Chapter 2
It Takes Energy to Get Energy

2.1 A Very Short History of Humanity and Energy Return on Investment

Imagine you are a prehistoric hunter-gatherer. Your primary motivation is to find food, as that is your only source of the energy which your body needs to stay alive and without it you will slowly starve and die. The balance between the amount of food energy gained in hunting and gathering, and the amount of energy expended in those activities is critical. If that ratio is not high enough you will still die from starvation, just more slowly than if you had no food at all. Let us say that for every usable calorie of energy you gain, you expend 1 calorie in the hunting and gathering process. Then you would be fine, would you not? Unfortunately not, as you would still starve to death, just even more slowly. Your body has a whole host of functions which are not directly related to finding food but critical to your survival. First of all, there is the need for water, without which you will die in about 5–10 days. Then, you have to digest the food, to transform it into useful calories, and you have to excrete the processed food and water otherwise your bladder and intestines would swell up rendering you painfully immobile. So, let us say all these other functions require a doubling of calorific intake, so you now get 2 calories for every calorie spent hunting and gathering. Now you are good, right? Still the answer is no as the human body also has the annoying need to sleep for approximately one third of the day otherwise you will slowly malfunction and start going somewhat mad. So, let us add another calorie for that. Therefore, 3 calories gained for every calorie spent in hunting and gathering make for a good balance. Things are now good, right?

Actually, no because apart from you leading an extremely boring life, where every waking hour is spent searching for food and water, your branch of the human race would go extinct. Sex helps with both the boredom and extinction issues. Problem is that even if you are not into multi-hour Tantric sex sessions there is still some reduction in hunting and gathering time and there are those troublesome children to feed and spend yet more none food finding time raising. Let us say we now have two adults, which does tend to make sex a lot more fun, plus children who are only marginally useful at gathering food until their teens. Probably, we are in the 5:1 ratio of calories gained from calories expended for long-term survival. Add to

R. Boyd, *Energy and the Financial System,* SpringerBriefs in Energy,
DOI 10.1007/978-3-319-04238-1_2,

that a lot of time for socializing with other relatives and clan members, and you get the kind of life style that our ancient hunter-gatherer ancestors enjoyed. The energy return on investment (EROI) for these hunter gatherers has been estimated at about 10:1, which allowed for a good amount of leisure time [1], needing only a few hours per day to find all the food they required. This did, however, involve a transient lifestyle, moving from place to place to take advantage of seasonal food sources, or after exploiting the food resources at a given place.

The first carbon-based fuels used by humans were predominantly wood and shrubs used to fuel a fire, with our ancestors learning to use and control such fire at least half a million years ago. A campfire could be used to ward off predatory animals, keep humans warm in colder climates, and to cook food which made it easier to digest while destroying dangerous parasites and microbes. Heating could also be used to dry and preserve foods for later consumption.

The hunter-gatherers that we would recognize as modern human beings, *Homo sapiens sapiens* (not a typo, this means, anatomically, modern humans), came along only about 200,000 years ago. It was not until about 50,000 years ago that some of the more advanced human traits developed, such as symbolic thought and standardized stone tools. For about another 40,000 years they continued to live in small groups of hunter-gatherers, and spread across the globe.

Approximately 11,000 years ago, some human groups took up farming. The experts disagree on whether this was forced upon them by a combination of environmental change and population growth, or it was a natural next step given our species' growing cleverness and tool-making capacities. Many hunter-gatherer groups do practice some control of the plants around them, for example by rooting out unwanted plants and clearing areas with fire to aid the growth of plants more beneficial to them. Thus, the move to agriculture may have been more of an incremental, rather than a revolutionary, change. What is not open to question is that the effects of this change were revolutionary, forming the basis upon which complex human societies have developed. Traditional agriculture has been estimated to have an energy return on investment [2] of about 15:1. Further, the ability to grow all the food required in a single place allowed for settled communities and, sometimes, a food surplus. Animal husbandry also developed, providing easily managed herds that could be slaughtered for consumption, dogs for hunting and to help manage those herds, and draft animals to provide the energy needed to pull ploughs. The surplus produced through agriculture and herding constituted excess energy beyond immediate needs which could be a source of power for those who controlled it. Agricultural societies started to diverge from the highly egalitarian hunter-gatherer groups into stratified societies where a majority of the population produced the food—and the energy surplus—while a minority controlled the use of that surplus. Those minorities became elites who could use the surpluses to feed individuals with new specialist skills such as metal workers, bureaucrats, and priests. They also fed fighting men to both control their tribe by force, where bureaucracy and religion failed, or to take over other tribes thus expanding the surplus available to them.

Over time these factors lead to the highly complex societies that started to appear about 6,000 years ago. It is within this incredibly small period of time, relative to the history of even our own species alone, what we refer to as *history* has taken place. The Egyptian, Mayan, Greek, and Roman civilizations, the Middle Ages, Renaissance, and the Industrial Revolution all took place in this brief period called *history*. Joseph Tainter refers to such complex societies as an "anomaly in history," as apart from this 6,000-year period. "Throughout the several million years that recognizable humans are known to have lived, the common political unit was the small, autonomous community [3]." However complex, these societies still relied upon the amount of food and other energy that could be provided by their surrounding ecosystem, and thus, were at the mercy of local climate changes and overuse of land. A further danger was posed by other societies which often went to war to gain new territory and slaves. Within these societies the tension between the poor masses that produced the surpluses utilized by the elites, and those elites, could also threaten to pull a society apart. Eventually the sheer complexity of these societies threatened their existence as ever greater amounts of energy were required to support them. In short, many factors could combine to greatly weaken a society; a few bad harvests could weaken military strength or exacerbate internal tensions as farmers struggled between feeding themselves and meeting the demands of the rulers. The fragility of such complex social arrangements has been demonstrated by their repeated collapses. Collapse awaited not only the relatively small and ecologically marginal societies, but also the highly developed ones at the peak of their power such as the Mayan, Sumerian, Greek, Roman and Khmer [4]. Civilizations could also be fractured into smaller parts: about 4,000 years ago during a 150-year drought that greatly reduced the Nile floods, Egypt was stretched to the breaking point [5]. The drought also seems to have played an important part in the collapse of the Bronze Age in the Eastern Mediterranean about 3,200 years ago, with complex societies such as the Mycenaean and Hittite collapsing into a "dark age" with much lower levels of political centralization and complexity [6, 7]. With a diversity of civilizations scattered thinly across the globe the failure of any individual civilization could not endanger human civilization as a whole. As civilizations rose and fell, humanity continued to grow in numbers, from 5 million people in 5,000 B.C., to 27 million in 2,000 B.C., doubling to 50 million by 1,000 B.C., and quadrupling to 200 million by 0 A.D.

About 5,300 years ago, in the Near East, Eastern Mediterranean, India, and China the need for energy greatly increased. The production of copper alloys, such as bronze required an intensity of heat that could only be provided by burning vast amounts of timber. This energy demand was further exacerbated by iron production, which started about 3,200 years ago, and required even higher temperatures that could only be provided by charcoal (wood heated in the absence of oxygen to produce a purer form of carbon). The resulting demands for timber as an energy source and for construction, plus the clearing of forest for agriculture, lead to the deforestation of huge areas as with the Mediterranean during the time of the Greeks and Romans.

The development of any civilization is limited by the amount of usable energy available to it, and the efficiency of energy use. The more energy and greater efficiency, the greater the percentage of the population that can be devoted to things other than sourcing that energy. More energy can also feed a greater the number of machines and extend human capabilities. Agricultural societies are limited by both the available biomass (predominantly food, fodder for animals, and wood) and the efficiency of the humans, horses, other draft animals in converting that biomass into useful energy. Human technology, through such things as the plough, wind-mill, and sail boat, can stretch that limit, but not fundamentally remove it. Defeating other societies, taking their land, and enslaving their people can also increase the amount of energy available. In most societies, small elites can live very well as they are able to capture the surpluses of the rest of the population. The celebrated democratic institutions of ancient Greece were only for a very small male minority, while most of the rest of the male population served as slaves and serfs. None of these factors removed the overall limit of complexity and development that agriculturally-based societies operate within. Ian Morris [8] developed an index of social development and noted that only three civilizations could be identified as reaching the low 40s on his index—the Song Dynasty, the Roman Empire, and modern civilization. As Morris [8] puts it "If someone from Rome or Song China had been transplanted to eighteenth-century London or Beijing, he or she would certainly have had many surprises… Yet more, in fact much more, would have seemed familiar… Most important of all, though, the visitors from the past would have noticed that although social development was moving higher than ever, the *ways* people were pushing it up hardly differed from how Romans and Song Chinese had pushed it up."

Only when human societies started to utilize the fossil fuels, with their high levels of energy density, was the limit upon their size and complexity removed. The Renaissance and the resulting scientific revolution may have stretched that limit, but without the utilization of fossil fuels they could not have broken free. With fossil fuels, the change in the energy available was revolutionary, driving the rapid changes to human civilization over the past two centuries. The ratio of energy gained to energy spent for the fossil fuels was at least 80:1 for coal, 100:1 for oil, and 18:1 for natural gas [9]. Also, the sheer volume of the energy that could be utilized dwarfed that which was previously available. Prior to this, the rate of energy use was limited by the depth and fertility of the soil, together with the vagaries of the weather. Now humanity had access to many millennia worth of photosynthesis which had been transformed into energy-dense substances and stored away under the ground. The only limitation was how quickly these new energy sources could be extracted. Naturally, the easiest ones went first. This huge increase in available energy has been the basis of modern industrial societies, which in turn have become addicted to this seemingly endless supply of cheap energy.

In this new age of fossil fuel, man has been referred to as the Anthropocene (anthropo means man) to delineate when humanity started to make a significant impact upon the ecology of the earth. Coal had been used in many areas including heating, after human demands lead to the destruction of forests, but the real revolution started when we worked out how to use coal to boil water into steam and to use this steam to drive an engine. These steam engines were first used in the coal mines to pump out water. In a few generations they found many others uses such as driving the wheels of trains and the propellers of ships, and driving turbines to create electricity. Coal could also be gasified to create town gas used for cooking and lighting. The available coal seemed endless, but the exponential growth facilitated by coal's concentrated energy drove an exponential demand for it. In the birthplace of the industrial revolution, the UK, the peak of coal production was reached in 1913 [9], just over a century after widespread adoption of the steam engine. Oil provided the additional energy needed for continued growth. It had been used as a heating and lighting fuel for thousands of years, but its combination with the internal combustion engine in the 1800s created the next revolutionary change. The use of the internal combustion engine expanded rapidly, producing a rapidly expanding demand for oil. As with coal, oil was seen as a nearly infinite resource, but the exponential growth in demand quickly reduced the huge amounts available. It took just over a century for the USA to reach its peak oil production, in 1972. The last part of the fossil fuel trinity, natural gas, had to wait until a transportation infrastructure of pipes was in place, which did not happen until the post World War II years. Since then its use has multiplied in the heating of homes, and the production of electricity. Humankind also discovered how to utilize these hydrocarbons as a raw material source in the production of new products, such as fertilizers, plastics, and organic chemicals which have become a ubiquitous and essential part of modern society. No matter how much we consider human ingenuity and the resulting technology to be the basis of our current living standards, the true determinant has been the finite fossil fuel resources that we first started to utilize extensively only a couple of centuries ago. Since that time our fossil fuels consumption has expanded nearly 800 times, with a 12-time increase during the twentieth century [10]. Without these fuels our modern society would not exist in its present form, and as we deplete them, we bring ever closer the day when we will have to do without them.

Some have argued that the advanced industrial countries have reduced their dependency on fossil fuels as more of their economies became service and computer based. This seems to be more a function of the advanced countries moving much of their energy-intensive manufacturing to countries such as Mexico and China. The energy intensity of what some countries produce may have gone down, but the energy intensity of their consumption which includes imported goods, has not. As for computers, a quick check of the data centers running an average Internet Service Provider, or Amazon, Facebook, or a major bank, will rapidly show the huge amounts of electricity that such computer-based organizations require, with much of that electricity provided by coal fired power stations—it is ironic, but the Internet ultimately dependent upon coal. Look around your own home at all those desktops, laptops, notebooks, tablets, cell phones, televisions, and gaming machines that need electricity. The growth of the economy and the complexity of our society are still very tightly linked to the energy available. Greater complexity tends to require greater levels of EROI, and lower levels of EROI lead to lower levels of complexity—i.e. simpler civilizations and economies. Less net energy equals poorer and simpler. As more energy is used to find and produce energy, Net Energy falls, meaning less is available to provide for anything else. And remember, 87 % of that energy is provided by fossil fuels [11].

2.2 The Fossil Fuels: 86.6 % of Human Society's Energy Usage

2.2.1 Oil: EROI 18:1 and Rapidly Declining; 32.6 % of Energy Usage (Excluding Ethanol and Biodiesel)

Oil provides 32.6 % of global energy usage [11]. Oil's EROI had declined to an average of 18:1 globally by 2005 [10]. Oil is an incredible substance with a phenomenally high energy density, combined with an ease of transportation and storage given its liquid state at room temperature. This makes it perfect as a liquid transportation fuel, its primary use in society today. A tank of gas costing C$ 65 was all that was needed to propel my family's Mini Cooper along the 300 miles (about 500 km) from Toronto to Montreal at speeds of up to 80 miles/h (about 130 km/h), with some gas to spare. Such things would have seemed miraculous only a few generations ago, but we now take them for granted. The cost of this wondrous substance has recently increased substantially. That same tank of gas cost only C$ 30 about a decade ago, and prices will rise further as oil from the newer sources costs much more than from the earlier ones.

Just like with an apple tree, where the lowest hanging apples tend to be taken first, the simplest and cheapest ways to produce oil were used first while the more complex and expensive ones were only exploited when needed. At the beginning, oil drilling only required a hollow steel tube to be pushed into the ground to a relatively shallow depth and the oil would gush out under its own pressure. Now that scene is confined to old movies where oil is struck and gushes up into the air with everyone jumping up and down for joy as they are covered in oil. Later, after the pressure normalized, a "nodding donkey" would be used to suck up the oil. The world's oil supply is still very dependent upon many of those older, easy-to-extract oil fields. Nearly half of the world's oil supply is provided by just over 120 giant oil fields, the majority of which were discovered many decades ago. In fact, nearly 70 % of current global oil production comes from fields discovered before 1970. These less expensive, high net energy fields, keep the average global EROI at a high enough level to support our complex civilization. As these fields age and their EROI falls, technological fixes such as horizontal drilling and pumping in water to drive the oil to the surface are needed. Their depletion subtracts relatively high net energy oil from the overall supply. The greatest of these mature fields is Ghawar in Saudi Arabia which has been operating since 1951 and still provides 5 million barrels of oil per day, or about 6 % of global oil production. Ghawar's output is about three times the 2012 production of the Canadian Oil Sands, which is optimistically forecast to produce 5 million barrels per day—but not until 2030. Unlike Ghawar, some of the other large conventional oil fields have seen very significant drops in production as they deplete, such as Cantarell in Mexico, Prudhoe Bay in the USA, and Samotlor in Russia. Recent oil finds are much less accessible and much more expensive to produce. Instead of gushers and simple "nodding donkeys" we have the complexities and costs associated with such things as ultra deep sea oil fields, tar sands, and shale oil.

The recently discovered large Lula ultra deep sea oil field is 160 miles off the Brazilian coast, below approximately 6,600 ft of ocean and 16,000 ft of salt, sand, and rock. Compare that to the world's tallest building which is only 2,700 ft in height. At these depths, the pressure within the piping rises as high as 15,000–20,000 pounds per square inch, not far away from the pressures used in industrial high pressure water machines used to cut metal. The drilling of the first 15 wells for Lula cost over US$ 1 billion, and the total field costs are estimated to be in the US$ 50–100 billion range. With development covering an area the size of Florida, the Canadian tar sands make this operation look small scale—and technically simple. The Canadian tar has to be first separated from the sand then mixed with other hydrocarbons to make synthetic heavy oil. When surface mined, it takes 2 t of tar sand to produce 1 barrel of synthetic crude oil; hence the army of huge trucks. The separation process also requires about 2–4 barrels of hot water and caustic soda per barrel of synthetic oil. With the cheaper surface deposits already being heavily exploited, the focus has moved to the deeper deposits which require drilling. To turn the tar sands into a liquid which will travel along the drill pipes, huge amounts of heat and hydrocarbon solvents are required. The heat required has been predominantly provided by the burning of natural gas, using up one fossil fuel to gain access to another. Another recent phenomenon is the production of shale oil using hydraulic fracturing (or "fracking") technology. This involves drilling a hole into a rock formation and then injecting large amounts of a complex mixture under pressure to fracture the rocks and thus free oil trapped within them. Each drill site produces relatively small amounts of oil and depletes much faster than conventional oil wells. This means drilling hundreds, then thousands of expensive new wells to maintain production. On average, the ratio of energy gained versus the energy expended for ultra deep sea, tar sands, and shale oil is about 5:1 or below—bad news for the future of our complex society.

There is also oil shale (which is different from shale oil). Oil shale does not contain oil, but rather Kerogen, a chemical precursor to oil. The EROI of mining this shale and turning it into synthetic oil has been estimated at 2:1 [12]. The burning of the oil shale in an electric power station has been proposed, but the low energy density of the oil shale would produce massive amounts of waste products. Synthetic oil products can also be produced from coal, a complex process called coal to liquids (CTL), but again, the conversion from coal to oil is a very energy intensive process reducing the EROI to about 4:1 [13]. CTL has only been utilized by countries that could not access enough conventional oil supplies, countries such as Germany in World War II and South Africa during the anti-apartheid oil embargo. The gas to liquids (GTL) process, where synthetic oil products are derived from natural gas is hardly any better. The use of these technologies is either a sign of desperation, or of large price discrepancies between oil and natural gas caused by a localized oversupply of natural gas, as is currently seen in North America.

Oil provides about a third of all the energy consumed in the world. It powers the vast majority of all the trains, planes, cars, trucks, ships and motorcycles in the world, and it provides chemical inputs to a large share of important industrial and consumer products. Its loss to humanity could render modern society non-viable. For the moment—and it is just a moment in human history—humanity is living off the remains of the easily accessible oil fields which produce very high Net Energy returns. But as those fields become depleted the average Net Energy for oil falls. In 2005 the EROI for global oil production was 18 to 1, and has quite possibly already fallen below the 10:1 danger point given the historical declining trend. That is an average of all fields, while the net energy available from new fields may be approaching the point of being economically unviable. These new fields require increasing levels of complexity and investment levels with many unknowns. Possible delays and other unforeseen problems could easily invalidate the cost assumptions that once made them appear profitable. A vivid example is that of the Deep Water Horizon. What will be that well's net energy level after all of the rescue and remediation costs are taken into account? The desperation of oil producers to find new oil to replace the depleting older wells has been shown by the attempts to drill in the Arctic by Shell Oil, even before all the ice has gone. Drilling was repeatedly impacted by drifting ice, and then a near hurricane in the North Pacific set the oil rig adrift for a few days [14]. Yet, at last report, Shell has vowed to return.

2.2.2 *Coal: EROI 20-80:1 and Slowly Declining; 30.3 % of Energy Usage*

Coal provides 30.3 % of global energy usage [11], and has an EROI ranging from 40 to 80 for the USA and about 20 for China, depending upon the mining conditions and the quality of the coal [10]. It is less energy dense than oil and is a solid which makes transport much harder and more expensive (trains and ships instead of pipelines). Coal also burns less cleanly than oil or gas. These factors limit both its use and the distances that it can be economically transported. Unlike oil, most coal is used within the region in which it is mined, with limited exports between countries. Even in China, the biggest importer of coal, imports represent less than 10 % of its consumption with a significant amount of those imports coming from neighbouring countries. Coal's use as a transportation fuel for ground and sea transportation was superseded by the much more efficient oil in the early twentieth century. Presently its main use is in power stations to produce electricity, and secondarily in the production of steel. The USA uses coal to produce about 40 % of its electricity.

By far the biggest user of coal is China, which gets approximately 80 % of its energy from coal and uses more than three times as much coal as the USA [15]. The sheer speed at which Chinese coal consumption has grown is shown by the fact that its coal use was only twice that of the USA just 5 years ago [11]. It has added the amount consumed by the whole of the USA in only about 5 years! Coal is not a homogeneous substance; rather, it is grouped into four general categories which correspond roughly to energy density. These are anthracite (the best), through bituminous and sub-bituminous, to lignite (the worst). At a lower energy density, more coal has to be mined to provide the same energy output. In addition, coal is found at different depths, and with different seam widths. As the depths increase and the seam widths decrease more energy is required to mine the coal, again reducing its EROI. As with oil, the easiest coal deposits were mined first, and thus, the quality and accessibility of coal deteriorates over time. As lower quality and less accessible ores become a greater and greater percentage of production, the amount of coal produced may not be a good indication of the energy being provided. This has been the case with the USA where increases in coal production have paralleled a *decreased* amount of energy provided due to ongoing reductions in the energy density of the coal.

With oil production at a plateau since 2005, and the Chinese focus on their huge coal reserves to fuel growth, coal is poised to regain the spot of the leading world energy source that it lost to oil in the twentieth century. This trend can only continue with the huge India population looking to fuel industrialization with their own coal reserves. In 2011 global energy use from coal grew by 5.4 %, but only 0.6 % for oil and 2.3 % for natural gas [8]. In 2012 Chinese coal imports increased 20 % to 290 million tons [16] although they aim to limit their coal consumption to "only" 3.9 billion tons by 2015 [17] an amount nearly 4 times that consumed by the USA. This is twice bad news for the environment not only because burning coal releases a lot more climate warming carbon dioxide and other poisonous gases than oil, but also because the lower the quality of coal, the more that is burnt for a given amount of energy. Opponents may have stopped the construction of new coal fired power stations in the USA, but their gains are overwhelmed by new coal fired plants in China and India. Carbon Capture and Storage (CCS), where the carbon dioxide produced by burning the coal is captured and pumped into huge storage areas such as depleted oil fields or the deep ocean, has been proposed by the coal industry to remedy the climate changing impacts. If utilized, this process is very energy intensive requiring 25–50 % more coal to produce the same energy output, thus reducing the energy available to society. So far, there are very few actual working examples of CCS to prove its viability.

2.2.3 Natural Gas: EROI 10:1 and Declining; 23.7 % of Energy Usage

Natural Gas supplies 23.7 % of global energy usage [11], and has a current global EROI of about 10:1 for conventional gas fields [10]. It was first treated as a useless by-product of oil extraction, being "flared off" at the well site. No one has documented how much natural gas was wasted in this way, but the amounts must have been huge. The use of natural gas has grown rapidly over the past few decades. It is increasingly being used for space heating, cooking, generating electricity, and in the production of synthetic fertilizers. The latter use played a large part in the post-war "Green Revolution" which facilitated the rapid growth of populations in many countries. Being a gas at room temperature NG is primarily moved overland via pipelines. To transport NG by sea it has to be cooled to −162° C at which point it becomes a liquid that can be carried in specially engineered liquid natural gas (LNG) ships. This is an expensive process which offsets some of the energy provided by the natural gas thus transported. These comparative factors support the construction of pipelines over many thousands of miles between Russian production fields and Europe via the Ukraine and Poland. Despite these limitations, LNG has grown rapidly to become a quarter of the global natural gas export market [4].

Presently many countries with large NG supplies cannot utilize it all, a number of richer countries have heavily depleted their fields, and there are large pricing discrepancies between regional markets separated by water. It is currently two to three times as expensive to buy natural gas in Europe as it is in North America while prices in the Far East are even higher. One possibility in “gas rich” countries is to use LNG as a transport fuel to replace oil, a strategy which has been successfully used in buses, trucks, and ships. This could definitely be an option to reduce the impact of declining cheap oil reserves, providing some more time for society to find alternative fuels and living arrangements. On the other hand, if such substitution was applied extensively it would significantly increase the demand for natural gas and thus speed up depletion of positive net energy reserves.

Another source of natural gas, shale gas, requires the use of fracking techniques (see oil fracking above) to exploit gas reserves that were otherwise not viable. This has greatly changed the dynamics of the market, especially in North America where conventional output was in significant decline. This new unconventional supply has caused a glut in North America due to government restrictions on exports. The resulting substantial fall in North American natural gas prices has lead to its greater use in the production of electricity, displacing coal. However, this may not be a tenable situation in the medium term as many current shale gas wells are unprofitable at anywhere near the current price. Shale gas wells also have very high rates of production decline over time, much higher than for conventional gas; greatly reducing the likelihood of production paying back the US$ 10 million that such wells cost. One researcher has estimated that the break even cost for shale gas is around US$ 9 per million British Thermal Units, rather than the current US$ 3.50 [18]. Further complicating the situation may be supply constraints as the profitable finds may be limited to relatively small sweet spots within an overall gas field. For shale gas estimates for EROI vary greatly, from as low as 5:1 to as high as 70:1 and above. This may reflect differences in how EROI was calculated for what is a relatively new resource, and the possibility of “sweet spots” where well productivity is much higher. On the plus side, natural gas does have a reputation for being more climate friendly than coal, with lower amounts of carbon dioxide being released when burnt. However, studies showing that significant amounts of methane can leak from the drilling and transportation processes [19] have undercut this advantage. While methane only stays in the atmosphere for about 14 years, for each of those years it can have a climate changing impact of up to one hundred times that of carbon dioxide.

2.3 Hydro and Nuclear: 11.3 % of Global Energy Usage

With the huge increases in available energy that these three fossil fuels have provided it has also been possible to develop other ways of gaining access to useful energy. The major ones have been the damming of rivers and the exploitation of nuclear energy.

2.3.1 Hydroelectricity: EROI 12:1 to 267:1 and Stable; 6.4 % of Energy Usage

Hydroelectricity supplies 6.4 % of global energy usage [11]. The net energy of hydroelectric dams varies greatly due to the specifics of each site, and range from 12:1 to 267:1 [10], all providing enough net energy for an advanced civilization. The vast majority of the energy expenditure on hydroelectricity is during the construction phase so existing dams have very high net energy levels. Most of the good dam sites in North America have already been utilized, but there are many unused sites around the world. As large areas are flooded, big dams create major social impacts which may limit the use of many possible sites. China has leapt heavily into dam building despite frequent widespread displacement of local populations, as with its huge Three Gorges dam project.

Hydroelectricity can also be provided through “run of the river” projects, where the ongoing river flow is used to drive turbines. These can be relatively small installations and are good candidates for providing localized electricity supplies. With such local supplies, complex electricity grid infrastructures are not needed to transfer the electricity from producer to consumer. In addition, the natural flow of the river is kept, fish populations are not impacted, and valuable land is not flooded.

Winter snow acts as a huge natural water storage device, many times the volume of any dam, keeping vast water supplies in place until the spring and summer melts. Glaciers provide the same service, increasing their flows during the warmer months. This is especially important in the sub-tropics, where the resulting river flows make up for a lack of local rainfall during the summer months. As climate change induced warming changes winter snows into rain, further shrinks the glaciers, and alters the “spring thaw” calendar, these storage mechanisms will become unreliable. The result will be much less dependable river flows available to hydroelectric facilities, possibly reducing the amount of electricity that can be produced economically. Warmer temperatures will also produce greater levels of evaporation from dam reservoirs which will reduce the water available to drive turbines and produce electricity. Electricity production could even cease entirely if the water level drops below the water intakes for the turbines. Many dams in the American Southwest, such as the Hoover Dam, and those on the heavily dammed rivers that flow from the Himalayas through China, India, and Pakistan will be affected. Brazil has already shown the possible impacts, as an ongoing drought reduced hydroelectric output at the start of 2013 [20]. In other areas, climate change may provide for more precipitation (both rain and snow) and thus increase the productivity of some hydroelectric dam sites. Probable beneficiaries in this regard are Canada, Northern Europe and Northern Russia.

2.3.2 Nuclear: EROI About 5:1 with Large Uncertainties; 4.9 % of Energy Usage

Nuclear power currently provides 4.9 % of global energy usage [11]. Of all energy sources, nuclear power is easily the most controversial, with the Chernobyl and Fukushima crises showing the risks of using nuclear fission to produce electricity. Among the casualties of such large and costly failures has been commercial insurance which is no longer a viable option for the nuclear industry. This hurdle has been overcome by governments taking on the responsibility for the excessive costs of accidents, or building and operating the plants themselves. In addition to insurance, no nuclear power station has ever been built without significant government backing, let alone all of the government funded research provided free to the industry. And when accidents happen many of the costs tend to be socialized as they overwhelm the ability of any private company to meet them. Other social costs include the victims who are also not compensated since cancers happening years later cannot be definitively linked to a single given cause. In truth, nuclear power is not competitive in a free market situation.

These large subsidies, as well as the cost of storing depleted nuclear material possibly for thousands of years into the future, are not reflected in industry cost structures. Given these very hard to account for cost issues, plus the highly divisive and politicized nature of nuclear power, it is very hard to gain an accurate EROI for nuclear power. Charles Hall [10] estimates it at probably no greater than 5:1, which is well below that needed to support our current civilization's level of complexity. Recently much of the fuel for American reactors has been provided through the conversion of American and Russian nuclear warheads. With this source of supply dwindling, there will be a greater need for newly mined uranium—a depleting resource with costs rising as lower grade ores are utilized. Fast breeder reactors promise more efficient use of the source materials, but also involve even greater levels of engineering complexity than conventional nuclear reactors, and no commercially viable fast breeder reactor has ever been built. There have been other possibilities proposed, such as Thorium-based reactors and the TerraPower traveling wave design, but these are still either on the drawing board or at the early prototype stage at best. The time from where they currently stand to large scale usage is possibly counted in decades.

The impact of the Fukushima crisis has been significant, with Germany committing to close down all nuclear generation and Japan doing the same. Global production of electricity from nuclear fuel actually fell 4.3 % in 2011 with the sharp declines in those two countries [11]. In addition, the Canadian province of Quebec recently decided to retire its only nuclear electricity plant and the state of Vermont reached a deal to retire the aging Vermont Yankee plant. Both China and India have major programs of nuclear power station development, but at the global level any new production will be significantly offset by the probable retirements of existing stations which are on average 26 years old [21]. The USA also has plans for new nuclear power stations, but popular resistance and the long permitting process will significantly limit the rate of new development.

2.4 Non-Hydro Modern Renewable Energy: 2.1 % of Global Energy Usage

In recent years renewable sources of energy, such as wind, solar, biofuels and wave, have been developed. These renewable resources still only constitute a small share of global energy supplies however, increasing from 0.7 % in 2001 to 2.1 % a decade later [11]. Some of these are more promising than others as candidates to provide the net energy rates required for our society to continue in its present form.

2.4.1 Wind: EROI Averaging 18:1; Approximately 1 % of Energy Usage

Humans have used wind energy for many centuries with the first windmills being used at least 1000 years ago, if not much earlier. In recent decades, the primary focus of new wind energy implementation has been to produce electricity, thus reducing the need to burn coal and natural gas in electric power stations. Wind power currently provides approximately 1 % of global energy usage [11].

As with property, the success of a wind energy installation is all about location, location, location. A wind farm needs to be where the wind is strong and reliable enough to drive the wind turbines, and both of these factors vary greatly from one place to another. Construction costs, together with operating delivery costs, will also be greatly affected by the distance between the wind farm location, population and/or industrial centers, and the supplies of the required components and skilled technicians. These factors drive the profitable size of a wind farm or of individual turbines. Larger wind turbines or a greater number of turbines in one farm tend to reduce some of the fixed and ongoing maintenance costs relative to the electricity produced.

These factors tend to benefit offshore wind farms which are easier to locate closer to population centers and are able to utilize more and larger wind turbines—plus the wind tends to be stronger and more reliable offshore. All of these benefits usually outweigh the extra complexities of building wind farms offshore. The coasts of the Atlantic Ocean, the North American Great Lakes and the Baltic Sea tend to be relatively shallow, providing good locations. The profitable size and power output for both wind farms and turbines may be lower in more compact countries, such as those in Europe, as average distances tend to be much less than in larger countries such as those in North America.

Unfortunately, wind energy cannot provide a reliable "base" level of electricity as it is dependent upon wind which can vary in strength and direction. To balance out the fluctuations of wind energy another energy source is required to provide a reliable "base load". Some countries, such as Spain and Denmark, have managed to get up to 20 % of their electricity generated by wind energy while using other sources of electricity for the base load. Germany, which currently uses wind energy for about 10 % of its electricity is targeting up to 25 % by 2020. Presumably they will use a mix of conventional and alternative energy to provide the "base." With a diverse set of renewable energies used, and wind farms located in varied locations with differing wind speed peaks and troughs, it could be theoretically possible to do without hydrocarbon fuels for the base load. There are many technical challenges though, that would have to be worked out before such a setup would be truly feasible.

Wind energy installations are growing rapidly, and this growing demand is fuelling rapid growth, greater efficiency, and technical advances in the industry. In 2011, wind energy produced approximately 240 GW of electricity globally (about 3 % of global electricity production), up about 20 % from the previous year, having grown at a compound rate of over 20 % for many years. It is forecast to keep growing by 15–20 % globally ongoing, doubling by 2016 [22], and doubling again by 2020 to 1,000 GW. China is very rapidly driving installations of wind energy to help serve its growing power needs, and with 3 % of its electricity coming from wind energy it has advanced, in only a few years, to having 26 % of all global installed capacity in 2011. The USA is second with 20 %, Germany third with 12 %, followed by Spain with 9 % and India with 7 % [23].

2.4.2 Biofuels: EROI of 1:1 to 18:1; Approximately 0.5 % of Energy Usage

Biofuels, such as ethanol and biodiesel currently provide approximately 0.5 % of global energy usage [11]. The EROI [10] of corn ethanol is close to 1:1, and it would surely not be a viable fuel source without the large government subsidies and mandates provided to its suppliers, especially in the USA. EROI [24] estimates for sugar cane ethanol range up to 10:1 in Brazil. Unlike corn and sugar cane ethanol, cellulosic ethanol is not in large scale production, and thus there is both a wider variability for input and output assumptions, and for possible future technical and scaling efficiencies. There are very wide variations in the estimates for the EROI of cellulosic ethanol, from such plants as switch grass and willow. The EROI [24] estimates range from as low as 1:1, to as high as 18:1. That of biodiesel [10] is about 3:1.

The EROI of all of the biofuels is significantly affected by growing conditions, as the biomass yield is a significant determinant of the net energy provided. Given the great variability in growing conditions for different geographic locations, the net energy of biofuels will also greatly vary between locations. Yields may also be significantly reduced by the effects of Climate Change, with less water, generally higher temperatures, and less predictable weather patterns. Such issues have become apparent recently in the USA where ongoing drought conditions reduced plant yields and have lead to calls for a reduction in corn ethanol production or usage mandates. With biofuels competing for acreage with food production, there is increasing conflict between the drive to produce such renewable fuels and the need of the world's population to secure enough food. The losers are those with lower incomes as food prices escalate due to reduced supplies.

2.4.3 Solar: EROI Between 2:1 and 12:1; Less Than 0.5 % of Energy Usage

The energy output for solar technologies is location specific, with areas nearer the equator having longer days and stronger sunshine year round compared to more northerly and southerly locations. This means the most productive possible locations are in areas such as the American Southwest and Saharan Africa that are distant from the populations that would use the power. To exploit this energy and deliver it to consumers, extensive investments in new high-voltage long-distance electric power lines would be required.

An additional issue is that solar power installations are assumed to operate for at least a couple of decades to arrive at the computed net energy levels. Over such a period the operation of "Murphy's Law" has a great amount of time to impact the assumed output; through such things as sand storms, greater component failure rates, theft and other unpredictable factors. For example would low income communities happily coexist with solar installations and long distance power lines that were to serve far away populations rather than themselves? At the least, this could create significant security costs, as with those in many oil and gas producing areas of the Middle East and Africa. A large solar power installation would be just as vulnerable as Nigerian oil pipelines or the Algerian natural gas plant attacked in early 2013 [25].

Solar PV uses solar panels that convert the sun's energy into electrical energy. Estimates of energy return for Solar PV [26] range between 6:1 and 12:1, although some researchers have calculated an EROI as high [27] as 38:1, and as low [28] as 2.5:1. Differing assumptions such as the useful life of the solar PV installation, the maintenance costs over time, and the range of input costs have driven these wide variances. Solar PV can be used in large scale industrial implementations, as well as for individual commercial and residential buildings.

Concentrated Solar Power utilizes arrays of mirrors or lenses to focus solar energy onto a single small area, where a heat engine utilizes the thermal energy to create steam that drives an electrical generator. Solar thermal does not produce electricity, but instead uses the sun's heat to directly warm water or the air in living spaces. This can be used for commercial buildings and private dwellings. Both Concentrated Solar and Solar Thermal have an EROI [26] between 5:1 and 2:1.

2.4.4 Wave: EROI Not Available; Negligible % of Energy Usage

The wave power industry is in its infancy, with a very limited set of installations and much uncertainty about how actual installations will behave during long term exposure to corrosive sea water and the affects of storms.

2.4.5 Geo-Thermal: EROI Not Available; Negligible % of Energy Usage

Geo-thermal power has only limited installations worldwide and is highly location specific, being most effective in areas near tectonic plate boundaries. Iceland, with a population of about 350,000, is the only country which currently derives a majority of its energy from geo-thermal sources.

2.5 Summary

Large scale industrial societies came into existence through the exploitation of phenomenally large fossil fuel energy sources which were both energy dense and cheap to access. The net energy derived from fossil fuels was very high, with energy return on investment ratios of 80:1 and more. The massive scale of these new resources combined with this high net energy has provided the huge amounts of energy required to drive our modern societies. Without fossil fuels the industrial revolution and the related advances in living standards would likely have stalled at the wind and water power stage of development.

The easiest to access fossil fuel deposits tended to be the first ones to be used. As these depleted, and more and more energy was required by exponentially growing human societies, more difficult deposits which provide lower amounts of net energy began to be used. This has led to an ongoing reduction in the net energy provided by oil and natural gas deposits. The most worrying of these is the fall in net energy of oil production, as this fuel powers the vast majority of global transportation, and provides one third of all energy used by human societies. Its EROI was approximately 18:1 globally in the late 2000s and continues to fall as lower and lower net energy deposits such as tar sands, deep ocean, and shale oil are brought into production. The net energy for natural gas is also falling with the exploitation of shale gas and the costs of transporting it in liquid form between continents. Natural gas may be useful in the short term as a substitute for declining cheap oil reserves, but if such substitution was done on a significant scale, the increased demand would deplete the viable natural gas reserves at a much faster rate than otherwise. Only coal has continued to provide a relatively stable level of net energy, but its contribution to global warming argues against increased use.

A hierarchy of minimum levels of societal net energy has been proposed for the support of the more complex parts of industrial societies [26]; with a societal EROI of up to 14:1 required to support such things as education, health care, and the arts. Newer oil and natural gas production may already be below this level, with coal and the older oil and natural gas fields providing the required net energy to support current living standards. As the older oil and gas fields continue to deplete, the overall level of net energy available to society will fall below that needed to support current living standards. Coal will be left as the only fossil fuel that can provide the needed levels of net energy. Faced with unacceptable environmental degradation, societies will have to simplify with living standards changing to match the net energy available.

The alternative is to find new energy sources which provide the required levels of net energy to support an advanced industrialized society without undue environmental costs. Of the alternatives only hydro, wind, some biofuels, and possibly solar PV, provide the right level of net energy. Hydro is limited by the availability of dam sites, most of which in Europe and North America are already being used. Through the usage of dam sites across the developing nations a doubling of current capacity is possible to about 12 % of global energy usage, but has to be balanced against the impact of climate change upon the output of some sites. Although important, such an increase would make up for less than one tenth of the energy currently provided by fossil fuels. The remainder would need to be met by wind, selected biofuels and solar PV, which currently provide less than 2 % of global energy needs. Such a transition will require continued rapid growth in new installations, together with extensive changes to energy infrastructures and end-user consumption. Historically such changes have required decades, as with the change from coal to oil for transport which involved the replacement of a much smaller amount of energy than would be the case for a fossil to non-fossil energy conversion.

Another complicating issue is that hydro, wind, and solar PV installations require large up-front investments, which draw on current energy supplies, while the resulting energy input is delivered in increments over decades, taking many years to offset the up-front energy investment. Given that very rapid growth is assumed for such installations over the next decade and more, the new renewable sector may not provide a net positive provision of energy to society for many years. The large investments in renewables may, in fact, require the reduction of energy use in the rest of the economy during the extended “build-out” period. In effect, society may have to accept static if not lower living standards to allow for the redirection of energy to the construction of the new energy sources.

References

1. Heinberg R (2009) Searching for a miracle, Post Carbon Institute. http://www.postcarbon.org/new-site-files/Reports/Searching_for_a_Miracle_web10nov09.pdf
2. Fischer-Kowalski M et al (2011) Sociometabolic transitions in subsistence communities: Boserup revisited in four comparative case studies. Hum Ecol Rev 18(2):2011
3. Tainter J (1988) The collapse of complex societies. Cambridge University Press, Cambridge
4. Diamond J (2004) Collapse: how societies choose to fail or succeed. Viking Adult, New York
5. Fagan B (2003) The long summer. Basic Books, New York
6. Bachhuber C, Roberts G (2009) Forces of transformation: the end of the bronze age in the mediterranean (BANEA Monograph). Oxbow Books, Oxford
7. Dickinson O (2007) The Aegean from Bronze Age to Iron Age: continuity and change between the twelfth and eighth centuries BC. Routledge, London
8. Morris I (2010) Why the West rules—for now: the patterns of history, and what they reveal about the future. Farrar, Strauss, and Giroux, London
9. N/A (2011) Jevons' coal question: Why the UK coal peak wasn't as bad as expected. The oil drum. http://www.theoildrum.com/node/8241. Accessed 27 Dec 2012
10. Hall C (2012) Energy and the wealth of nations: understanding the biophysical economy. Springer, New York
11. N/A (2012) BP statistical review of world energy June 2012, British Petroleum. http://www.bp.com/assets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/statistical_review_of_world_energy_full_report_2012.pdf. Accessed 10 March 2013
12. Mearns E (2012) Unconventional oil and gas, a game changer? Presented at the 2012 Association for Peak Oil conference. http://www.aspo2012.at/wp-content/uploads/2012/06/Mearns_aspo2012.pdf. Accessed 12 March 2013
13. Talberth J (2009) Economic feasibility of coal to liquids development in Alaska's interior, Centre for Sustainable Economy. http://www.sustainable-economy.org/main/news/1. Accessed 10 March 2013
14. Efstathiou Jr J (2013) Rig grounding revives debate over Shell's arctic drilling, Bloomberg. http://www.bloomberg.com/news/2013-01-03/rig-grounding-revives-debate-over-shell-s-arctic-drilling.html. Accessed 15 March 2013
15. N/A (2012) Coal facts 2011, World Coal Association. http://www.worldcoal.org/resources/coal-statistics/. Accessed 25 May 2013
16. N/A (2012) Yearbook 2012: global market energy review, Enerdata. http://www.enerdata.net/enerdatauk/press-and-publication/publications/world-energy-statistics-supply-and-demand.php. Accessed 9 March 2013
17. N/A (2012) China to restrict coal demand, output to 3.9 billion tons, Bloomberg. http://www.bloomberg.com/news/2012-03-22/china-to-restrict-coal-demand-output-to-3-9-billion-tons.html. Accessed 10 March 2013
18. Melling A (2010) Natural gas pricing and its future: Europe as the battleground, Carnegie endowment. http://www.carnegieendowment.org/files/gas_pricing_europe.pdf. Accessed 11 March 2013
19. Romm J (2013) Bridge to nowhere? NOAA confirms high methane leakage rate of up to 9% from gas fields, cutting climate benefit, think progress. http://thinkprogress.org/climate/2013/01/02/1388021/bridge-to-nowhere-noaa-confirms-high-methane-leakage-rate-up-to-9-from-gas-fields-gutting-climate-benefit/. Accessed 20 May 2013
20. Boadle A (2013) Brazil's hot, dry summer may lead to energy rationing. Reuters. http://www.reuters.com/article/2013/01/07/us-brazil-energy-rationing-idUSBRE9060TL20130107?feedType=RSS&feedName=environmentNews&utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+reuters%2Fenvironment+%28News+%2F+US+%2F+Environment%29. Accessed 11 May 2013

21. Schneider M, Froggart A, Thomas S (2012) The World Nuclear Industry Status Report 2010–2011. Worldwatch. http://www.worldwatch.org/system/files/NuclearStatusReport2011_prel.pdf. Accessed 11 May 2013
22. N/A (2012) Global statistics. Global Wind Energy Council. http://www.gwec.net/global-figures/graphs/. Accessed 15 May 2013
23. N/A (2012) Cumulative installed wind power capacity in top ten countries and the world, 1980–2011. Earth Policy Institute. http://www.google.ca/url?sa=t&rct=j&q=&esrc=s&source=web&cd=5&sqi=2&ved=0CFEQFjAE&url=http%3A%2F%2Fwww.earth-policy.org%2Fdatacenter%2Fxls%2Findicator10_2012_all.xls&ei=BHLuUO6CDs3aqQHxuYC4BA&usg=AFQjCNE2fx8PmPAP2055qt-Mr1vTvH0s2Q&bvm=bv.1357700187,d.aWc. Accessed 15 May 2013
24. Hall C, Dale B, Pimentel D (2011) Seeking to understand the reasons for different energy return on investment (EROI). Estimates for biofuels, sustainability 2011, 3. http://www.google.ca/url?sa=t&rct=j&q=&esrc=s&source=web&cd=9&ved=0CG0QFjAI&url=http%3A%2F%2Fwww.mdpi.com%2F2071-1050%2F3%2F12%2F2413%2Fpdf&ei=670vUYLGDuSMyAHOzoD4AQ&usg=AFQjCNEmKNyJNNb8PdlA2_isXKlJQAtvUg&bvm=bv.43148975,d.aWc. Accessed 15 May 2013
25. Reed S (2013) North Africa's prospects as energy goliath are fading. New York Times. http://www.nytimes.com/2013/02/23/business/global/23iht-natgas23.html?_r=0. Accessed 25 May 2013.
26. Lambert H, Balogh P, Gupta A (2012) EROI of global energy resources: preliminary status and trends. State University of New York. http://www.dpuc.state.ct.us/DEEPEnergy.nsf/fb04ff2e3777b0b98525797c00471aef/a546c841171f7a8485257ac90053565a/$FILE/R.%20Fromer%20Attachment%20-%20EROI%20of%20Global%20Energy%20Resoruces.pdf. Accessed 26 May 2013
27. Raugei M et al (2012) The energy return on energy investment (EROI) of photovoltaics: methodology and comparisons with fossil fuel life cycles. Brookhaven National Laboratory: U.S. Department of Energy. http://www.bnl.gov/pv/files/pdf/241_Raugei_EROI_EP_revised_II_2012-03_VMF.pdf and http://www.nytimes.com/2013/02/23/business/global/23iht-natgas23.html?_r=0
28. Prieto P, Hall C (2013) Spain's photovoltaic revolution. The Energy Return on Investment. Springer, New York

http://www.springer.com/978-3-319-04237-4

Energy and the Financial System
What Every Economist, Financial Analyst, and Investor Needs
to Know
Boyd, R.
2013, VII, 80 p. 12 illus. in color., Softcover
ISBN: 978-3-319-04237-4