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Powering Civilization Sustainably

by Chris Phoenix, CRN Director of Research, January 2006

Most products, and almost all high-tech products, use energy. Exponential molecular manufacturing is expected to build a large quantity of products, and the energy use of those products raises several interesting technical questions.

Energy must come from a source, be stored and transmitted, be transformed from one form into another, and eventually be used; the use will generate waste heat, which must be removed. Encompassing all of these stages are questions of efficiency and power budget. Several factors may limit desired uses of energy, including availability of energy, removal of heat, and collective side effects of using large amounts of energy.

Energy Source

The use of fossil fuels as an energy source is problematic for many reasons. The supply, and more importantly the rate of extraction, is limited. The source may be politically troublesome. Burning of fossil carbon adds carbon dioxide to the atmosphere. Some forms of energy, such as coal and diesel fuel, add pollutants to the atmosphere in addition to the carbon.

Nuclear energy has a different set of problems, including political opposition and nuclear weapons proliferation. It is alleged that modern techniques for pre-processing, use, and post-processing of fission fuel can largely avoid disposal problems and can release less radiation into the environment than burning an equivalent amount of coal; it remains to be seen whether non-engineering problems can be overcome.

Today, solar energy is diffuse, fluctuating, expensive to collect, and difficult to store. Solar collectors built by nanofactories should be far less expensive than today's solar cells. The diffuse nature of solar energy may be less problematic if solar collectors do not have to compete for ground area. High-altitude solar-powered airplanes such as the Helios, successor to the existing Centurion, are already planned for round-the-clock flight using onboard energy storage. With lighter and less expensive construction, a high-altitude airplane, flying above the weather that troubles ground-based collection, could capture far more solar energy than it needed to stay aloft.

A fleet of solar collection airplanes could capture as much energy as desired, providing a primary power source for terrestrial use--once the energy was delivered, converted, and stored for easy access, as explained below. Their high altitude also would provide convenient platforms for communication and planet-watching applications, serving military, civilian, and scientific purposes. Although individual planes would be too high to see from the ground, if flown in close formation they could provide partial shade to an area, modulating its microclimate and perhaps providing a tool for influencing weather (e.g. removing heat from the path of a hurricane).

Power Budget

Robert Freitas calculated (*Nanomedicine, Volume I*, 6.5.7) that for a future population of 10 billion, each person would be able to use perhaps only 100 kW without their aggregate heat dissipation causing damage to the Earth's climate. An automobile's engine can deliver 100 kW of useful power today (100 kW = 134 HP), while producing several times that much waste heat. This indicates that power usage cannot be assumed to be unlimited in a post-MM world. Because a lot of power will probably be allocated to governmental projects, and wealthy people will presumably use more power than average, http://www.crnano.org/essays06.htm#1,Jan

I will assume that world power usage will equal a trillion kW, with a typical person using ten kW--about what the average European consumes today. (Americans use about twice as much.)

Energy Storage and Transmission

In chapter 6 of *Nanomedicine I*, Freitas analyzes energy storage (section 6.2), conversion (6.3), and transmission (6.4). The highest density non-nuclear energy storage involves stretching or rearranging covalent chemical bonds. Diamond, if it could be efficiently oxidized, would provide 1.2×10^{11} J/m^3. Methanol's density is almost an order of magnitude lower: 1.8×10^{10} J/m^3 (5000 kWh/m^3). In theory, a stretched diamond spring could provide an energy density of up to 2×10^{10} J/m^3, slightly better than methanol, and not quite as good as a diamond flywheel (5×10^{10} J/m^3).

Human civilization currently uses about 1 quadrillion BTU, or 10^{18} J, per day; somewhat over ten billion kW--about 1% of the maximum environmentally-sound level. This indicates that many people today use significantly less than even one kW, which is impressive considering that the human body requires about 100 W (2000 kcal/day).

To store a typical (future) personal daily energy requirement of 10 kW-days in a convenient form such as methanol or diamond springs would require about 50 liters of material, 1/20 of a cubic meter. To store the entire daily energy supply of our future civilization would require 5 billion cubic meters of material.

An efficient and compact way to transmit energy is through a rapidly rotating diamond rod, which can carry about a gigawatt per square centimeter (*Nanomedicine* 6.4.3.4). A person's daily power could be transmitted through a one-square-millimeter rod in a little less than a second. On the other hand, in order to transfer all of civilization's future budget of 10^{15} W, 100 m^2 of rotating diamond rods would be needed. To transfer this energy halfway around the planet (20,000 km) would require two billion cubic meters of diamond, which is quite feasible given a carbon-based exponential molecular manufacturing technology. (The atmosphere contains 5×10^{14} kg of carbon, and two billion cubic meters of diamond would weigh 7×10^{12} kg.)

Solar Collection Infrastructure

Let's go back to the idea of using high-altitude aircraft to collect solar energy. In space, the sun shines at 1366 W/m^2. Considering the inefficiency of solar cells, the angle of the sun (it may be hard to fly the airplane at odd angles to make the solar collectors directly face the sun all through the day), and nighttime, the wing surface may collect only about 100 W/m^2 on average. The Centurion solar airplane has a wing area of 153 m^2, which would collect about 1 billion J/day. To store that much power would require about 232 kg of diamond springs; the weight of Centurion when configured for flight to 80,000 ft is 863 kg.

It seems, then, that a fleet of 100 billion light-weight auto-piloted aircraft, each making contact with the Earth for a few seconds every few days to transfer its stored power, would be able to provide the full 10^{15} W that the Earth's civilization would be able to use sustainably. (Remember that a billion J can be transferred through a 1 cm^2 rod in 1 second. Several other power transfer methods could be used instead.) The total wing area would be about ten million square kilometers--about 2% of the Earth's surface area. The total mass would be about 3×10^{13} kg, about 6% of the carbon in the Earth's atmosphere. Of course, removing this much carbon from the atmosphere would be a very good idea.

As calculated in my paper, Design of a Primitive Nanofactory, building a kg of diamond might require as much as 200 kWh, or $7x10^8$ J. (Special-purpose construction of large simple diamond shapes such as springs and aircraft structure could probably be done a lot more efficiently.) Thus, in a day, an airplane could collect more than enough energy to build another airplane. While flying for a day, it would also have the opportunity to collect a lot of carbon dioxide. The energy cost to convert carbon dioxide to suitable feedstock would be a small fraction of the 200 kWh/kg construction cost, since most of that cost went for computation rather than chemistry. Thus it seems that the airplane fleet could in theory be doubled each day, requiring only a little over a month to double from 1 airplane to 100 billion.

Energy Use, Transformation, and Efficiency

Energy can come in many forms, such as mechanical energy, electrical energy, light, heat, and chemical energy. Today, energy is most easily stored in chemical form and transported in chemical or electrical form. (Actually, the ease of chemical storage comes largely from the fact that we find it already in that form. Manufacturing energy-rich chemicals from any other form of energy is quite difficult, costly, and inefficient with today's technology.)

Energy has a wide variety of uses, including transportation, powering computers, illumination, processing materials, and heating or cooling. In general, applications that are implemented with molecular manufacturing can be at least as efficient as today's technology.

With molecular manufacturing, it will be possible to build extremely dense conversion systems. Much of today's technology runs on electricity, and electromechanical conversion (motors and generators) can be built extremely small, with rotors less than 100 nm across. This is good news because such systems increase in power density as they shrink. A nanoscale motor/generator could have a power density of 10^{15} W/m^3. This means that these components will take almost negligible volume in almost any conceivable product.

There's even more good news. Nanomachines should lose less energy to friction as they are operated more slowly. Thus, if some of their astronomical power density is traded for efficiency--incorporating one hundred times as many motors, and running them 1/100 as fast--then the efficiency, already probably pushing 99%, will become even better. This means that most products will have far less internal waste heat to get rid of than if they were built with today's technologies.

Today's laptop computer might be replaced with one that contained millions of high-performance CPU's working in parallel--while using less power. This is because today's computers are quite inefficient; they spend huge amounts of energy pushing electrons back and forth in sufficient quantities to maintain a clean signal, and the energy of each signal is thrown away billions of times per second. Nano-built computers will have better ways of retaining signals, and will be designed to re-use much of the energy that is thrown away in today's designs. It is safe to say that a nano-built computer could provide more processing power than today's programmers would know what to do with, without using more than a tiny fraction of the personal power budget.

Modern food production is a major resource drain--not only fossil fuels for machinery and fertilizer, but also water, topsoil, and land area, plus the costs of associated pollution. Much of this drain could be eliminated by enclosing agriculture in inexpensive greenhouses with automation. Further efficiency improvements could be achieved by a gradual switch to manufactured food; although it would have seemed science-fictional just a few decades ago, people today are already eating "energy bars" and other high-tech food products that have little in common with natural food.

The biggest power source in the world today is fossil fuel. This is usually burned and used to run heat engines, which inevitably throw away more than half the energy as waste heat. Fuel cells are not heat engines, and are not limited by Carnot efficiency. Today, fuel cells are finicky, fragile, and expensive. However, nanofactory-built fuel cells should be less fragile, more compact, and certainly cheaper. In addition, direct chemomechanical conversion should be possible for at least some fuels, and may be reasonably efficient.

Because fuel poses storage and safety problems, and needs an air supply, it seems likely that many nano-built products will use mechanical power storage, which can be recharged and discharged quickly and efficiently. As noted above, the power density of diamond springs is about as good as some liquid fuels--far superior to batteries.

Handling Heat

Several authors, including Eric Drexler, Josh Hall, and Robert Freitas have pointed out that large masses of nanomachinery may generate far too much waste heat to be cooled conveniently--or at all. However, the same high power density that reduces the allowable mass of nanomachinery also means that only small quantities will be needed to implement functionality equivalent to that found in today's products. In fact, nano-built products will typically be quite a bit more efficient. Instead of the mass of active nanomachinery, a more useful metric is the power generated by the machinery.

To achieve the same results as today's products, nano-built products will have to handle less heat, because they will be more efficient. This is especially true in the case of fuel-burning engines, since no nano-built product will need to use a heat engine; instead, they will be able to store mechanical energy directly, or at the worst will use a compact and efficient fuel cell.

Products that interact energetically with the environment, such as water pumps and vehicles, will still need a lot of energy to overcome friction (and probably turbulence) and accomplish their task. However, their internal mechanisms will only be transforming the energy they use, not converting much of it to heat. Energy that is used to overcome fluid resistance will typically be carried away by the fluid; only in extreme cases, such as supersonic airplanes, do products suffer significant structural heating.

Summary

Molecular manufacturing will provide the capability to engage in planet-scale engineering, such as building a new petawatt solar-gathering capability in a month or so. This could be used to provide perhaps 100 times more energy than we use today--as much as we can safely use without harming the environment. The collected energy could be delivered in a near-continuous stream, close to where it was needed. Even if divided with a moderate degree of inequity, there should be enough energy for everyone on the planet to enjoy a Western standard of living.

Many of today's applications can be made significantly more efficient. In particular, the waste associated with fuel-burning engines and power plants can be eliminated. However, the energy cost associated with transportation is likely to remain high, especially since new technology will enable greater speed.