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The Heart of Energy Evolution

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Five thousand years ago the Chinese recorded in the *The I Ching* that perseverance brings good fortune. It still does. The perseverance of the nuclear industry the past few decades creates the conditions for immense growth of nuclear energy in our new century. The cause of my confidence comes from the heart of energy evolution.

Decarbonization

The central measure of energy evolution is **decarbonization**. Consider our hydrocarbon fuels as blends of carbon and hydrogen, both of which burn to release energy. Molecules of the main so-called fossil fuels, coal, oil, and natural gas, each have a typical ratio of carbon to hydrogen atoms (Figure 1). A good coal's ratio of C:H is about 2 to 1, an oil such as kerosene is 1 to 2, and methane, CH_4, is obviously 1 to 4. Other elements, such as sulfur and mercury, contaminate the real resources, especially coal and oil, but let us focus on the fuel elements. Importantly, wood has an even more primitive C:H ratio, 10:1.[i] Carbon of course is the element that blackens miners' lungs, endangers urban air, and threatens climate change. Hydrogen is as innocent as an element can be, ending combustion as water.

Suppose we placed all the hydrocarbon fuels humanity used each year since about 1800, when British colliers first mined thousands of tons of coal, in a blender, mixed them, and plotted the yearly ratio of carbon to hydrogen (Figure 2). While the trend may waver for a decade or two, over the long term H gains in the mix at the expense of C. The consequent decarbonization is the single most important fact from 25 years of energy studies, the heart of our learning. When my colleagues Cesare Marchetti, Nebojsa Nakicenovic, Arnulf Grubler, and I discovered decarbonization in the 1980s, we were pleasantly surprised. When we first spoke of it, many disbelieved and some ridiculed the word. Now prime ministers and presidents speak of decarbonization. Neither Queen Victoria nor Abraham Lincoln decreed a policy of decarbonization. Yet, the energy system pursued it. Human societies had been pursuing decarbonization for 170+ years before anyone noticed.

Consistently, if world economic production or all energy rather than all hydrocarbons form the denominator, the world is also decarbonizing (Figure 3). Moreover, China and India as well as France and Japan decarbonize. Economically and technically, carbon seems fated to fade gradually over this century. By 2100 we will feel nostalgia for carbon as some do now for steam locomotives. Londoners have mythologized their great fogs, induced by coal as late as the 1950s, and Berliners already reminisce about the "East Smell" of burnt lignite whose use collapsed after the fall of The Wall in 1989.

The explanation for the persistence of decarbonization is simple and profound, characteristics that help account for its extraordinary persistence. The overall evolution of the energy system is driven by the increasing spatial density of energy consumption at the level of the end user, that is, the energy consumed per square meter, for example, in a city. Finally, fuels must conform to what the end user will accept, and constraints become more stringent as spatial density of consumption rises. Rich, dense cities accept happily only electricity and gases, now methane and later hydrogen. These are the fuels that reach consumers easily through pervasive infrastructure grids, right to the burner tip in your kitchen.

A few decades ago, some visionaries dreamed of an all-electric society. Today people convert about 35-40% of all primary fuel to electricity. The fraction will rise, but now even electricity enthusiasts (as I am) accept that finally not much more than ½ of all energy is likely to be electrified. Reasons include the impracticality of a generating system geared entirely to the instant consumption of energy and lack of amenability of many vehicles to reliance on electricity.

So, ultimately the behavior of the end user drives the system. Herein lies the problem with wood, coal and other competitors: if New Orleaners tried to run their present city with wood, the problems of transport and storage would become enormous. Imagine the woodpile to run the steam engines to provide the power to cool the Superdome. Going a step further, if the product coming out of the burner tip in celebrity chef Emeril Lagasse's restaurant kitchen is methane, it is much easier to begin with methane than to begin with coal and gasify it.

When the end user wants electricity and hydrogen, over time the primary energy sources that can produce on the needed scale while meeting the ever more stringent constraints that attend growth in turn will win. Economies of scale are a juggernaut over the long run. Think, for better or worse, of Walmart.

Appropriately, the historical growth of world primary energy consumption over the past 150 years shows rises in long waves of 50-60 years, each time formed around the development of a more desirable source of energy that scaled up readily. Coal lifted the first wave and oil the second. A new growth wave is underway, lifted by methane, now almost everyone's favorite fuel.

Note that the popular specter of *resource exhaustion* played little or no role in the long-run evolution of the system. Plenty of wood and hay remained to be exploited when the world shifted to coal. Coal abounded when oil rose. Oil abounds now as methane rises. Advocates of nuclear energy and so-called renewables foolishly point to depletion of oil and natural gas as reasons for their own fuels to win. Oil and natural gas use may peak in coming decades but not because Earth is running out of them.

Appreciate also that action to minimize possible climate change does not *cause* the decarbonization. Minimizing human-induced climate change may *appear* as the reason, but philosophers who study causation would find it odd to attribute decarbonization to a phenomenon that followed it by a couple of centuries, assuming such climate change is now underway. Indeed, decarbonization began a century before Swedish meteorologist Gustav Arrhenius published the first paper about carbon dioxide and global warming in 1894. Canonically, cause precedes effect. The present anxiety about global warming cannot be a cause but only an *ex post* rationalization for long-time decarbonization. More sympathetically, global warming might be viewed as the popular current emblem for the set of challenges associated with increasing spatial density of energy consumption.

If business continues as usual, by 2020 the reference point for the world's energy will be CH_4, methane, as Figure 2 indicates. Still, energy's evolution should not end with methane. The completion of decarbonization ultimately depends on the production and use of pure hydrogen. 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 US production, which is about 1/3 of the world, multiplied tenfold between 1970 and 2000 (Figure 4). Over 10,000 miles (16,000 kilometers) of pipeline transport H_2 gas for big users, with pipes at 100 atmospheres as long as 250 miles (400 kilometers) from Antwerp to Normandy. High pressure containers such as tube trailers distribute the liquid product to small and moderate users throughout the world.

The catch is that the present hydrogen comes from cooking hydrocarbons. About 85% comes from steam reforming of methane and the rest from oil residues or coal gasification. 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 in decarbonization, large-scale production of carbon-free hydrogen should begin about the year 2020. So how will we begin introducing more H_2 into the system to lift the average above the norm of methane? The obvious competitors are nuclear and the so-called renewables, the false and minor, yet popular, idols.

The false and minor idols

Let's consider the renewable idols. In the 21 years from 1979 to 2000 the percentage of US energy from renewables actually fell from 8.5% to 7.3%. In the US renewables really mean dammed rivers. Almost 80% of so-called US renewable energy is hydro, but the trend has already shifted from dam building to dam removal for ecological and other reasons. The World Commission on Dams issued a report in November 2000 that essentially signaled the end of hydropower development globally. While the Chinese are constructing a few more dams, few foresee even tens of thousands of megawatts of growth from hydropower. Though electricity and hydrogen from hydro would decarbonize, the idol of hydro is itself dammed.

In the US, after hydro's 80% comes biomass' 17% of renewables. Surprisingly, most of this biomass comes not from backyard woodsmen or community paper drives but from liquors in pulp mills burned to economize their own heat and power. In terms of decarbonization, biomass of course retrogresses, with 10 Cs or more per H.

If one argues that biomass is carbon-neutral because photosynthesis in plants recycles the carbon, one must consider its other attributes, beginning with productivity of photosynthesis. Although farmers usually express this productivity in tons per hectare (10,000 square meters or 2.5 acres) per year, in the energy industry the heat content of the trees, corn, and hay instead quantify the energy productivity of the land. For example, the abundant and untended New England forests produce firewood at the renewable rate of about 1200 watts (thermal) per hectare (0.12 watts per square meter) averaged around the year. Excellent management can multiply that figure ten times.

Imagine, as energy analyst Howard Hayden has suggested, farmers use ample water, fertilizer, and pesticides to achieve 12,000 watts thermal per hectare. Imagine replacing a 1,000 MWe nuclear power plant with a 90% capacity factor. During a year, the nuke will produce about 7.9 billion kWh. To obtain the same electricity from a power plant that burns biomass at 30% heat-to-electricity efficiency, farmers would need about 965 square miles (250,000 hectares or 2,500 square kilometers) of land with very high productivity. Harvesting and collecting the biomass are not 100% efficient; some gets left in fields or otherwise lost. If processors concentrate the corn or other biomass into alcohol or diesel, another step erodes efficiency. Such losses mean that in round numbers a 1,000 MWe nuclear plant equates to more than 1000 square miles of prime land. A typical Iowa county spans about 400 square miles. A nuclear power plant consumes about 25 acres (10 hectares) per unit or 100 acres (40 hectares) for a power park.

Note also that pumping water and making fertilizer and pesticides also consume energy. Shifting entirely from baconburgers to kilowatts, Iowa's 55,000 square miles might yield 50,000 MWe. The US already consumes about 10 and the world about 40 times the kilowatt hours that Iowa's biomass could generate. Prime land has better uses, like feeding the hungry, while plowing marginal lands will require ten or twenty times the expanse and increase erosion. Here the lack of economies of scale loom again. Because more biomass quickly hits the ceiling of watts per square meter, it can become more extensive but not cheaper. If not false, the idol of biomass is not sustainable on the scale needed and will not contribute to decarbonization.

Although or because wind provides only 0.2% of US electricity, the idol of wind evokes much worship. The basic fact of wind is that it provides about 1.2 watts per square meter or 12kW per hectare, or 5000 watts per acre of year round average electric power. So, 100 windy square meters, a good size for a Manhattan apartment, can power one lamp, but not the computers, tv, microwave oven, clothes dryer or dozens of other devices in the apartment, or the apartments above or below it.

One problem is that two of the four wind speed regimes produce no power at all. Calm air means no power of course, and gales faster than 25 meters per second (about 55 miles per hour) mean shutting down lest the turbine blow apart. Heyden considers the $212 million wind farm 20 miles south of Lamar, CO, where 108 1.5 MWe wind turbines stand 262 ft tall, their blades sweeping to 377 ft. The wind farm spreads over 11,840 acres (4,800 hectares). At 30% capacity, peak power density is 4100 watts per acre. More compact than biomass, a wind farm occupying 300 square miles could produce as much energy as one 1,000 MWe nuke. To meet 2002 US electricity demand of 4 million MWhr with around-the-clock-wind would require wind farms covering over 300,000 square miles (780,000 square kilometers), about Texas plus Louisiana. Rapidly exhausted economies of scale stop wind. The idol of wind would decarbonize but will be minor.

Although negligible as a source of electric power today, photovoltaics also earn a traditional bow. Sadly, PVs remain stuck at about 10% efficiency, with no breakthroughs in 30 years. Today performance reaches about 5-6 watts per square meter. But no economies of scale inhere in PV systems. A 1,000 MWe PV plant would require about 60 square miles (150 square kilometers) plus land for storage and retrieval. Present US electric consumption would require 150,000 square kilometers or a square more than 240 miles on each side. The PV industry now makes about 600 meters by 600 meters per year. About 600,000 times this amount would be needed to replace the 1,000 MWe plant, but only a few square kilometers have ever been manufactured in total.

Viewed another way, to produce with solar cells the amount of energy generated in one liter of the core of a nuclear reactor requires 2.5 acres (one hectare) of solar cells. To compete at making the millions of megawatts for the baseload of the world energy market, the cost and complication of solar collectors still need to shrink by orders of magnitude while efficiency soars.

Extrapolating the progress (or lack) in recent decades does not carry the solar and renewable system to market victory. Electrical batteries, crucial to many applications, weigh almost zero in the global energy market. Similarly, solar and renewable energy may attain marvelous niches, but seem puny for providing the base power for 8-10 billion people later this century.

In truth, solar and renewables, despite their sacrosanct status, are also dirty. The appropriate description for PVs comes from the song of the Rolling Stones, "Paint It Black." Painting large areas with efficient, thus black absorbers evokes dark 19th century visions of the land. I prefer colorful desert to a 150,000 km^2 painted black. Some of the efficient PVs contain nasty elements, such as cadmium. Wind farms irritate with low-frequency noise and thumps, blight landscapes, interfere with TV reception, and chop birds and bats. At the Altamont windfarm in California, the mills kill 40-60 golden eagles per year. Dams kill rivers. Windfarms, solar arrays, and biomass all gobble land from nature.

Moreover, solar and renewables in every form require large and complex machinery to produce many megawatts. Berkeley engineer Per Petersen reports that for an average MWe a typical wind-energy system operating with a 6.5 meters-per-second average wind speed requires construction inputs of 460 metric tons of steel and 870 cubic meters of concrete. For comparison, the construction of existing 1970-vintage US nuclear power plants required 40 metric tons of steel and 190 cubic meters of concrete per average megawatt of electricity generating capacity.

Bridging the cloudy and dark as well as calm and gusty weather takes storage batteries (and their heavy metals). Without vastly improved storage, the windmills and PVs are supernumeraries for the coal, methane, and uranium plants that operate reliably round the clock day after day. Since 1980 the US DOE alone has spent about $6 billion on solar, $2 billion on geothermal, $1 billion on wind, and $3 billion on other renewables. The nonhydro renewable energy remains about 2% of US capacity, much of that the wood byproducts used to fuel the wood products industry noted above. Cheerful self-delusion about new solar and renewables since 1970 has yet to produce a single quad of the more than 90 quadrillion Btu of the total energy the US now yearly consumes.

Recognizing the challenges of solar and renewables, some stress that energy conservation and efficiency will negate the need for new and larger supply. These offset but do not eliminate demand growth. Energy use will keep rising. One reason is that computer chips could well go into 1000 objects per capita, or 10 trillion objects worldwide, as China and India log into the game. Consumers who have filled their homes with cable modems, wifi, and set-top boxes have noticed more kilowatts on their monthly bills even if they purchased a more efficient refrigerator. Anyone who has visited Shanghai or Bangalore knows the spatial density of energy consumption is zooming to new heights. The feasible increments of solar and renewable megawatts finally look puny in a 20 or 50 million megawatt world, and even in today's 10 million megawatt world. Let's stop sanctifying false and minor gods.

Nuclear

How then can we meet more stringent consumer demands and stay on course for decarbonization? The inevitable reply is nuclear energy. I should mention that I am not naïve about nuclear. Privileged to work with Soviet colleagues who participated in the Chernobyl clean-up, I saw the Dead Zone in 1990 with my own eyes. In Figure 5 I stand in front of the concrete sarcophagus encasing the blasted reactor with employees of the site management enterprise and the contaminated car of then Soviet prime minister Ryshkov.[ii] But I trust the members of the Nuclear Energy Assembly know more than I about safety, waste disposal, and proliferation. I need not echo the litany.

Rather, recalling the decarbonization of Figure 2, I suggest you observe what people do rather than what they say. As of 31 January 2004 440 reactors were operating with a capacity of 362,000 MWe. Defying those who forecast frequent Chernobyls, the managers of the plants have achieved about 8,000 reactors-years of operation since Chernobyl without a serious accident. In 2003 China and Korea connected new plants to the grid and Canada reconnected a couple of plants, netting an increase of about 2,000 MWe. For all the arm-waving, new wind farms added fewer kilowatts to the world energy system than nuclear added in 2002 plus 2003. China plans to open three nuclear plants in 2005, and more than 30 plants are under construction around the world. Vietnam, with 80 million people, has nuclear plans. Even in Europe, observe what people do and not what they say. Finland is building a new unit. Although Italians say they have not built nuclear plants, five French nuclear plants essentially export electricity to Italy. While Italians use nuclear power; they cleverly get the French to build and operate the plants. Keep your eye on what people do and pay much less attention to what they say.

Turning to the US, as statistics reported on the Nuclear Energy Institute site show, year after year nuclear plants have been performing at record levels. Nuclear's share of electric power soared from 4.5% in 1973 to 10% in 1979, the year of Three Mile Island, to above 20% in 2002. Absolute output grew from 628,000 MWe in 1997 to 780,000 MWe in 2002, almost 5% per year. 88% of the 1,100 MWe Seabrook plant sold in 2003 for $837 million. Many US plants are printing money because they work efficiently, are almost fully depreciated, and face ample demand for electricity. To my eyes, the industry is doing well, notwithstanding what many newspapers might make their readers think. Recent applications to the Nuclear Regulatory Commission starting the licensing process hint the US will soon build more nukes, too. Big additions to electric capacity are just returning to fashion, after the experience of shortages in California and concerns about reliability.

Nuclear needs to tell its true, impressive story. A 1,000 MWe light water reactor that produces energy for one million typical homes produces approximately 1080 kg of fission products per year, 4 milligrams per person. The 300 people who attended the Nuclear Energy Assembly would produce annually high-level radioactive waste equal to about a small jar of aspirin tablets. Over 500 years, in a fully nuclear world the high level radioactive wastes might amount to 700,000 million tones, less than the 800 million tons of coal Americans burn in one year to produce 1/2 our electricity. Hayden calculates all the reactors from 500 years of production of 100% of the world's energy could be stacked one high in an area of a little over 100 square miles, about the land area for a solar farm to provide 1,000 MW of power. I recur to scale. Nuclear energy is compact enough to grow.

A methane nuclear alliance

Importantly, it will be under the wing of methane that nuclear grows again. The biggest fact of the energy system over the next twenty-thirty years will be massive expansion of the gas system, methane for the present. Many people may feel more comfortable with the addition of nuclear power plants if they know that methane, a very attractive fuel in many ways, is taking the overall energy lead. Anyway, to stay on track in decarbonization, methane must prevail.

Our fundamental question then becomes, from where will the hydrogen come? Methane and water will compete to provide the hydrogen feedstock, while methane and nuclear will compete to provide the energy needed to transform the feedstock.

Steam reforming of methane to produce hydrogen is already a venerable chemical process. Because methane abounds, in the near term steam reforming of methane, using heat from methane, will remain the preferred way to produce hydrogen. Moreover, because much of the demand for hydrogen is within the petrochemical industry, nepotism gives methane an edge. Increasingly, as new applications such as fuel cells demand hydrogen, nuclear's chance to compete as the transformer improves.

Over the long term, the production of hydrogen will revolutionize the economics of nuclear power, much more than standardizing plants or building plants quicker. First, hydrogen manufacture allows nukes to address the half of energy demand that will not be electricity. Second, it gives nuclear power plants the chance to make valuable product 24 hours per day. Recall that a great problem the electric power industry faces is that, notwithstanding the talk of the "24/7 society," electric power demand remains asymmetrical. Users demand most electricity during the day. So, immense capital sits on its hands between about 9 o'clock at night and 6 or 7 o'clock in the morning. Turning that capital into an asset is incredibly valuable. Like the hotel and airline industries, the power industry would rather operate at 90% capacity than 60% capacity. The nuclear industry is limited to providing baseload electric power unless it reaches out to hydrogen to store and distribute its tireless energy.

While I stated just above that methane and nuclear compete, they can also cooperate in the hydrogen market. Let's accept that in the near term steam reforming of methane will dominate hydrogen making. Nuclear power as well as methane can provide the energy for the reforming. Here let me share a big technological idea, **methane-nuclear-hydrogen (MNH) complexes**, first sketched by Cesare Marchetti. An enormous amount of methane travels through a few giant pipeline clusters, for example, from Russia through Slovakia. These methane trunk routes are attractive places to assemble MNH industrial complexes. Here, if one builds a few nuclear power plants and siphons off some of the methane, the nuclear plants could profitably manufacture large amounts of hydrogen that could be re-introduced into the pipelines, say up to 20% of the composition of the gas. This decarbonization enhances the value of the gas. Meanwhile, the carbon separated from the methane becomes CO_2 to be injected into depleted oil and gas fields and profitably help with tertiary recovery. The hydrogen mixture could be distributed around Europe, or the world, getting users accustomed to the new level of decarbonization.

Over the next 10-15 years, I will keep my eye on the places where much gas flows and see whether these regions initiate this next generation energy system. The experience of working with hydrogen will benefit the nuclear industry as it put nukes at the nodes of the webs of hydrogen distribution, anticipating the shift from CH_4 to H_20 as a feedstock. In summary, the methane-nuclear-hydrogen complexes can be the nurseries for the next generation of the energy system.

The Continental SuperGrid

The surprising longevity of nuclear power plants, observed by Alvin Weinberg, spurs us to look beyond the imminent methane era to complete decarbonization. Nuclear energy's long-range potential is unique as an abundant, scalable source of electricity for electrolysis and high-temperature heat for water splitting while the cities sleep. A 2003 Electric Power Research Institute report about the virtues of thermochemical and electrolytic pathways to make hydrogen is resuscitating needed technical debate about water splitting. At about 950°C core outlet temperature, a high temperature reactor could successfully drive, for example, a sulfur-iodine thermochemical process. The right catalysts will be key to economical success for the thermochemical path.

The thermochemical processes in the long run may have more promise than electrolysis for producing hydrogen because of the large plant areas required for electrolysis, especially if the plants have very low power density, like photovoltaics. The power density of the machinery and thus the space required for a plant makes the use of electrolysis for large-scale production of hydrogen problematic. Economies of scale again. Thermochemically, nuclear plants could nightly make H_2 on the scale needed to meet the demand of billions of consumers. Hydrogen production can draw the nuclear industry to a scale of operation an order of magnitude larger than today, meeting future demand for hydrogen and electricity in immense dense cities.

Here let me introduce a second, even bigger technological concept, the **continental SuperGrid** to deliver electricity and hydrogen in an integrated energy pipeline. Championed by Chauncey Starr of EPRI, the Supergrid is doubly super: first because it is the apex, like the Superbowl, and second because it employs superconductivity. Specifically, the SuperGrid would use a high-capacity, superconducting power transmission cable cooled with liquid hydrogen produced by advanced nuclear plants.

The fundamental design, vetted at the first Supergrid conference in the fall of 2002, is for liquid hydrogen to be pumped through the center of an evacuated energy pipe (Figure 6). Thus, 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.

By continental, I mean coast-to-coast, indeed all of North America, making one market for electricity. SuperGrids should thrive on other continents, of course, but as an American I hope North America builds first and dominates the market for these systems, which in rough terms might cost \$1 trillion, or \$10 billion per year for 100 years. The continental scale makes the electric power system much more efficient by flattening the electricity load curve which still follows the sun. Superconductivity solves the problem of power line losses. 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 nearing many of North America's large cities. Power converters would connect the direct current SuperGrid at various points to existing, high-voltage alternating current transmission substations.

In its early realization some forty 100-km long sections of the joint cable/pipeline might be joined by nuclear plants of several thousand MW supplying to the SuperGrid both electricity and hydrogen. High-temperature reactors with coated-particle or graphite-matrix fuels promise a particularly high-efficiency and **scalable** route to combined power and hydrogen production. Nuclear power fits with the SuperGrid because of its low cost of fuel/kwhr and its operational reliability at a constant power level. The latent hydrogen storage capacity of the SuperGrid, combined with fuel cells, 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. Tunneling in coal mines may have no future but tunneling for utilities and trains does. 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. Department of Energy laboratories including Fermi have profound experience with tunneling from building particle colliders. Since 1958 Russia has operated underground nuclear reactors near Zheleznogorsk in Central Siberia. Wes Myers and Ned Elkins of Los

Alamos National Lab have suggested that the region near Carlsbad, New Mexico, which has enormous caverns from potash mining, and thus a rail and highway system, water supply network, and electrical power distribution might be well-suited for the first US underground nuclear park. 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 Atlantic to Pacific in 1 hour. I am now looking ahead 100 years, but that is our time frame for complete decarbonization, and let's recall that 101 years ago on December 17 1903 in Kitty Hawk 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. Thomas Overbye of the University of Illinois, Paul Grant of EPRI, and I are organizing the Supergrid II conference 25-27 October at the U. of Illinois. The long road to the continental SuperGrid begins with the first 10 to 20 km segment addressing an actual transmission bottleneck, and Nuclear Energy Institute members should commit now to help build it.

Coal's exit

Having inspired you, I hope, with vision, let me add the incentive of what we might overcome. Examining US electricity generation, we find that in the early 1970s methane was poised to take off and become the lead fuel. Several members of the Nixon and Carter administrations, in cahoots with leaders of firms in the coal industry and their friends in the Congress, stymied the progress of gas. We know during the last decade that almost all orders for new power plants were gas, and that gas will become dominant in the next 10-20 years. In the end, the system wins, decarbonization happens. But the US wasted 25 years, and incurred lots of unnecessary worries, such as rising greenhouse gas emissions, by protecting old king coal with rules that allow antiquated plants to burn on and on. The US wasted a quarter of a century it could have spent learning to use the system of the future.

Learning typifies technological evolution. Industries such as the chemical and airframe industries use learning curves. They plot the cost evolution of a manufacturing operation against time, or better, of the total integral amount of the goods manufactured in that industry sector. A famous example of learning is the computer chip industry. Since the late 1980s, the semiconductor manufacturers have introduced one generation after another of chip at lower initial cost and chopped the price for each chip over its lifetime. The rate of price reduction per doubling of cumulative sale averages about 28%. While the measures in the nuclear power industry are less sure and generations less quick, we calculated an impressive learning rate between 1984-1999 when comparing uranium inventories per Kw generated versus cumulative electricity generation from nuclear (Figure 7). Natural gas has sustained a rate of 8% since 1970 (Figure 8), and ZEPPs open the way for more decades of learning.

Contrast the chip, nuke, and gas industries with the record of the coal industry since 1920 (Figure 9). Give coal its due. Between 1920-1970 the coal industry did manage to extract more energy from each kilogram of coal it burned, averaging a learning rate 8-15%. Not bad. However, since 1970, the performance of the coal industry by this measure has worsened, a negative 4.2. Some blame the worsening on costs associated with controlling emissions of sulfur and other pollutants. Yet, most industries have met environmental goals AND lowered costs as they gain experience.

The reality is coal simply does not fit the ever higher spatial density of energy consumption. Blame it on the need for massive rail networks to move the coal around. Or focus on wastes and take your pick of elemental reasons, sulfur, nitrogen, mercury, or carbon. An American now yearly emits about 5 tons of carbon per year or 14 kg per day, while with uranium we deal in grams per capita per year. Globally we produce already about 15 cubic kilometers of carbon waste, quite a brick. Nuclear wastes are measured in liters. Scaling up coal causes environmental nightmares. Numerous utilities employ both nuclear and coal. Managers, seeing decarbonization, should also see they have lucratively ridden the old gray nag as far as she can go. Now put coal gently out to pasture.

Conclusion

Let me return to the heart of energy evolution, decarbonization. Because hydrogen is much better stuff for burning than carbon, the hydrocarbons form a clear hierarchy (Figure 10). Methane tops the ranking, with an energy density of about 55 megajoules per kilo, about twice that of black coal and three times that of wood.

But, I am old enough to have been impressed by schoolbooks of the 1960s that asserted that the splitting and fusing of atoms was a giant step, akin to harnessing fire and starting to farm. A postcard (Figure 11) from my first visit to Oak Ridge helps recall that atomic spirit, naïve in some ways but also reflecting a deep, abiding truth.

The energy density of nuclear fuel is 10,000 or even 100,000 times as great as methane (Figure 12). The dense heart of the atom, the nucleus, has much to offer. The extraordinary energy density of nuclear fuel allows compact systems of immense scale, and finally suits the ever higher spatial density of energy consumption at the level of the end user, logically matching energy consumption and production.

During the past 100 years motors have grown from 10 kilowatts to more than 1,000 megawatts, scaling up an astonishing 100,000 times, while shrinking sharply in size and cost per kilowatt. 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 to make the electricity and hydrogen from the 13,000,000 MW years in 2002 to 50,000,000 in 2100. Modestly, we may expect that the most powerful machines in the energy system will grow 5 to 10 times. 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.

Readers might well wonder from this essay whether they need DO anything. In Figure 2 history appears automatic. At one level this is true. Yet, we also know that the trend of decarbonization is the outcome of all the blood, sweat, and tears of persistent workers, engineers, managers, investors, regulators, and consumers. If people stop bleeding, sweating, and crying, the game producing decarbonization could just stop. As players, it is good to be on the side of growth, and the nuclear industry is. The sweat in doing nuclear right will be rewarded. The policy prescriptions are clear: allow coal to fade gracefully, fight for a growing market share of electric power, ally with methane in producing hydrogen from methane, and begin to make hydrogen from water. Generate electricity by day and hydrogen at night. Start the Continental Supergrid. In short, decarbonize. Looking forward, we recognize nuclear as the heart of energy evolution. Keep it beating**.**

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Figure captions

Figure 1: Molecular models of coal, oil, and gas showing C:H ratios

Figure 2: Decarbonization as the evolving C:H ratio. The evolution is seen in the ratio of hydrogen (H) to carbon (C) in the world fuel mix, graphed on a logarithmic scale, analyzed as a logistic growth process and plotted in the linear transform of the logistic (S) curve. Although data begin in 1860, the process inevitably began with the rise of coal mining in the late 18th century in Britain, when wood and hay began to lose market share. Progression of the ratio above natural gas (methane, CH_4) requires production of large amounts of hydrogen fuel with non-fossil energy.

Figure 3: Decarbonization as falling global carbon intensity of total world primary energy

Source: N. M. Victor and J. H. Ausubel

Data sources: IIASA, BP (1965-2001), CDIAC, http://cdiac.esd.ornl.gov/trends/emis/em_cont.htm

Figure 4: USA hydrogen shipments growth to 2000

Data source: Dale Simbeck/SFA Pacific.

Figure 5: In front of the Chernobyl sarcophagus, 1990

The author is third from right wearing a beret.

Figure 6: Supergrid energy pipe for electricity and hydrogen

Source: http://www.epri.com/journal/details.asp?id=511&doctype=features

Figure 7: Learning curve in US nuclear power plant material usage

Source: N. M. Victor and J. H. Ausubel

Figure 8: Learning curve for gas consumed at US electric utilities

Source: N. M. Victor and J. H. Ausubel

Figure 9: Learning curve for coal consumed at US electric utilities

Source: N. M. Victor and J. H. Ausubel

Figure 10: Energy density ranking of hydrocarbon fuels

Source: N. M. Victor and J. H. Ausubel

Figure 11: Postcard from circa 1960 of Oak Ridge American Museum of Atomic Energy

Published by Southern Post Card Company, 501 N Main St, Goodlettsville, TN 37072-1580, 615-859-4121.

Figure 12: Energy density of nuclear and hydrocarbon fuels

Source: N. M. Victor and J. H. Ausubel

[i] To choose an appropriate hydrogen-carbon ratio for wood considered as an energy source, recognize first that wood is made of cellulose and lignin. The mix varies among woods but in bounds. Most wood is cellulose. Cellulose is a carbo-HYDRATE. Carbohydrates can be represented as CH_2O or H-COH. By simple heating, the weak bond of H<>OH breaks, reforming water. The key is that: cellulose + O_2 > CO_2 + water initially present as H_2O or H-HO. There is no $O_2 + 2H_2$ process. This view is supported intuitively by the fact that in heating cellulose H_2O leaves as H_2O and what remains is charcoal, almost pure carbon, which approaches a zero H:C ratio.

So, the H:C ratio for wood depends on lignin, which has a complex benzenic structure. As a frame of reference, take woods as 80% cellulose and 20% lignin, means of means. Observing the rough formulas of lignin [e.g., C(10)H(13)O(4)], we must take away the H_2O also from it. This leaves an H:C ratio about 0.5. Combining the pure carbon of cellulose and the 0.5 ratio of lignin, wood with 20% lignin effectively has an H:C ratio of 0.1.

Of course, telling what actually burns is hard. The heat of combustion from burning a complex molecule comes from all its component atoms. Because of energetic links inside the molecules, attributing, in terms of shares, the heat of combustion to each component is difficult. And, we can visualize HCOH as H_2-CO or H_2O-C. Chlorophyll basically decomposes water into H_2 and ½ O_2. H_2 is used to reduce CO_2 to formaldehyde. The pundits of photosynthesis might be able to use isotopes to trace the reactions exactly. This would be fun, but is probably splitting hairs.

Alternatively, corroboration might come from the energy balance of charcoal production. Charcoal was (is) used because it is much lighter than wood, while retaining most of the heat value. It has the minimum of imbibed H_2O, within the molecules or on the loose, so to speak. The basic point is the 0.1 ratio is conceptually right, and does not claim excessive precision.

[ii] Arriving at the restricted zone a two-hour drive north of Kiev, my Soviet colleague and I were stopped by a road block and transferred into cars used only in the contaminated area. Surprisingly, we were given a large black limousine that we were told belonged to Prime Minister Ryzhkov. Several months before, Ryzhkov had driven from Moscow to tour the site and was reportedly not warned that once he drove around the site, his car would be contaminated and its use restricted to the site. So, the "Pripet Research Industrial Association" (PRIA), which managed the Chernobyl site, had one more property besides the sarcophagus.