Decarbonization: The Next 100 Years

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“When history looks at the 20th century," wrote Alvin Weinberg in an influential 1961 essay, "she will find in the monuments of Big Science--the huge rockets, the high energy accelerators, the high-flux research reactors--symbols of our time." In that essay, Alvin coined the term, "Big Science." Five years later Alvin introduced the term “technological fix” to describe engineering solutions for society’s grand challenges. Today I want to discuss with you decarbonization, a grand challenge requiring Big Science and a couple of big technological fixes, namely Zero Emission Power Plants and the Continental SuperGrid.

Introduction

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.

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 1]. 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 2]. 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 3]. 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 4]

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 high-rise 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 or New York. 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.

Globally we are destined to use about 50-80 billion tons more coal. This is about one-third what humans have mined in all our earlier history, and about 30 years at present levels of production, so all the participants in the coal industry have a generation or so in which to remodel themselves. We should squeeze the maximum electricity from the black rocks with the minimum fallout of nasties, but coal is not our primary concern because its use will fade anyway. In fact, coal companies would better concentrate on extracting methane from coal seams and sink CO_2 there, staying in business without coal extraction. Using CO_2 to displace methane (CH_4) adsorbed in coal beds provides a two for one bargain. Tunneling, as we shall see, matters immensely for future human well being, so the coal industry also has a valuable skill to sell.

If it is dusk for coal, it is mid-afternoon for oil, which already has lost in energy markets other than transport. Globally, drivers and others will consume close to 300 billion tons more oil, before the fleet runs entirely on hydrogen separated from methane or water. This amount is almost double the petroleum that has so far been extracted, and about 50 years at present production, so oil companies can choose to play business as usual for a while. But the entry under the car's hood of fuel cells or other motors fueled by hydrogen dooms oil, over the decades required for the turnover of the fleet, and makes a huge niche for the easy ways to make the needed hydrogen fuel.

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.

Through fuel cells we will adopt methane in transport as well as for electric power. Fuel cells, essentially continuous batteries, can be fed by hydrogen extracted from the methane. In replacing the internal combustion engine, they will multiply automotive efficiencies and slash pollutants. Wood and coal fogged and blackened cities, and oil gave us brown clouds of smog; methane can complete the clearing of the skies of Los Angeles, Sao Paolo, and other cities in the world, soon to come, of one billion motor vehicles. Governments will need to make it easier to build and access gas pipelines. Attention must also be given to the safety and environmental aspects of gas use because pipelines and tanks can explode tragically. Refiners need to shift their focus to transforming methane into hydrogen and CO_2.

Very Large ZEPPs

Now let me introduce a couple of big technological fixes, like Oak Ridge's K-25 and Y-12 separation plants. My first is zero emission electric power plants or ZEPPs, *very large* ZEPPs. The emission of concern is, of course, carbon, feared because of climate change. Although simply substituting methane for coal or oil reduces CO_2 emissions by a third to a half, the peak use would correspond to 2 to 3 times today's carbon emission to dispose annually. Even in 2020, we could already need to dispose carbon from natural gas alone equal to half today's emission from all fuel and later methane would 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. One reason is the information economy. Even with efficiency increasing, the information economy demands huge amounts of electricity. Observe the recent rapid growth of demand in a college dormitory. Chips could well go into 1000 objects per capita, or 10 trillion objects, as China and India log into the game.

Big total energy use means big 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. Although the last wave of power station construction reached about 1.5 gigawatts (GW), growth of electricity use for the next 50 years can reasonably raise plant size to about 5 GW. For reference, my city, New York, now draws above 12 GW on a peak summer day.

The fact that maximum power plant size has stagnated for a couple of decades should not mislead us. Like most systems, power plants grow in spurts, as seen in Figure 5 which shows the maximum size of US power plants over time. Each line represents an S-shaped (logistic) curve normalized to 100 percent, with estimates for the midpoint of the process and saturation level indicated. F represents the fraction of the process completed. So, the pulse centered in 1929 quickly expanded power plants from a few tens of megawatts (MW) to about 340. After a period in which plant size stagnated, the 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. Note the projection for another spurt in plant size centered around the year 2020, quadrupling the maximum again, to more than 5 GW.

Bigness is a plus for controlling emission. Although one big plant emits no more than many small plants, emission from one is easier to collect. Society cannot close the carbon cycle if we need to collect emissions from millions of microturbines.

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 6 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 such as ORNL to open a grand concourse of designs.

Fortunately for transmitting mechanical power, the high pressures shrink the machinery in a revolutionary way and so permits 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 we are thinking of the year 2020 and beyond.

The requisite oxygen for a 5 GW ZEPP also 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 50-55% peak performance of gas turbines today. [Figure 7]

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. The best way to sequester the emissions is in caverns underground, where coal, oil, and gas came from. 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. 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. Aquifers in silicate beds could be used to move the waste CO_2 to the silicates where “weathering" would make carbonates and silica, an offset good for millions of years.

In short, the ZEPP vision is a supercompact, superpowerful, superfast turbine: 1-2 m diameter, potentially 10 GW 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 500 5 GW 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 in America and its offshore exclusive economic zones. Research on ZEPPs could occupy legions of academic researchers, and restore an authentic mission to the Department of Energy’s National Laboratories, working on development in conjunction with private companies. ZEPPs need champions, and I hope ORNL will be one. ORNL's leaders should whip the imaginations of the 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.

The Continental SuperGrid

Still, energy’s history will not end with natural gas. The completion of decarbonization ultimately depends on the production and use of pure hydrogen. Environmentally, hydrogen is the immaterial material; 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. [may add Figure] 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. Over 10,000 miles of pipeline transport H_2 gas for big users, with pipes at 100 atmospheres as long as 250 miles 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.

Among the alternatives, including solar routes, nuclear energy fits the context best. 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. The energy density of nuclear fuel is 10,000 or even 100,000 times as great as natural gas. [Figure 8] While the world already worries about 15 cubic kilometers of carbon waste, nuclear wastes are measured in liters. 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.

America should persist in peacefully applying Albert Einstein's revolutionary equations. It seems reasonable, for the reasons Alvin Weinberg has patiently explained, that understanding how to use nuclear power, and its acceptance, will take a century and more. Still, fission is a contrived and extravagant way to boil water if steam is required only about half of each day to make electricity.

Nuclear energy's special potential is as an abundant source of electricity for electrolysis and high-temperature heat for water splitting while the cities sleep. Nuclear plants could nightly make H_2 on the scale needed to meet the demand of billions of consumers. Windmills and other solar technologies cannot power modern people by the billions. Reactors that produce hydrogen could be situated far from population concentrations and pipe their products to consumers. A new EPRI report about the virtues of thermochemical and electrolytic pathways is resuscitating needed technical debate about water splitting [add ref]. At about 950°C core outlet temperature, a high temperature reactor could successfully drive a sulfur-iodine thermo-chemical process.

Here let me introduce a second big technological fix, the continental SuperGrid to deliver electricity and hydrogen in an integrated energy pipeline. Championed by Chauncey Starr, Alvin's long-time friend, 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 is for liquid hydrogen to be pumped through the center of an evacuated energy pipe [Figure 9]. 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. Continental 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 allows much greater efficiency in the electric power system, flattening the electricity load curve which still follows the sun. Superconductivity solves the problem of power line losses. By high capacity, I mean 40-80 gigawatt (GW). 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.

Initially some forty 100-km long sections of the joint cable/pipeline might be joined by nuclear plants of a few GW 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. Charles Forsberg of ORNL is among the leaders in design of such reactors, and increased activity by the Technical Working Group on Gas Cooled Reactors of the IAEA might signal the needed new pulse in this domain. 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. Fortunately ORNL is already improving Supercable design and partnering with the Ultera Corporation to demonstrate perhaps this year the performance of high temperature superconducting wire at commercial electrical current levels. [Figure 10] The next step, achievable over 2-3 years, might be a flexible 100 meter Supercable, 10 cm overall diameter, 5000 volts, 2000 amperes, 10 MW dc, with a 3 cm diameter pipe for 1 m/s H_2 flow, using magnesium diboride 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.

Speaking of the system, for safety, security, and aesthetics, let's put the entirety, including cables and power plants, underground. I mentioned earlier that tunneling has a future even if coal mining does not. The decision to build underground critically determines the cost of the SuperGrid. But, benefits include reduced vulnerability to attack by human or other nature, public acceptance by lessening right-of-way disputes, reduced surface congestion, and real and perceived reduced exposure to real or hypothetical accidents and fallout. By the way, Department of Energy laboratories including Fermi have profound experience with tunneling from building particle colliders.

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 speaking now of 100 years, but that is our time frame, and let's recall that 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 would help spread the infrastructure cost over multiple uses.

As with ZEPPS, magic words for the SuperGrid are hydrogen, superconductivity, zero emissions, and small ecological footprint, to which we add high temperature reactors, energy storage, security, and reliability. The long road to the continental SuperGrid begins with the first 10 to 20 km segment addressing an actual transmission bottleneck, and ORNL should commit today to help build it.

Conclusion

Evolution is a series of replacements. Replacements also mark the evolution of the energy system. Between about 1910 and 1930 cars replaced horses in the United States. Earlier steam engines had replaced water wheels and later electric drives replaced steam engines. These replacements required about 50 years in the marketplace. It required about the same amount of time for railways to replace canals as the lead mode of transport and longer for roads to overtake railways and for air to overtake roads.

Decarbonization is a series of replacements. Considering primary sources of energy, we find that coal replaced wood and hay, and oil in turn beat coal for the lead position in the world power game. Now natural gas is preparing to overtake oil. The so-called oil companies know it and invest accordingly. We must favor natural gas strongly everywhere and prepare the way for hydrogen, which is a yet better gas.

Importantly, the superior performance of the technology or product fits a larger market. Hydrogen and electricity can cleanly power a hundred megacities.

The global energy system has been evolving toward hydrogen but perhaps not fast enough, especially for those most anxious about climate change. With business as usual, the decarbonization of the energy system will require a century or more. [Figure 3 again] To assuage social anxiety about possible climate change, we should start building large methane ZEPPs, which will pay anyway because of their efficiency. ZEPPs could also provide juice for the early Supergrid and be conceived for the transition from methane to neat hydrogen.

When increasing spatial density of energy consumption drives the system, we must match it with economies of scale in production and distribution. The coming world of ten billion people needs jumbo jets as the backbone of the energy system, not 2-seater Piper Cubs. Of course, the little planes play crucial roles in the capillary ends of the system and in providing back-up and flexibility. Most effort on the energy system the last couple of decades has been retouching here and there.

Now is the time to think and act big again. ZEPPs and the SuperGrid will bring riches to companies and nations and glory to engineers and scientists and the institutions that nurture them, such as ORNL. Let's commit now, as Alvin Weinberg has prepared us to do, to the technological fixes that will complete the grand and worthy challenge of decarbonization.

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This talk expands on "Decarbonization: The Next 100 Years," delivered 25 April 2003 at the Geology Foundation in Austin, Texas, and draws from:

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