Big Ways to Decarbonize the Energy System

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Introduction

Thanks very much to Tom Overbye and his colleagues here at the University of Illinois for hosting the 2nd conference on the Continental Supergrid. I hope many of you will attend the meeting the next 3 days. The Supergrid is a full employment program for energy engineers and will make a lot of people deservedly rich and famous. I hope some people in this room are among them.

While my subject is energy, I will begin with computing. Urbana won worldwide fame in the 1990s for its supercomputers and web browsers. The Internet reminds us that to become larger systems must become smaller. The Internet is a triumph 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 about 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.

Decarbonization

Before outlining ZEPPs and the Supergrid I need to introduce decarbonization, the essential trend which, along with scalability, defines the evolutionary fitness of ZEPPs and the Supergrid.

About 750,000 years ago some of our ancestors made a wood fire in a cave in the south of France near Marseilles. From such early fires until about the year 1800 energy supply changed little. The system relied on carbon, like a backwoods blackpot still in Southern Illnois, say in Carbondale.

The most important and surprising fact to emerge from energy studies during the past two decades is that, for the last 200 years, the world has progressively pursued a path of decarbonization, a decreasing relative reliance on carbon [**Figure 3**]. Think of decarbonization as the course over time in the ratio of tons of carbon in the energy supply to the total energy supply, for example, tons of carbon per tons of oil equivalent encompassing all energy supplies.

Alternately, think *hydro*carbons. Both hydrogen and carbon burn to release heat, so we can consider decarbonization as the ratio of hydrogen and carbon in our energy mash. When the energy system relied on hay and wood, it relied most heavily on carbon. Wood is made of much cellulose and some lignin. Heated cellulose leaves charcoal, almost pure carbon. Lignin is a hydrocarbon with a complex benzenic structure. Wood effectively burns about ten carbon for each hydrogen atom. Coal approaches parity with one or two C's per H, depending on the variety **[Figure 4]**. Oils are lighter yet, with, for example, with two H per C, as in kerosene or jet fuel. A molecule of methane, the typical natural gas, is a carbon-trim CH_4.

Thus, the inverse of decarbonization is the ascendancy of hydrogen [**Figure 5**]. Think of hydrogen and carbon competing for market niche as did horses and automobiles, or audio cassettes and compact discs, except the H/C competition extends over 300 years. In 1800 carbon had 90% of the market. In 1935 the elements tied. With business continuing dynamic as usual, hydrogen will garner 90% of the market around 2100.

Because carbon becomes soot or the feared greenhouse gas CO_2, and hydrogen becomes only water when combusted, carbon appears a bad element, the black hat, and hydrogen a good one, the white hat. So, decarbonization is not only a fact but a happy fact.

Let me explain the course of decarbonization. Neither Thomas Jefferson nor Queen Victoria decreed it. Why then does decarbonization happen? The driving force in evolution of the energy system is the increasing spatial density of energy consumption at the level of the end user.

By 1800 or so, in England and other early loci of industry, high population density and the slow but steady increase in energy use per capita increased the density of energy consumption. The British experience demonstrates that, when energy consumption per unit of area rises, the energy sources with higher economies of scale gain an advantage. Eventually, higher density of energy consumption at the level of the end user favors the primary fuels with higher energy density themselves. [**Figure 6**]

Wood and hay, the prevalent energy sources at the start of the 19th century, are bulky and awkward to transport and store. Consider the outcome if every Lake Shore Drive resident needed to keep both a cord of wood on her floor for heat and a pile of hay in the garage for the SUV. Think of retailing these goods in the costly real estate of Chicago. Sales of fuel wood in cities now are, of course, limited to decorative logs providing emotional warmth. Biomass gradually lost the competition with coal to fuel London and other multiplying and concentrating populations, even when wood was abundant.

Coal had a long run at the top of the energy heap. It ruled notwithstanding its devastating effects on miners' lungs and lives, the urban air, and the land from which it came; but about 1900, the advantages of an energy system of fluids rather than solids began to become evident. On the privacy of its rails, a locomotive could pull a coal car of equal size to fuel it. Coal-powered automobiles, however, never had much appeal. The weight and volume of the fuel were hard problems, especially for a highly distributed transport system. Oil had a higher energy density than coal—and the advantage of flowing through pipelines and into tanks. Systems of tubes and cans can deliver carefully regulated quantities of fuel from the scale of the engine of a motor car to that of the Alaska pipeline. It is easy to understand why oil defeated coal by 1950 as the world's leading energy source.

Yet, despite many improvements from wellhead to gasoline pump, distribution of oil is still clumsy. Fundamentally, oil is stored in a system of metal cans of all sizes. One famous can was the Exxon Valdez. Transfer between cans is imperfect, which brings out a fundamental point. The strongly preferred configuration for very dense spatial consumption of energy is a grid that can be fed and bled continuously at variable rates. There are two successful grids, gas and electricity.

Natural gas is distributed through an inconspicuous, pervasive, and efficient system of pipes. Its capillaries reach right to the kitchen. It provides an excellent hierarchy of storage, remaining safe in geological formations until shortly before use. Natural gas can be easily and highly purified, permitting complete combustion.

Electricity, which must be made from primary energy sources such as coal and gas, is both a substitute for these (as in space heating) and a unique way to power devices that exist only because electricity became widely available. Electricity is an even cleaner energy carrier than natural gas and can be switched on and off with little effort and great effect. Electricity, however, continues to suffer a disadvantage: it cannot be stored efficiently, as today's meager batteries show. Electrical losses also occur in transmission; with the present infrastructure, a distance of 100 km is normal for transmission, and about 1,000 km is the economic limit. Moreover, because of its limited storage, electricity is not good for dispersed uses, such as cars.

Nevertheless, the share of primary energy used to make electricity has grown steadily in all countries over the past 75 years and now approaches 40%. The Internet economy demands further electrification, with perfect reliability. Thus, the core energy game for the next 30 to 50 years is to expand and flawlessly operate the gas–electric system.

In contrast to what many believe, the stable dynamics of the energy system permit reliable forecasts. Decarbonization essentially defines the future of energy supply.

For methane, it is midmorning, and the next decades will bring enormous growth, matching rising estimates of the gas resource base, which have more than doubled over the past 20 years. Preaching the advent of the Methane Age 20 years ago I felt myself a daring prophet but now this prophecy is like invoking the sunrise. Between its uses to fuel turbines to make electric power and for fuel cells for transport, gas will dominate the primary energy picture for the next five or six decades. I expect methane to provide perhaps 70% of primary energy soon after the year 2030 and to reach a peak absolute use in 2060 of about 30×10^{12} m^3, ten times present annual use, meaning 4% per year growth.

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?

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. 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. Let me try to leave ZEPPs indelibly in your minds.

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. For many technologies, a tenfold larger scale shrinks units costs by two-thirds. As we have seen, methane tops the hydrocarbon fuels in heat value measured in joules per kilogram and thus lends itself to scaling up.

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 **(Figure 7**). 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 8** 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. Obviously we need to get some of the potential fizz out of the system at certain points. 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 9)**.

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 10)**. 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 11)**. 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 12)** 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. 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 13)**. 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, even if they appear consistent with the arrow of the compass of decarbonization.

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 14)**.

ZEPPs and SuperGrids can multiply the power of the system by 5 or 10 times while also shrinking it in a revolutionary way.

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