Big Green Energy Machines

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Jesse H. Ausubel **(Figure 1)**
Director, Program for the Human Environment
The Rockefeller University
1230 York Avenue, New York NY 10021
http://phe.rockefeller.edu
ausubel@rockefeller.edu

Introduction

The World Wide Web, honored by the first Millennium Technology Prize, reminds us, that to become larger systems must become smaller. The Web and Internet more generally are triumphs of scalability and economies of scale. If every computer still occupied the footprint of a mainframe computer of the 1960s, the Internet could never have succeeded. The miniaturization of every element of computer systems, from chips to video display, enabled the Internet to become pervasive and at the same time unintrusive. The elements also became cheaper. Think of the drop in price per calculation as semiconductor manufacturers introduced successively more powerful generations of chips and learned to fabricate each generation better. The shrinking of the elements of the system in cost, size, and intrusiveness enabled the system as a whole to multiply in power, features, and reach.

During the past 100 years electric motors have grown from 10 kilowatts to 1 million kilowatts, scaling up an astonishing 100,000 times. Yet, a power station today differs little in size from fifty or one hundred years ago. Regard the cathedral-like Bankside power station in London along the Thames opened in 1953 and converted in 2000 to serve as the modern gallery of the Tate Museum **(Figure 2)**. The station, soaring 100 meters high and covering 3.5 hectares, provided at its peak a couple of hundred megawatts. A comparably powerful generator installed today, fueled by methane rather than heavy oil, might need 10 percent of the Bankside space. Alternately, the site could accommodate ten times the power. Fortunately, today a 2000 megawatt station need not cover 35 hectares nor soar one thousand meters.

As with computer systems, scale matters to the electricity consumer as well as producer. Economist William Nordhaus observed a middle-class urban American household in 1800 would have spent perhaps 4 percent of its income on illumination: candles, lamps, oil, and matches. A middle-class urban American household today spends less than 1 percent of its income on illumination, and consumes more than 100 times as much artificial illumination as did its predecessor of two centuries ago. Happily, lamps do not occupy 100 times the space they occupied 200 years ago. Increases in luminous efficacy and decreases in cost of fuel allowed light to spread. (Improvements in safety counted too; lamps do not spark 100 times as many fires as formerly.)

Affordable electric power contributed as much as any technology to lifting human well-being in the 20th century. Mobility afforded by the internal combustion engine contributed hugely too. Electric power and mobility both depend on primary energy. During the 21st century, global primary energy demand is likely to grow from the present 13 terawatts to 50 or even 100 terawatts. One cause is chips going into 1000 objects per capita, or 10 trillion objects, as China, India, and other nations log into the game. A second is that all people continue to seek to increase their range, thereby increasing their access to jobs, education, and enjoyment. Let's assume a big increase in efficiency gains and reduction in population growth. Still, a mere 1.5% per year growth of total energy demand during the 21st century, about two-thirds the rate since 1800, will multiply demand for primary energy three to four times between 2004 and 2100.

If size and power, of individual machines or the total system, grow in tandem, use of materials and land and other resources becomes unacceptably costly. Technologies succeed when economies of scale form part of their conditions of evolution. I seek an energy system that is 5 to 10 times more powerful than the present system but fits within, or better, reduces its present footprint, a system of engines big in power and green in impact.

Modestly compared to the 20th century, we may expect that the largest machines in the energy system will grow 5 to 10 times. Bigness is a plus for economizing on total use of materials as well as for controlling emissions because, although one big plant emits no more than many small plants, emission from one is easier to collect. Society cannot close the carbon cycle, for example, if we need to collect emissions from millions of microturbines. I will share with you two visions for big green energy machines suiting the context of the 21st century. The first is the very powerful Zero Emission Power Plant (ZEPP) burning methane. The second is the Continental SuperGrid to deliver electricity and hydrogen in an integrated energy pipe.

Very Powerful ZEPPs

The ZEPP, my first big green energy machine, is a supercompact, superfast, superpowerful turbine putting out electricity plus carbon dioxide that can conveniently be sequestered. Investments by energy producers will make natural gas, methane basically, overtake coal globally as the lead fuel for making electricity over the next two to three decades. Methane tops the hydrocarbon fuels in heat value measured in joules per kilogram and thus lends itself to scaling up **(Figure 3)**. Free of sulfur, mercury, and the other elements that contaminate coal (and oil), methane is the best hydrocarbon feedstock. Although methane produces about half the carbon dioxide per unit of energy that coal does, it does still yield this greenhouse gas. Indeed, even in 2020, we could need to dispose carbon from methane alone equal to half today's emission from all fuel and later methane might cause about 75% of total CO_2 emissions. So, prevention of climate change must focus on methane. Can we find technology consistent with the evolution of the energy system to dispose economically and conveniently the carbon from making kilowatts? The practical means to dispose the carbon from generating electricity consistent with the future context is the very large ZEPP. Let me try to leave ZEPPs indelibly in your minds.

The basic idea of the ZEPP is a gas power plant operating at very high temperatures and pressures, so we can bleed off the CO_2 as a liquid and sequester it underground in porous formations like those that harbor oil.

A criterion for ZEPPs is working on a huge scale. Big total energy use means powerful individual ZEPPs because the size of generating plants grows even faster than use, though in spurts. Plants grow because large is cheap, if technology can cope. A famous engineering rule of thumb is that costs grow as the square root of size.

Analysis of the maximum size of power plants shows the maximum size grows in intense spurts. In the USA, one pulse, centered in 1929, quickly expanded power plants from a few tens of megawatts to about 340. After a period in which plant size stagnated, a pulse centered in 1965 quadrupled maximum plant size to almost 1400 MW. The patterns for the world and a dozen other countries we have analyzed closely resemble the USA. For reference, my city, New York, now draws above 12,000 MW on a peak summer day.

The stagnation of maximum power plant size for the past couple of decades should not narcotize today's engineers. Growth of electricity use for the next 50 years can reasonably quadruple maximum plant size again. I project another spurt in plant size centered around the year 2020 to more than 5,000 MW.

Big ZEPPs means transmitting immense mechanical power from larger and larger generators through a large steel axle as fast as 3,000 revolutions per minute (RPM). The way around the limits of mechanical power transmission may be shrinking the machinery. Begin with a very high pressure CO_2 gas turbine where fuel burns with oxygen. Needed pressure ranges from 40 to 1000 atmospheres, where CO_2 would be recirculated as a liquid. The liquid combustion products would be bled out. **Figure 4** shows a simple configuration offered by colleagues from Tokyo Electric Power with the six major components, combustor, turbine, regenerator, condenser, pump, and generator.

This scheme is a little rustic. We might let oxygen circulate and add methane when needed by local injection to make expansion almost isothermic. Dual cycles, maximum capacity, and changes in temperature in the regenerator with such dense gases all need to be considered by top engineers in laboratories to open a grand concourse of designs.

Fortunately for transmitting mechanical power, the high pressures shrink the machinery in a revolutionary way and so permit the turbine to rotate very fast. The generator could then also turn very fast, operating at high frequency, with appropriate power electronics to slow the generated electricity to 60 cycles.

Our envisioned hot temperature of 1500 degrees C will probably require using new ceramics now being engineered for aviation. Problems of stress corrosion and cracking will arise at the high temperatures and pressures and need to be solved. Power electronics to slow the cycles of the alternating current also raises big questions. What we envision is beyond the state of the art, but power electronics is still young, meaning expensive and unreliable, and the art of the year 2020 and beyond may make our vision a reality.

The requisite oxygen for a 5000 MW ZEPP exceeds present capacity but could be made by cryoseparation. Moreover, the cryogenic plant may introduce a further benefit. Superconductors fit well with a cryogenic plant nearby. Superconducting generators are a sweet idea. Already today companies are selling small motors wound with high temperature superconducting wire that halve the size and weight of a conventional motor built with copper coils and also halve the electrical losses. Colleagues at Tokyo Electric Power calculate the overall ZEPP plant efficiency could reach 70%, well above the 55% peak performance of gas turbines today **(Figure 5)**.

With a ZEPP fueled by natural gas transmitting immense power at 60 cycles, the next step is sequestering the waste carbon. At the high pressure, the waste carbon is, of course, already liquid carbon dioxide and thus easily-handled. Opportunity for storing CO_2 will join access to customers and fuel in determining plant locations. Because most natural gas travels far through a few large pipelines, these pipelines are the logical sites for ZEPPs.

A logical place to sequester CO_2 emissions is in caverns underground, where coal, oil, and gas came from. The logic is encouraged by fact. On a small scale, CO_2 already profitably helps tertiary recovery of oil. In regions such as Texas, extensive systems pipe CO_2 for geologic storage in depleted oil fields for potential reuse in other nearby fields. In fact the past 20 years have proven the CO_2 storage industry. Commercial enterprises now store without leaks more than 30 million tons per year for enhanced oil recovery.

The challenge is large scale. The present annual volume of CO_2 from all sources is about 15 km^3, about 500 times what oilmen now use. Of course natural geological traps only occasionally contain hydrocarbons, so one can extend storage to the traps that lack oil and gas that prospectors routinely find. Grasping another opportunity, one could use aquifers in silicate beds to move the waste CO_2 to the silicates where “weathering" would turn it into carbonates and silica good for millions of years.

In short, the ZEPP vision is a supercompact, superpowerful, superfast turbine: 1-2 m diameter, potentially 10,000 MW or double the expected maximum demand, 30,000 RPMs, putting out electricity at 60 cycles plus CO_2 that can be sequestered. ZEPPs the size of a locomotive or even an automobile, attached to gas pipelines, might replace the fleet of carbon emitting antiques now cluttering our landscape.

I propose starting introduction of ZEPPs in 2020, leading to a fleet of five hundred 5000 MW ZEPPs by 2050. This does not seem an impossible feat for a world that built today's worldwide fleet of some 430 nuclear power plants in about 30 years. ZEPPs, together with another generation of nuclear power plants in various configurations, can stop CO_2 increase in the atmosphere near 2050 AD in the range 450-500 ppm, about one-quarter more than today, without sacrificing energy consumption.

ZEPPs merit tens of billions in R&D, because the plants will form a profitable industry worth much more to those who can capture the expertise to design, build, and operate them. They offer the best chance for safe use of the immense wealth of hydrocarbons. Research on ZEPPs could occupy legions of researchers, working on development in conjunction with private companies. ZEPPs need champions. Let's whip the imaginations of electrical engineers to design and test power plants five times today's largest, chemical engineers to make more efficient processes suitable for plants two orders of magnitude larger than present fertilizer plants, and geo-engineers to expand leak-proof CO_2 sequestration industries.

Like the jumbo jets that carry the majority of passenger kilometers, compact ultra-powerful ZEPPs could be the workhorses of the energy system in the middle of the next century. Yet, power companies could insert ZEPPs into densely settled regions such as eastern China without much change to the footprint of the energy system.

The Continental SuperGrid

Here let me introduce a second, even bigger green energy machine, the **Continental SuperGrid** to deliver the preferred energy carriers, electricity and hydrogen, in an integrated energy pipeline. The fundamental design is to wrap superconducting cable around a pipe pumping liquid hydrogen that provides the cold needed to maintain superconductivity **(Figure 6)**. The SuperGrid is doubly super: first because it is the apex, and second because it employs superconductivity. The SuperGrid would not only transmit electricity but also store and distribute the bulk of the hydrogen ultimately used in fuel cell vehicles and generators or refreshed internal combustion engines.

While methane is a good energy carrier, environmentally hydrogen is better. Its combustion yields only water vapor and energy. In the 1970s journalists called hydrogen the Tomorrow Fuel, and critics have worried that hydrogen will remain forever on the horizon, like fusion. For hydrogen tomorrow is now today. Long popular as rocket fuel and in other top performance market niches, hydrogen is a thriving young industry.. World commercial production in 2002 exceeded 40 billion standard cubic feet per day, equal to 75,000 MW if converted to electricity, and USA production, which is about 1/3 of the world, more than tripled between 1990 and 2000 **(Figure 7)**. Over 16,000 kilometers of pipeline transport hydrogen gas for big users, with pipes at 100 atmospheres as long as 400 kilometers from Antwerp to Normandy. But the scale I have in mind is orders of magnitude larger.

By continental, I mean coast-to-coast, for example, across the 4,000 kilometers of North America, making one market not only for hydrogen but also for electricity. Superconductivity solves the problem of power line losses, and the continental scale makes the electric power system much more efficient by flattening the electricity load curve which still follows the sun. By high capacity, I mean 40,000-80,000 MW. The cable would carry direct current and might look either like a spine or a ring. Power converters would connect the direct current SuperGrid at various points to existing, high-voltage alternating current transmission substations. Continental SuperGrids should thrive on all continents. A continental system might cost about $1 trillion, or $10 billion per year for 100 years

In its early realization some forty 100-km long sections of the grid might be joined by nuclear plants of several thousand MW supplying to the SuperGrid both electricity and hydrogen. Present hydrogen comes from cooking hydrocarbons, about 85% from steam reforming of methane and the rest from oil residues or coal gasification. To spare the chores and costs of carbon capture and sequestration, hydrogen, of course, must eventually come from splitting water, and the energy to make the hydrogen must also be carbon-free. According to the historical trend of decarbonization, large-scale production of carbon-free hydrogen should begin about the year 2020.

Nuclear power fits with the SuperGrid because of its low cost of fuel per kilowatt hour and its operational reliability at a constant power level. High-temperature reactors with coated-particle or graphite-matrix fuels promise a particularly efficient and scalable route to combined power and hydrogen production. Thermochemically, high-temperature nuclear plants could nightly make H_2 on the scale needed to meet the demand of billions of consumers. Nuclear energy is inherently 10,000 or even 100,000 times as compact as hydrocarbons **(Figure 8)** and thus scalable. Like ZEPPs, high temperature reactors could be 5,000 to 10,000 megawatts. Thus, the acreage for power parks and even the number of plants need differ little from today. In many regions and countries the future energy system can fit within the footprint of the present energy system.

Operating 24 hours per day, the plants would double the basic efficiency of the capital stock of the electric power industry, which is geared to peak demand, about twice the level of baseload but unused half the time. The latent hydrogen storage capacity of the SuperGrid, combined with fuel cells or other new engines, may allow electricity networks to shift to a delivery system more like oil and gas, away from the present, costly, instant matching of supply to demand.

Technical choices and challenges abound, about cryogenics and vacuums, about dielectric materials under simultaneous stress from low temperature and high fields, about power control and cable design **(Figure 9)**. Engineers need to improve Supercable design and demonstrate performance of high temperature superconducting wire at commercial electrical current levels.

The next step, achievable over 2-3 years, might be a flexible 100 meter Supercable, 10 centimeters overall diameter, 5000 volts, 2000 amperes, 10 MW direct current, with a 3 centimeter diameter pipe for 1 meter per second H_2 flow, using magnesium diboride or other wire demonstrating constant current under variable load and low ripple factor. Looking forward, joints and splices are tough problems, emblematic of the general problem of making parts into a system that works, a problem that challenges engineers to their greatest achievements.

For ultimate safety, security, and aesthetics, let's put the SuperGrid, including its cables and power plants, underground. The decision to build underground critically determines the cost of the SuperGrid. But, benefits include reduced vulnerability to attack by human or other nature, fewer right-of-way disputes, reduced surface congestion, and real and perceived reduced exposure to real or hypothetical accidents and fallout. Since 1958 Russia has operated underground nuclear reactors near Zheleznogorsk in Central Siberia. The SuperGrid multiplies the chances to site reactors that produce hydrogen far from population concentrations and pipe their products to consumers.

An even more evolved concept for the underground corridors combines energy with transport. Sharing the tunnels, magnetically levitated trains in low pressure tubes would run on linear motors of superconducting magnets, speeding from one edge of a continent to another in 1 hour **(Figure 10)**. I am now looking ahead 100 years, but that is a good time frame for major infrastructure systems. Let's recall that 101 years ago the Wright Brothers launched the first successful airplane with a 12 horsepower engine for 59 seconds. The maglevs could spread the infrastructure cost over multiple uses.

Magic words for the SuperGrid are hydrogen, superconductivity, zero emissions, and small ecological footprint, to which we add high temperature reactors, energy storage, security, reliability, and scalability. The long road to the continental SuperGrid begins with the first 10 to 20 km segment addressing an actual transmission bottleneck. The prize is that the SuperGrid pipe can carry ten or more times the power of a cable today within the same diameter.

Conclusion

Small is indeed beautiful, when small also means powerful and cheap, like the machinery of the Internet. The energy system requires economical green ideas that are comparably big in power yet small in impact.

Solar and the so-called renewables are not green when considered on the large scales required. In round numbers a single 1,000 MWe nuclear plant equates to prime farmland of more than 2500 square kilometers producing biomass, to a wind farm occupying 750 square kilometers, or a PV plant of about 150 square kilometers plus land for storage and retrieval. On large scales, we are stuck with about 0.4 watts per hectare from biomass, 1.2 watts per square meter from wind, and 5-6 watts per square meter from light. While a present natural-gas combined cycle plant uses about 3 metric tons of steel and 27 cubic meters of concrete per average megawatt electric, a typical wind-energy system uses a horrifying 460 metric tons of steel and 870 cubic meters of concrete. Solar and renewables in every form require large and complex machinery to produce many megawatts. Inherently, they lack efficiencies and economies of scale. Like fixed low-yield agriculture, to produce more calories solar and renewables simply multiply in extent, linearly. Unlike the Internet, solar and renewables cannot become much smaller as they become much larger. Thus, they will grow little.

Fortunately, the enabling technologies of the new millennium such as high temperature ceramics and superconductors make possible big green energy machines such as ZEPPs and Continental SuperGrids **(Figure 11)**. ZEPPs and SuperGrids can multiply the power of the system by 5 or 10 times while also shrinking it in a revolutionary way. Engineers in practice and training today will bring these machines to beautiful fruition and earn future Millennium Technology Prizes.

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