it has influenced both biological and human evolution.

1.1. Background: The History of Formal Thought on Surplus Energy

Energy surplus is defined broadly as the amount of energy left over after the costs of obtaining the energy have been accounted for. The energy literature is quite rich with papers and books that emphasize the importance of energy surplus as a necessary criteria for allowing for the survival and growth of many species including humans, as well as human endeavors, including the development of science, art, culture and indeed civilization itself. Most of us who have thought about this issue deeply would even say that energy surplus is the best general way to think about how different societies evolved over time. To chemists Frederick Soddy and William Ostwald, anthropologist Leslie White, archeologist Joseph Tainter, historian John Perlin, systems ecologist Howard T. Odum, sociologist Frederick Cottrell, economist Nicolas Georgescu-Roegan, energy scientist Vaclav Smil and a number of others in these and other disciplines, human history, including contemporary events, is essentially about exploiting energy and the technologies to do so. (image)

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While each acknowledges that other issues such as human culture, nutrient cycling, and entropy (among many others) can be important, each is of the opinion that it is energy itself, and especially surplus energy, that is key. Survival, military efficacy, wealth, art and even civilization itself was believed by all of the above investigators to be a product of surplus energy. For these authors the issue is not simply whether there is surplus energy but how much, what kind (quality), and at what rate it is delivered. The interplay of those three factors determined net energy and hence the ability of a given society to divert attention from life-sustaining needs such as agriculture or the attainment of water towards luxuries such as art and scholarship. Indeed humans could not possibly have made it this far through evolutionary time, or even from one generation to the next, without there being some kind of net positive energy, and they could not have constructed such comprehensive cities, civilizations or wasted so much in war without there being substantial surplus energy in the past.

1.2. Surplus Energy and Biological Evolution

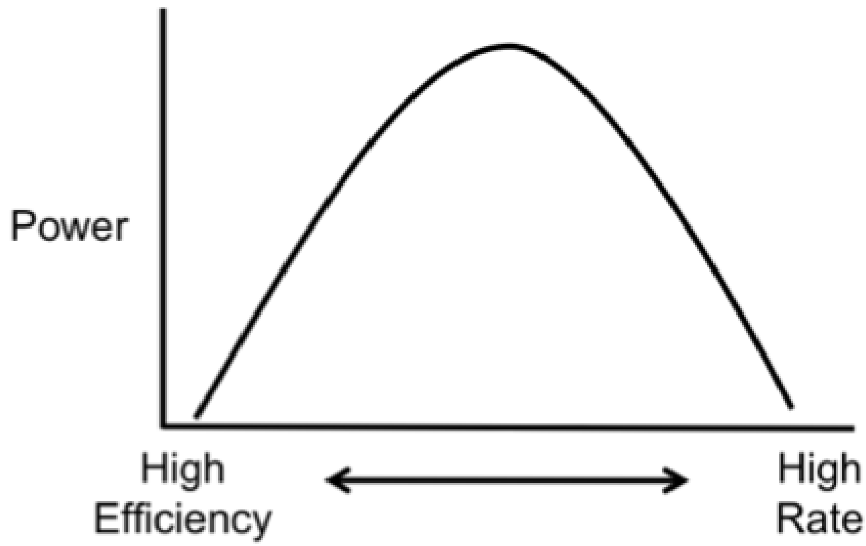
The interplay of biological evolution and surplus energy is far more general, as emphasized a half century ago by Kleiber, Morowitz, Odum and others. Plants and animals are subjected to fierce selective pressure to do the “right thing” energetically; that is to insure that whatever major activity that they undertake gains more energy than it costs, and beyond that gets a larger energy net return than either alternative activities or their competitors. It is obvious that a cheetah, for example, has to catch more energy in its prey than it takes to stalk it and run it down, and considerably more to make it through lean times and also to reproduce. Plants too must make an energy profit to supply net resources for growth and reproduction, as can be seen easily in most clearings in evergreen forests where living boughs on a tree that are in the clearing are usually lower down than they are in the more densely forested and hence shaded side of the tree. If the bough does not carry its weight energetically, that is if its photosynthesis is not greater than the respiratory maintenance metabolism of supporting that bough, the bough will die (or perhaps even be sloughed off by the rest of the tree). (image)

Every plant and every animal must conform to this iron "law" of evolutionary energetics: if you are to survive you must produce or capture more energy than you use to obtain it, if you are to reproduce you must have a large surplus beyond metabolic needs, and if your species are to prosper over evolutionary time you must have a very large surplus for the average individual to compensate for the large losses that occur to the majority of the population. In other words every surviving individual and species needs to do things that gain more energy than they cost, and those species that are successful in an evolutionary sense are those that generate a great deal of surplus energy that allows them to become abundant and to spread. While we are unaware of any official pronouncement of this idea as a law, it seems to us to be so self-obvious that we might as well call it a law – the law of minimum EROI - unless anyone can think of any objections.

While probably most biologists tacitly accept this law (if they have thought about the issue) it is not particularly emphasized in biological teaching. Instead biology in the last century focused mostly on fitness; that is on the ability of organisms to propel their genes into the future through continuation and expansion of populations of species. But in fact energetics is an essential consideration as to what is and what is not fit, and many believe that the total energy balance of an organism is the key to understanding fitness. It took the development of double-labeled isotopes and the exquisite experimental procedures by the likes of Thomas et al. [10] to show how powerfully net energy controlled fitness.

Thomas et al. studied tits (chickadees) in France and Corsica and found that those birds that timed their migrations, nest building, and births of their young to coincide with the seasonal availability of large caterpillars, which in turn were dependant upon the timing of the vernalization of the oak leaves they fed upon, had a much greater surplus energy than their counterparties that missed the caterpillars. They fledged more, larger and hence more-likely-to-survive young while also greatly increasing their own probability to return the next year to breed again. Those of their offspring that inherited the proper "calendar" for migration and nesting were in turn far more likely to have successful mating and so on. Tomas et al. also showed how the natural evolutionary pattern was being disrupted by climate change; the tits that tended to get to their nesting sites too late to capitalize upon the caterpillars, who were emerging earlier in response to earlier leaf out, had lower survival rates. Presumably as climate warming continues natural selection will favor those tits which happened to have genes that told them to move North a bit earlier.

Howard Odum has argued that it is not just the net energy obtained but the power, that is the useful energy per unit time, that is critical in an evolutionary context. From this perspective there is generally a tradeoff between the rate and the efficiency for any given process; that is, the more rapidly a process occurs the lower its efficiency, and vice versa. Under a given set of environmental conditions it is not advantageous to be extremely efficient at the expense of the rate of exploitation, nor to be extremely rapid at the expense of efficiency. For example, a trout that feeds on drifting food in a rapidly flowing stream will acquire large amounts of food drifting by but at a low efficiency; i.e. much of the energy surplus created by the consumption of a large amount of food is spent in muscle contraction for the trout so that it can fight the faster current. Likewise a trout in slow water can be very efficient because its swimming costs are lower, but the slower water brings with it less food, and thus the overall energy surplus will be limited by the lower rate at which food is provided. Dominant trout will pick an optimum intermediate current speed, which will result in faster growth and more offspring [11]. Subdominant trout will be found in water moving a little faster or a little slower. In some experiments trout with no competitive power will be found drifting aimlessly in still water slowly starving to death.



This kind of tradeoff can be found throughout the plant and animal kingdoms and even rates of power plant operation in industrial society [12]. It explains why we must shift gears to stay near the middle of each gear range in a stick shift car when we want to accelerate, and why most businessmen once chose to take jumbo jets to cross the Atlantic rather than the Concorde or ocean liners. In fact it can be used to explain why the Concorde went extinct, and perhaps why the second Queen Mary was much smaller than the first.

Of course life in all of its diversity also has a diversity of energy life styles that have been selected for - sloths are just as evolutionarily successful as cheetahs, while warm blooded animals pay for their superior ability to forage in cold weather with a higher energy cost to maintain an elevated body temperature – the list is endless. Yet there remains a rate-efficiency tradeoff within each lifestyle. While drift-feeding trout choose areas of intermediate current to maximize the energy surplus, suckers have "chosen" through natural selection (i.e. have been selected for) to maximize energy surplus by processing lower quality food on the bottom, and probably have an optimum power output for that set of environmental conditions.

Nevertheless each life style must be able to turn in an energy profit sufficient to survive, reproduce and make it through tough times. There are few, if any, examples of extant species that barely make an energy profit – for each has to pay for not only their maintenance metabolism but also their "depreciation" and "research and development" (i.e. evolution), just as a business must, out of current income. Thus their energy profit must be sufficient to mate, raise their young, "pay" the predators and the pathogens and adjust to environmental change through sufficient surplus reproduction to allow evolution. Only those organisms with a sufficient net output and sufficient power (i.e. useful energy gained per time) are able to undertake this through evolutionary time, and indeed some 99 plus percent of all species that have ever lived on the planet are no longer with us – their "technology" was not adequate, or adequately flexible, to supply sufficient net energy to balance gains against losses as their environment changed. Given losses to predation, nesting failures and the requirements of energy for many other things the energy surplus needs to be quite substantial for the species to survive in time.

2. Application to Human Populations

Likewise human populations must generate sufficient net energy to survive, reproduce and adapt to changing conditions. Humans must first feed themselves before attending to other issues. While people in most industrial societies today hardly worry about getting enough to eat, for much of the world and much of humanity's history and prehistory getting enough food was the most important issue. For at least 98 percent of the 2 or so million years that we have been recognizably human the principal technology by which we as humans have fed ourselves, that is obtained the energy we need for life, has been that of hunting and gathering. Contemporary hunter gatherers -- such as the !Kung of the Kalahari desert in southern Africa -- are probably as close to our long term ancestors as we will be able to understand. Most hunter-gatherer humans were probably little different from cheetahs or trout in that their principal economic focus is on obtaining food and for getting their requirement for surplus energy directly from their environment. Studies by anthropologists such as Lee [13] and Rapaport [14] confirmed that indeed present-day (or at least recent) hunter-gatherers and shifting cultivators acted in ways that appeared to maximize their own energy return on investment.

According to such anthropological studies as we have, the !Kung life style, under normal circumstances, generates a quite positive energy return on investment (i.e. generates a large surplus) from their desert environment, perhaps an average of some 10 Kcal returned per their own Kcal invested in hunting and gathering. In normal times these cultures had plenty to eat, and the people tended to use their time made available from their relatively high EROI lifestyles in socializing, child-care and story telling. The downside was that there were periodic tough times, such as droughts, during which starvation was a possibility. It is probable that our ancestors had a fairly positive EROI for much of the time, although periodic droughts, diseases and wars must have occasionally, or perhaps routinely, taken a large toll. Thus even though they had a relatively high EROI, perhaps 10:1, their populations tended to be relatively stable over a very long time, for human populations barely grew from thousands of years before Christ until about 1900. Thus even the relatively high energy return was not enough to generate much in the way of net population growth over time.

The rate at which plants and animals can exploit their own resource base changes slowly through evolution. All must adapt to climate and other changes, and animals must also adapt to the fact that their food is also going through its own defensive evolutionary changes. Humans are different, for the human brain, language and the written word have allowed for much more rapid cultural evolution. The most important of these changes were energy-related: the development of energy-concentrating spear points and knife blades, agriculture as a means to concentrate solar energy for human use, and more recently the exploitation of wind and water power and, of particular interest to this paper, fossil fuels. What is important from our perspective is that each of these cultural adaptations is part of a continuum in which humans increase the rate at which they exploit additional resources from nature, including both energy and non-energy resources.

The development of agriculture allowed the redirection of the photosynthetic energy captured on the land from the many diverse species in a natural ecosystem to the few species of plants (called cultivars) that humans can and wish to eat, or to the grazing animals that humans controlled. Curiously the massive increase in food production per unit of land brought on by agriculture did not, over the long run, on average, increase human nutrition but mostly just increased the numbers of people [15]. Of course it also allowed the development of cities, bureaucracies, hierarchies, the arts, more potent warfare and so on – that is, all that we call civilization, as nicely developed by Jared Diamond in Guns, Germs and Steel [16]. Throughout most of human history, humans themselves did most of the work, often as slaves but more generally as physical laborers which, in one way or another, most humans were.

Over time humans increased their control of energy through technology, although for thousands of years most of the energy used was animate -- people or draft animals -- and derived from recent solar energy. A second very important source of energy was from wood, which has been recounted in fascinating detail in Perlin [17], Pointing [18] and Smil [19]. Massive areas of the Earth's surface – Peloponnesia, India, parts of England and many others have been deforested three or more times as civilizations have cut down the trees for fuel or materials, prospered from the newly cleared agricultural land and then collapsed as fuel and soil become depleted. Archeologist Joseph Tainter [20] recounts the general tendency of humans to build up civilizations of increasing reach and infrastructure that eventually exceeded the energy available to that society.

In summary, it seems obvious that both natural biological systems subject to natural selection and the pre-industrial civilizations that preceded ourselves were highly dependant upon maintaining not just a bare energy surplus from organic sources but rather a substantial energy surplus that allowed for the support of the entire system in question – whether of an evolving natural population or a civilization. Most of the earlier civilizations that left artifacts that we now visit and marvel at – pyramids, ancient cities, monuments and so on – had to have had a huge energy surplus for this to happen, although we can hardly calculate what that was. An important question for today is to what degree does the past critical importance of surplus energy apply to contemporary civilization with its massive although possibly threatened energy surpluses.

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