The Oil Drum
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

Work, Exergy, the Economy, Money, and Wealth

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This is a guest post by George Mobus. George is an Associate Professor of Computing and Software Systems at the University of Washington, Tacoma. His blog is Question Everything.

This is something of a tutorial on the relationship between energy and the economy. I have been dismayed by how often people express their lack of knowledge about that relationship. Such expressions come in the form of beliefs that money is what drives the economy. Or the belief that the human desire to accumulate monetary wealth is the motive force for economic growth. Indeed I doubt that most people ever think of physics when they think of the economy.

But the reality is that the economy is very much a physical process that requires energy to continue operating. All of the money in the world will not suffice to maintain the motivation of the wheels of industry unless it can be used to exchange for energy flow. Here is a guide regarding how the real wealth of nations is created and a more concise look at the nature of energy flow needed to do so.

Wealth Production, Movement, and Work

Let's start with a basic definition of wealth as all physical and abstract assets that have some value to some human being(s) at some time somewhere. And to generalize the concept a bit more, let's include human, pet, and ornamental plant biomass as part of that definition. We certainly value ourselves and consider human beings (their minds and efforts) as instrumental in making more wealth. We value our non-food animals and lawns and flowers. We are willing to spend money to acquire and maintain them.

Humans convert natural resources into assets by performing various kinds of physical work on those resources. The resources must be extracted from the natural world. They must be moved about and modified in various ways. Wealth is the product of various work processes in which atoms are moved and rearranged according to our desires. This applies to what we ordinarily call services as well. The provider of the service did some work, if nothing more than moving signals around in their brain, or moving their muscles. It is all work in the pure physical sense.

In all such activities work requires highly specific forms of kinetic energy (energy in motion). The amount of work that can be accomplished depends on the form and quality of the energy applied and the characteristics of the work process that can employ that energy. Energy that is specifically qualified to do useful work is called *exergy*. There can be a lot of energy in a flow but only a fraction of that energy is able to be coupled to the process in such a way that actual work is accomplished. The rest is dissipated, usually as waste heat.

In our industrial economic systems machines and furnaces are used to produce mechanical and thermally-based transformations of materials (motion, shaping, and composition). These machines, etc., typically referred to as 'prime movers and heaters' are designed to extract as much transformation out of an energy flow as is feasible given the level of technology or the thermodynamic limits of efficiency.

In any of the many forms of energy that are used in the industrial and domestic economies (e.g. electricity or liquid fuels) is found the exergy that runs everything we do. Let's take a look at a specific example of an economic activity that is valued by some human beings. There won't be a visible physical asset produced from this activity, but we assume that the activity was undertaken because the people involved will be better off economically in some fashion.

Suppose a family elects to move from town A to town B and decides to carry all of their possessions on top of their car. Mass has to be moved from point A to point B. The definition of mechanical work is that a mass is moved from one location to another by applying a force that changes the kinetic energy of the mass. We measure the change in velocity of the object and its mass and then we know how much its kinetic energy was changed.

The unit of work is the *joule*, defined as a force of one *newton* over one meter, which is the same for energy content of potential energy (energy in storage). Thus we can calculate how much work is done to move the family if we know the mass of the family, their belongings, and the vehicle. Like all good physics thought experiments we are ignoring friction (road and air) and most other relevant factors just to demonstrate the principle. These other factors could readily be determined and computed as well to get a more realistic number.

The fuel (e.g. gasoline at a particular octane rating) contains a specific number of joules per unit weight (or volume). At the end of the trip we can compute the number of joules actually used by the weight or volume consumed. The difference between the computed work and the actual energy consumed was given off in heat from that friction and inefficiencies of the engine. The total energy of the system (fuel going in and heat given off plus the work accomplished) is conserved in accordance with the First Law of Thermodynamics. The exergy that was represented in the fuel is the same as the actual work accomplished (in joules) not the total potential energy in the fuel.

Figure 1 shows the relevant factors.

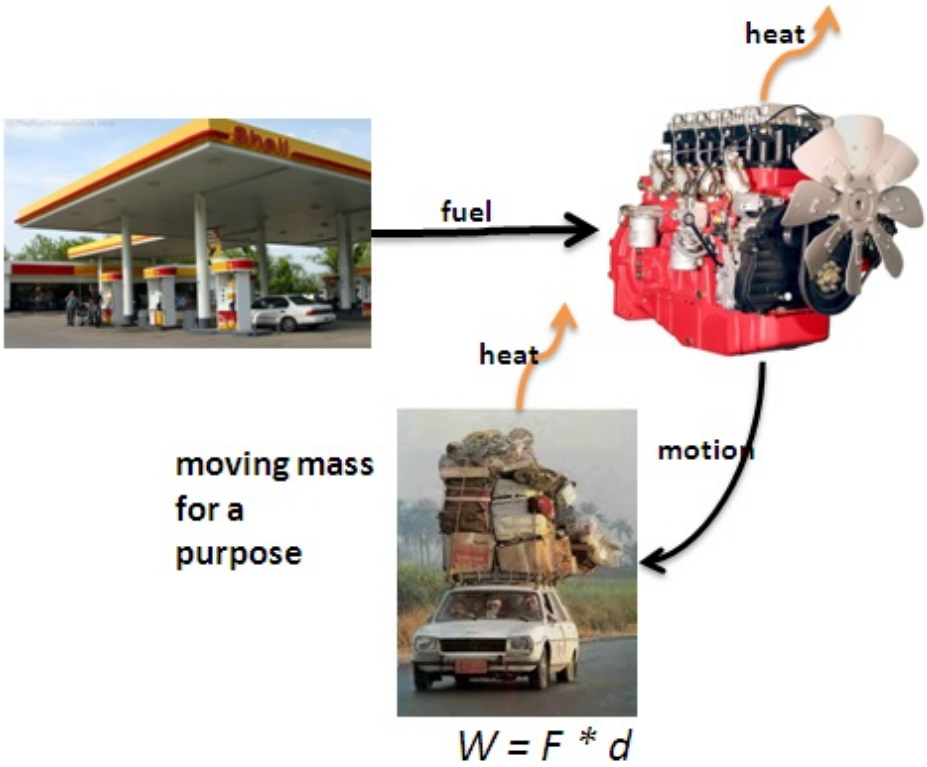

Figure 1. *Exergy is the amount of energy contained in the fuel (potential energy) that is able to be used by the machine to do the mechanical work of moving the mass over some distance. Once the work is done the exergy is used up, but the energy is dissipated as waste heat.*

We are assuming that the move represents some potential greater wealth for the family (as in moving to take a better paying job).

Of course the fuel had to first get into the car tank before this work could be done. For that to happen many steps were needed to go from raw oil deep underground to the product pumped at the gas station into the car. And the relations between many of the relevant factors here are not simple linear ones. Exergy is supplied from a very complex web of transformations. In other words, much work had to be accomplished just to get the fuel to the gas station. Figure 2 shows the network of a few of the major relations. Note that electricity is needed in order to run electric motors to drive pumps to move the fuels in the various forms.

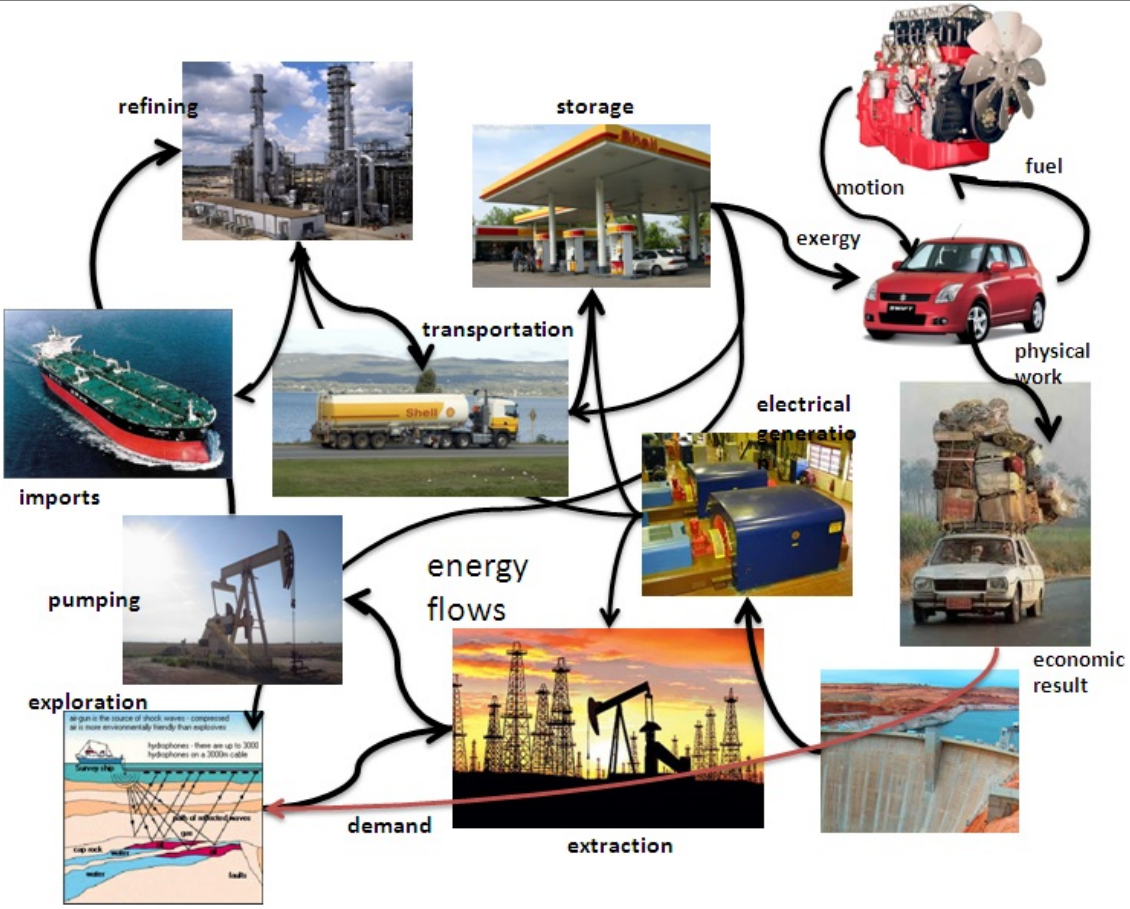

Figure 2. *The exergy web is a complex set of relations describing the transformations of raw oil to its final form (gasoline) in the tank of the car. This diagram does not account for the energies used in manufacturing and emplacement of the exploration, drilling, refining, and transportation equipment, nor for the electrical generation and delivery system. These are capital costs that could be accounted for with some effort. The red arrow from the car to the exploration represents the information feedback from the users to the oil producers (dollars spent on fuel) to spur further production.*

At each transformation the energy going into the work process is greater than the actual exergy available since no transformation is 100% efficient. If we were to work backwards from the car trip to the oil extraction we would find that a great many energy units of oil would be needed to provide the exergy needed for the trip.

Energy Return on Energy Invested — EROEI (EROI)

A great deal of work has gone on in the analysis of energy flow regarding how much energy is returned for every unit of energy invested in acquiring that energy (see: EROEI, Encyclopedia of Earth - EROI, and this by David Murphy & Charles Hall).

Generally, when done on oil or other fossil fuels, the energy returned is measured in terms of the raw energy content of the oil (usually given in barrels of oil equivalent) and not in terms of the actual exergy itself. As can be seen from the above diagram doing so would involve calculating (or collecting data on) the energy losses at every transformation from raw oil to final gasoline in the tank. This is a daunting task. Nevertheless, it is only the final exergy for the automobile under the specific load that counts as energy returned since that determines the amount of actual economic

work that is done.

In other words, we are probably vastly overstating the EROEI with regard to actual economic work since no form of energy comes to us from a raw source. One problem is that at each node in the above web there is a periodic building of new machinery that, on the face of it, might reduce the energy consumed to accomplish the intermediate work (e.g. the gasoline delivery truck can deliver more gas per unit of diesel fuel used), but requires considerably more investment energy to build out. In truth we don't actually know if the newer equipment's higher efficiency offsets the consumption of investment energy so that there is a net energy gain to society. The reason we don't know this is that we don't do energy accounting and under the conditions of constantly increasing availability of energy (as more oil was pumped per unit time) the effects of declining return on investment could easily be masked by the volume effects (we lose $0.02 on every transaction but we make it up on volume!)

This is what concerns me the most about the current state of energy analysis. We are acting too much like the drunk who looks for his keys under the street lamp even though he lost his keys down the street: there is more light under the lamp. Thorough EROEI analysis is next to impossible to perform for the reasons just mentioned- no data. So we really don't know how much actual exergy we are supplying to the economy to do our economic work. Hall, Balogh, and Murphy did tackle the problem to estimate total net energy that is needed to support just the transportation system (which is why I chose this example - see "What is the Minimum EROI that a Sustainable Society Must Have?" , *Energies* 2009, 2, 25-47; doi:10.3390/en20100025). However, they limited their boundary to just the energy used up in the transformation and did not consider energy consumed by other operating factors (e.g. labor) or capital investments in infrastructure. This might suffice as a second-order approximation that would likely not be substantially changed by adding in amortized investment costs, but in truth we just do not know. We won't know until someone tackles this very hard problem. I just hope we don't get an unpleasant surprise in the answer.

Exergy is the net energy that goes into economic work processes to accomplish that work. Net energy is the difference between gross or raw energy in the extracted fossil fuels and the exergy supplied to the prime movers/heaters, etc. We can estimate the first-order net energy as the number of barrels of oil (or joule contents of a barrel of benchmark oil) less the number of equivalent barrels it took to get it out of the ground and to the refinery, and maybe through the refinery as Hall, et al did.

But for non-transportation sectors like manufacturing, households, and services the situation is much less clear. In the above diagram I showed electricity as another form of exergy produced by the energy contained in the water behind the dam. This is what complicates the analysis so much--the mix of energy forms that have to be taken into account working backward from the point of use in economic work to the raw sources.

Money and Wealth

Howard Odum noted that money flows in the direction opposite the flow of energy through the economic system (see: 2007, *Environment, Power and Society for the Twenty-First Century: The Hierarchy of Energy*, with Mark T. Brown, Columbia University Press.)

Figure 3 captures this in an 'idealized' and 'simplified' economic system. In this figure there are five kinds of energy flows. We start with 'raw' but high potential energy from a suitable source (e.g. fossil fuels — ancient solar energy). This energy is captured by special equipment (or by

crops on the farm) that extracts the exergy that the economy needs. This is distributed to all work processes, including the extraction processes (internal exergy within the energy extraction process is not shown). Consumption of food provides the labor pool with energy that is returned to the work processes. The fourth kind of energy is embodied in the material flow that ends up in consumption. Finally, all energies are consumed in one way or another and all work processes produce low grade or waste heat that must be carried away in the atmosphere and eventually radiated to deep space.

Raw material resources are extracted from nature and worked upon to produce intermediate products, the parts that will be used to construct a final product (or service). The materials contain some emergy from the Earth's natural energy flows that produced, for example, high grade (low entropy) ores (the black straight arrows surrounded by white outlines). The intermediate products (grey straight arrows with white outlines) represent more embodied energy as work was accomplished to make the raw materials useful in production.

The final product goes to the consumption process, where end consumers are people. In turn, people form the labor pool and supply human energy back to the various work processes. The ultimate fate of all materials (over sufficiently long time scales) is as waste that is essentially dumped back into the environment as high entropy by products of economic activity.

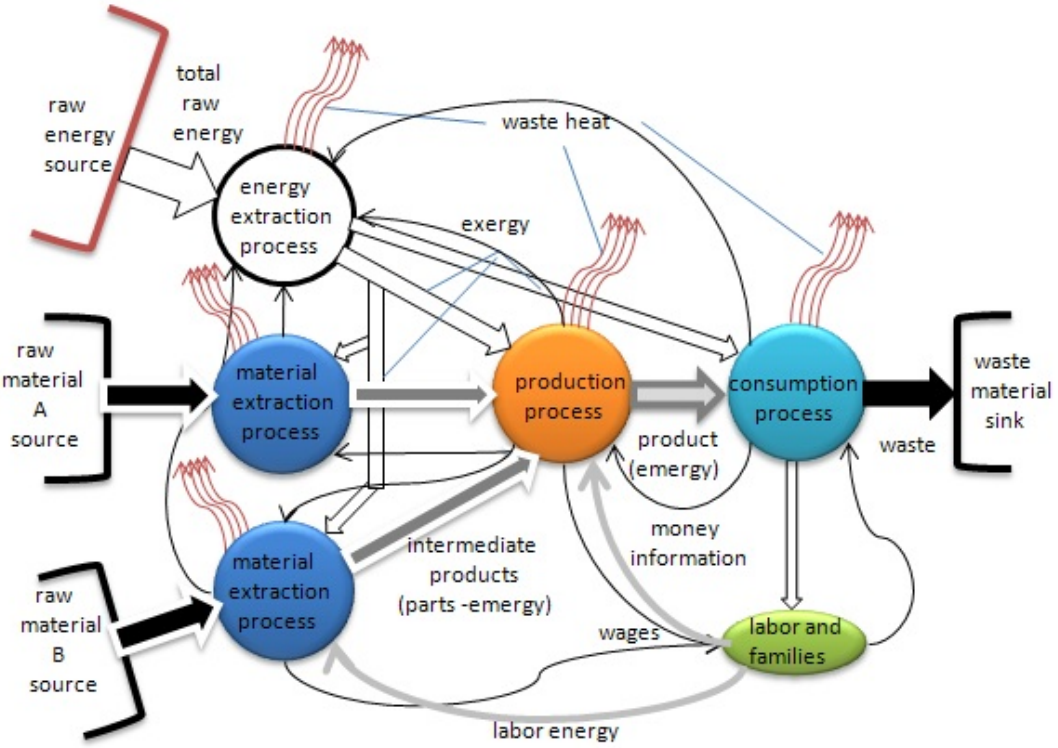

Figure 3. *The economy is viewed as a set of flows of material, energy, and information. The physical resources flow from left to right. Every process requires specific exergy to perform its work. That energy is consumed and dissipates as waste heat (red curvy arrows). Eventually the consumption process produces waste materials (actually the work process and extraction processes do also, but it is not shown to keep the diagram simple). Consumption helps to produce labor energy (grey curvy arrows) which is fed back into the extraction and production processes. Money (dark, thin, curvy arrows) flows in the opposite direction of exergy and embodied energy (emergy) flows. Money is used to purchase labor energy which is how money gets recycled even while all energies flow in only one direction, out to the environment as waste heat.*

In this view of an economy, each downstream process must signal the providers of materials and exergy of their needs/desires. They do this by using a very abstract message token called 'money'. When anyone buys a product or service they are signaling the producer that there is a continuing demand for that product or service. The producer then signals his suppliers by buying the goods and services he needs to produce his output. The flow of money, represented in the figure by thin black curvy arrows, runs exactly counter to the flow of exergy and emergy, including labor energy (which we might label *lexergy*). Since people provide the lexergy in the system, money then recycles through the economy.

What should we count as wealth in this picture? Currently economists count wealth as being the sum of all money transactions (purchases). As long as the monetary form being used (such as a fiat currency) actually was used as shown in Figure 3, then this would be a correct approach since all money would represent the actual work being accomplished in all forms. Typically this will boil down to the production of goods and services that are deemed economically useful.

But, unfortunately, we people have gotten into some very bad habits that cause a major distortion in this measure of wealth. And those distortions have a positive feedback effect on those bad habits. The distortions make it look like we are producing more wealth as measured by that summation of transactions (the Gross Domestic Product, GDP) than there actually is physical wealth in the system. This leads to doing the things that caused the distortions in the first place and makes us feel good about how much supposed wealth we have made.

Finance

The bad habits I refer to have to do with the false creation of more money that is not represented by an equivalent amount of exergy. The bad habits are actually venerated today. They are collectively called 'financing'! Some time back I wrote more about this insidious practice that evolved out of our historical and very reasonable practice of borrowing from past savings to stimulate some new economic activity.

Bankers are to blame for stepping onto the slippery slope first. Fractional reserve banking originated as a means to provide loaned money to people who were going to do something new and useful economically. As long as the bankers maintained a reasonable reserve as backup against too many savers wanting their funds, this was an effective way to take advantage of opportunities to create new wealth. For a short period of time it looked like there was a bit more money than there really was, because savers assumed that their savings were intact or could be made whole again in a reasonable amount of time. But the bankers were not satisfied with the marginal profits they made by managing this process. How to make more profits? Lend more money and keep fewer reserves! What made this work was that most people had become relatively comfortable leaving their savings where the savings were safe (until they weren't!).

As time went on, and except for a few business cycle-caused hiccups, the practice of keeping smaller and smaller reserves seemed like a good idea to even conservative bankers and regulators. But what they didn't grasp, mostly because they had long since forgotten that money = ability to do work, is that this trick only worked as long as the supply of exergy was on the increase. Financing in this manner, and other more sophisticated forms of borrowing from the future, depends entirely on economic growth.

Economic growth can only take place as long as there is growth in the availability of exergy. It's that simple. For all those years we have been increasing the production of fossil fuels, even with declining EROEIs, there has been an increase in exergy year over year. This is what has

'financed' growth in the economy and the seeming effect of a rising tide raising all boats. I've written about this as well (see also: this earlier piece).

Financing based on betting on the future was not a completely unreasonable approach while the whole system expanded. But it did create a false impression of the availability of exergy. It began to be treated as a foregone conclusion that there would always be more wealth created in the future and that that wealth would more than compensate for the 'risk' of being caught with our pants down if it didn't happen. In other words, it didn't seem all that risky. So the practice was expanded, especially in the past few decades, with all kinds of creative ways to make more money than was warranted on energy standards alone. The stock and bond markets and various derivatives, the housing market with rising prices, the cheaper goods coming from overseas manufacturing (where the energy demands of the workers is far greater than in the OECD countries), and many other false signals simply provided a kind of reward feedback that just kept us inventing more ways to fool ourselves into thinking we were producing massive wealth.

But reality is starting to bite. Starting back in the 1970s the flow rates of exergy began to slack off, even as the flow of raw energy, mostly oil and gas, were increasing dramatically. This was due to the negative impact of diminishing EROEI. By the 1990s the flows were probably past the peak and starting to actually decline. That is when there was a tremendous explosion of new tricks in finance that were meant to maintain the illusion of wealth creation.

As things currently stand, the economists, politicians, talking heads, and pundits all believe that the problem with the economy is that we are simply not spending enough money, thereby increasing the GDP and causing jobs to be created. They are universally calling for a return to growth. The politicos scrambled to save the financial system because they knew it was the 'engine' of creating new money. And the new money always made it look like GDP was growing. By inference, then, the economy must be healthy when the GDP is growing. Except, of course, it isn't. Only the growth of exergy can support a growth of real wealth. Money has no causative power whatsoever, except perhaps to drive men mad. It certainly seems to be doing so today.