Power Density and the Nuclear Opportunity

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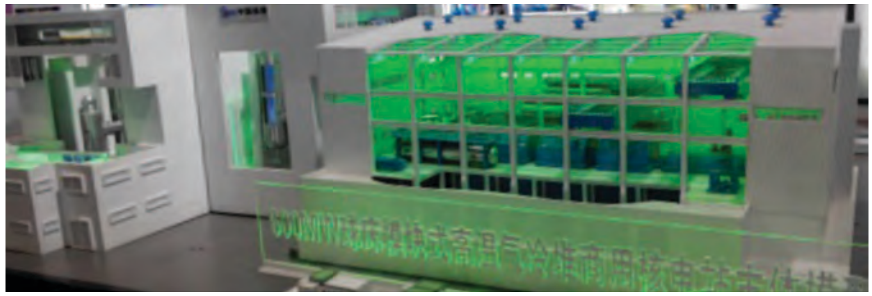

Model of 600 MWe high-temperature nuclear reactor on display in Shanghai. High temperatures can not only boil water to run turbines to make electricity but also facilitate many chemical reactions and thus open new markets for nuclear reactors. The provincial development and reform commission has permitted preliminary work at Ruijin, and construction of two such reactors is expected to start in 2017, with grid connection in 2021. Image: François Morin, WNA

Fact: One gram of uranium could produce the same amount of energy as a metric ton of oil, a ratio of one million times. In the long run, this is an astronomical advantage for nuclear power.

The advantage derives from understanding that increasing spatial density of energy consumption at the level of the end user drives the overall evolution of the energy system. Spatial density means, for example, the energy consumption per square meter 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. Said simply, big, tall cities drive the system.

If energy consumption per unit of area rises, the energy sources with higher economies of scale gain an advantage. Otherwise, one must exploit a vast hinterland and overcome the many barriers that controlling territory requires. Energy technologies succeed when economies of scale form part of their conditions of evolution. Economies of scale favor fuels suited to higher power density and thus also decarbonization, as will become evident.

One contributor to economies of scale is the heat value of the fuel per kilo. Hence the advantage of nuclear power. But for many generators of electricity there is a problem. In developed countries, generators face saturated markets, especially for large increments of power. Obviously, nuclear must concentrate its growth where electricity demand will still multiply. Or where demand for heat that would otherwise make electricity will grow. In fact, in the long run, success of nuclear depends on more outlets for nuclear heat. Fortunately, cars now turn to fuel cells, and thus hydrogen. That opens nuclear opportunity, as does electricity demand in Asian cities. That is my argument.

But first let me say I am not naïve about the challenges the nuclear industry faces. I visited the Chernobyl reactor complex in December 1990. I had the privilege to spend a week working with Soviet colleagues on the cleanup. In 2011 Japanese colleagues in Sendai invited me to see with my own eyes the tsunami damage just north of Fukushima. I tried to imagine running through a rice field in front of a wave of water 45 feet high moving as fast as a four-minute miler, Olympic speed. Let's assume that the industry, including its regulators, excels in risk and safety management and associated areas such as sensors and materials science crucial to its success. Let's instead probe the opportunity of density.

Power density

When we speak of energy or power density, there are several ways to assess it. The most obvious are gravimetric, by weight, and volumetric, by volume or area. Early in 2015, the outstanding energy analyst Vaclav Smil published an entire book on *Power Density*, which I highly recommend.

Smil considers areas mined for minerals and chemicals, land and materials for tanker terminals and gas pipelines, and every other nuance and possible claim relating to density. I will concentrate only on the major measures of weight and volume or area.

Figure 1 quantifies the fuel mass per energy of both hydrocarbons and nuclear fuels in kilograms per gigajoule. Uranium in a light water reactor is at least four orders of magnitude, ten thousand times, denser than coals, oils, and hydrocarbon gases. A fast breeder reactor would multiply the ratio another hundred times or more. Keep faith in breeders. Their time will come.

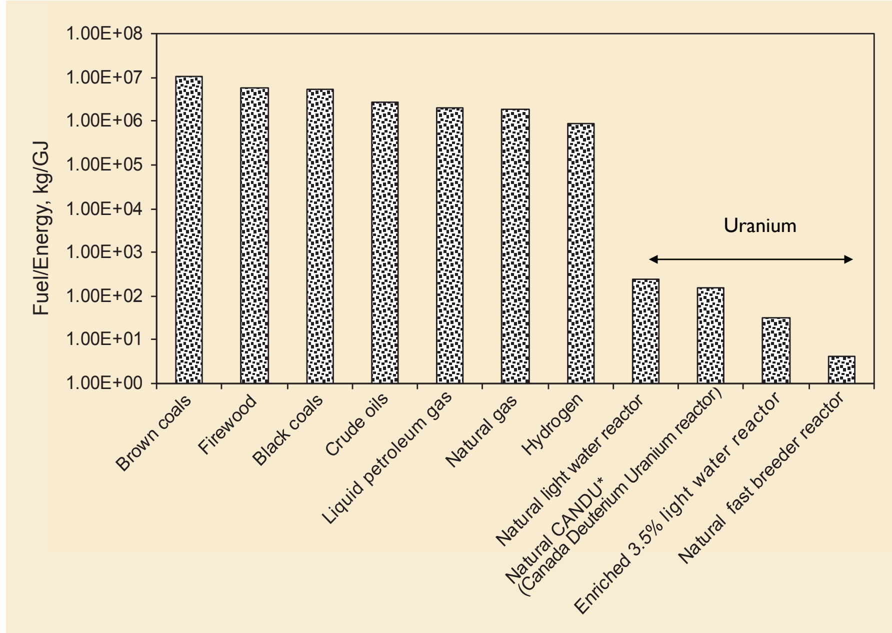

Figure 1. Fuel mass per energy, including nuclear fuels. Economies of scale favor fuels suited to higher power density, thus decarbonization and finally nuclear sources, at least 10,000 times more compact than hydrocarbons. Note: *CANDU is a pressurized heavy water reactor. Sources: JH Ausubel, 2007, and https://en.wikipedia.org/wiki/Energy_density.

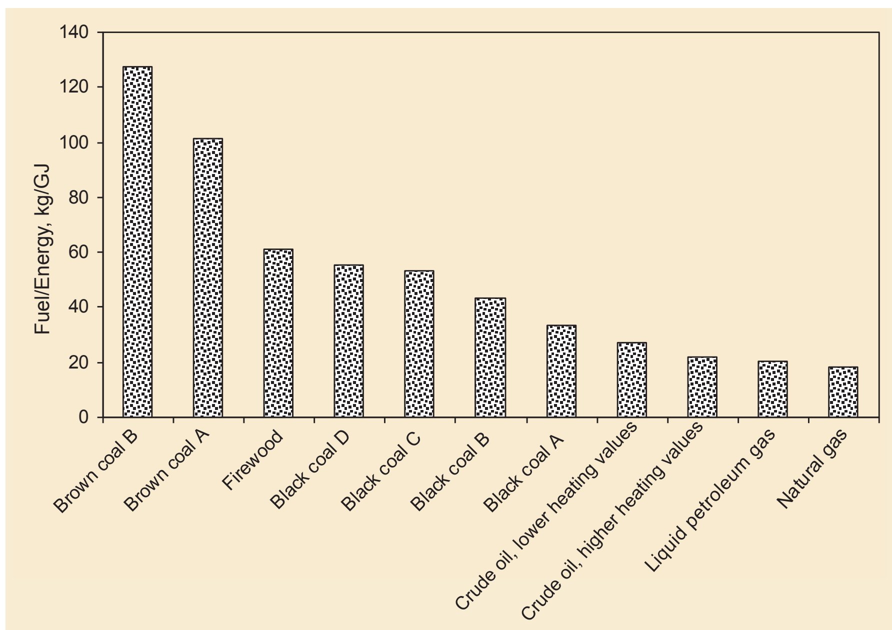

Figure 2. Fuel mass per energy of hydrocarbons.
Sources: JH Ausubel, 2007, and https://en.wikipedia.org/wiki/Energy_density

While the hydrocarbons form a family (**Figure 2**), they are not identical. Gravimetrically, natural gas, methane, beats brown coals by five to six times and black coals by two to three. Every power plant manager knows that storage of gas requires less acreage than coal. The energy system has been evolving from left to right, to mixtures with a lower ratio of carbon to hydrogen atoms. In an elemental sense, human societies have moved from use of almost pure carbon, charcoal, to the carbon-heavy blends of coals, to oils like kerosene (CH_2), to the CH_4 of methane. Pure hydrogen (H_2) would cap the process.

This evolution is the light path of energy development, which has prevailed for centuries, a movement from bulky, heavy wood and hay to coals to oils to gases. The evolution of the energy system resembles, somewhat surprisingly, that of computers and other systems that grow in power even as they become more compact. Densification opens market opportunities, as compact powerful computers show. In the developed countries, new energy systems fit comfortably in the footprint of the old ones. The Bankside Power Station, London, which was repurposed as the Tate Modern museum in 2000 after some 50 years of power production, covered 3.5 acres. Today a power plant of comparable capacity would fit in one-tenth the space.

For the next 50 years or so, the dynamics strongly favor natural gas.

Gas is a very tough competitor, because it can be compact and clean as well as very cheap and addable in units of many sizes. The most attractive gas technology to me comes from rocketry. The California company Clean Energy Systems (CES) has some especially attractive combustion technologies now in demonstration that also allow carbon capture and sequestration. Basically, the trick is to run the equivalent of a space shuttle engine for 30 years instead of a few hours. At high pressure and temperature, a new 200 MW gas turbine fits inside a container the size of a Winnebago. The CES facility in Bakersfield, California, formerly housed a 5 MW biomass plant. Gas is wonderful for retouching and improving the present energy system, and will smoothly substitute for coal at many of the 7000 or so units in about 2300 coal-fired power stations around the world.

Naturally one wonders about the so-called new renewables, solar and wind. These may be renewable but they are neither new nor green. They are brown because of their miserable energy density, which requires vast acreage. Gravimetrically too, the structures and infrastructure to harness wind power take five to ten times more concrete and steel per megawatt than nuclear. The size of the wind equipment dwarfs human scale, yet the colossal machines of wind farms produce a pitiable 1.2 watts per square meter.

Table 1. Renewable energy production density.

	watts/meter^2	sq km to produce 1000 megawatts
Hydro		
Hoover Dam	0.0014	714,286
Hydro: all US dams	0.049	20,408
Hydro: Ontario	0.012	83,333
Biomass		
Ethanol from corn (net)	0.047	21,277
New England forest	0.12	8,333
Ocean biomass	0.6	1,667
Corn (whole plant)	0.75	1,333
Sugar cane	3.7	270
Wind	1.2	833
Solar thermal (actual)	3.2	313
Photovoltaics	6	150

Data sources: Howard C. Hayden, *The Solar Fraud*, Vales Lake Publishing, 2nd ed., 2004; and others.

Consider closing the two 1100 MW reactors of California's Diablo Canyon nuclear power station and replacing them with wind. The wind farm would require a huge 1600 square kilometers, more than the land area of Marin County. **Table 1** summarizes the sad story of renewables. Weak and dilute to begin, they suffer rather than benefit from increases in scale as they require linear or rising amounts of land and materials to produce more kilowatts. Illusionists and delusionists, some in high positions in government, industry, finance, and academia, promote a renewable vision. Running counter to density's arrow of destiny, wind and solar will fail, at considerable cost and embarrassment and damage to the landscape. Mad crowds have their day, so there is little we can do except go about our own business constructively.

More power, less stuff

We do need to unburden ourselves of our own illusions, foremost that electricity remains tightly coupled to economic growth, which it did for most of the 20th century. America and the world have entered an era in which economic growth and performance are decoupling from stuff — materials, energy, water, land.

Over the last 50 years, world GDP has risen sharply while per capita food supply has risen slightly. Growth does not require more potatoes. And more calories do not require more land, as evidenced by 50 years of sharply rising corn production from flat corn acreage. Smarter farming, in part using more energy (fertilizer) but mainly more information in forms ranging from better seeds to more accurate weather forecasts, decouples corn from land.

Georgia farmer Randy Dowdy set the world record for corn yield in 2014 with an astonishing 503 bushels per acre, about four times the average yield in Iowa. Corn farmers like Mr. Dowdy generally are getting bigger gains without increasing their inputs. Until about 1980 American farmers were adding more nitrogen, phosphate, and other chemicals and energy in tandem with rising yields. For the past 25 years or more, yields and production have risen with flat or falling inputs of agricultural chemicals, water, and land. Farmers do now make use of variable rate zone management maps generated by unmanned aerial vehicles, and the cabs of their tractors and home offices are instrumented like the cubicle of a Wall Street trader.

The decoupling of production from traditional inputs is true not only for agriculture but also for many other industries. Absolute amounts of most inputs to the US economy have been falling for a couple of decades, since well before the Great Recession. America is peaking in its use of natural resources, not because resources are exhausted but because of changing demand and rising efficiency.

Many people are surprised that the USA has peaked in its water withdrawals. Withdrawals have retreated to levels of the 1960s, when there were 110 million fewer Americans, and the USA exported about half the tonnage of grain it has in recent years (about 40 versus 80 million metrics tons). After smarter farming, increased water use efficiency in the power sector has been the second largest reason.

And the economy and energy are decoupling in the USA and many other countries, as energy consumption falls in relation to GDP, vexing the energy industries (**Figure 3**). Electric power believed that it was exceptional, but around 1980 electricity use stopped growing faster than the US economy, and the USA may well now be at peak use of kilowatt hours (**Figure 4**).

Some still argue that cheaper, more accessible electricity will lead to an offsetting rebound, but the many instances of saturation from

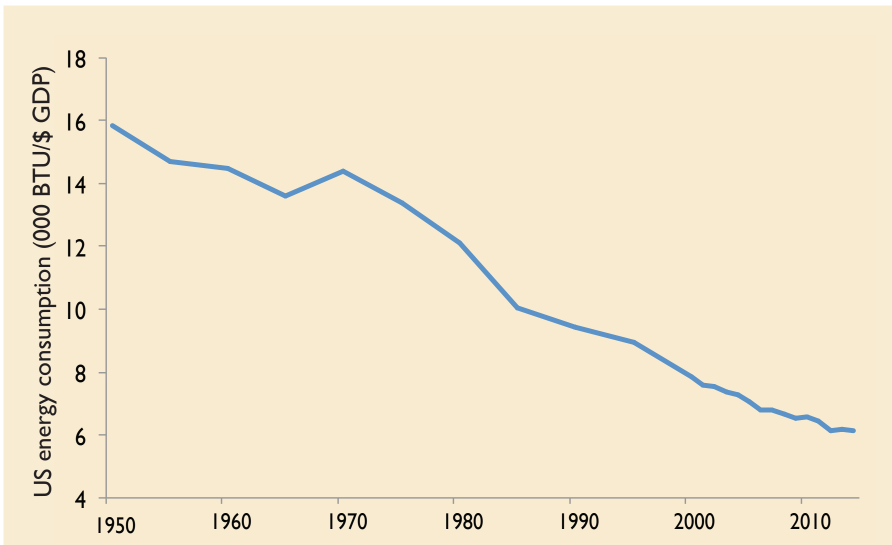

Figure 3. Decoupling of US economy and energy consumption. Changes in structure of economy, better generation and transmission, and better end-use devices all contribute. Data source: US Energy Information Administration.

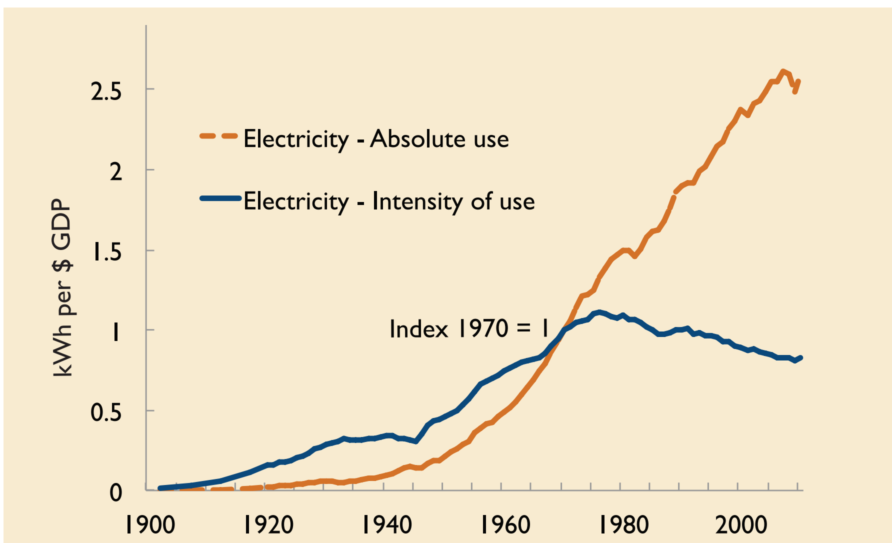

Figure 4. Peak electricity in US? Use no longer grows in tandem with economy (kWh per $ GDP / indexed to 1970).
Data source: US Energy Information Administration.

the past 20 years suggest that rebound will not be high enough to cause growth.

If we accept that demand won't change much in the developed countries, what about India and China? Will India and China repeat at the same pace the experience of the USA, or will they catch up faster, benefiting from what others have learned? My bet is the latter. Later adopters of technologies tend to build more efficient systems composed of more efficient elements. Illumination in India in 2030 will not be accomplished with the light bulbs of 1930.

Electric consumption in China and India is still rising, but like the USA, Japan appears saturated and Korea nearly so. Analyzing in detail and projecting, we find that the average Chinese citizen may demand only half the electric power of a Japanese, who in turn uses half that of the average American.

As hinted, a main promoter of rising efficiency is information. While we may increasingly spare water, land, materials, and energy, we are in the information century and seem insatiable for it. We may be at peak stuff but not at peak information. Information is really what is lifting yields in "precision agriculture" and also decreasing energy demand. With a better weather forecast farmers need not irrigate before rain.

More generally, we are experiencing dematerialization. We are living in a world of more bits but not more kilograms or even kilowatts. The bits and bytes demand perfect power, but they also spare power.

So, the market for new kilowatts may focus in a few developing regions, especially the new megacities of Asia, but what about the market for mobility?

Nuclear research and development focus on production of electricity for good reason. A substantial 40% of primary energy makes electricity, for which production is still concentrated in large units where reactors show their economics. Almost nothing has been done to penetrate the 60% of the primary energy market where our society is geared to burning a wide variety of chemicals.

Power motor vehicles

Happily, car fuels and engines are in play after a century when the internal combustion engine and petroleum held the market. In 2015 Toyota introduced the Mirai, its fuel-cell vehicle, even though its hybrid electric Prius has gained popularity during almost a decade on the road. The temptation for the electric power industry is to side with batteries, recharging them, but is this wise? First, let's appreciate that petroleum is hard to beat, precisely because of its excellent volumetric and gravimetric densities and its advantages for storage and transport.

Consider the many routes from well to wheel, that is, the means by which primary energy in "fossil" fuels, nuclear power,

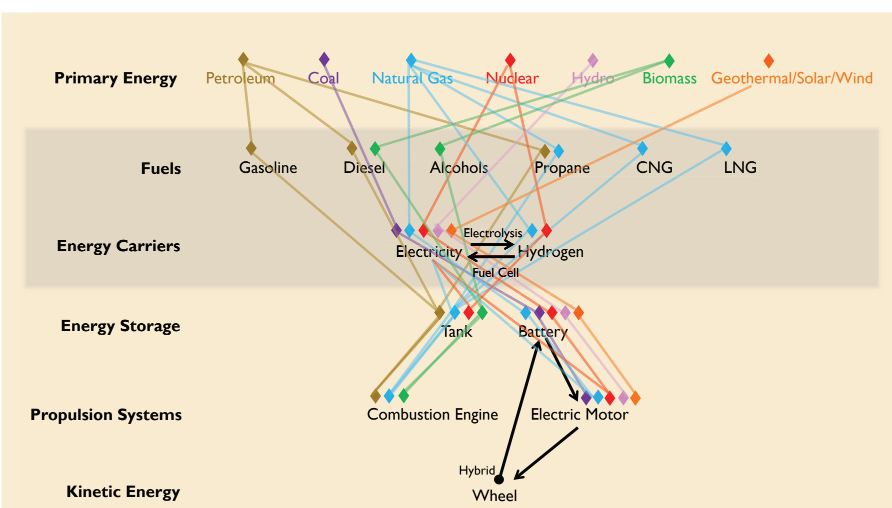

Figure 5. Many routes "well to wheel."
Credit: Alan Curry.

biomass, and even hydro, solar, and wind power can be converted for use in automobiles (**Figure 5**). Nuclear can run on two routes, provision of electricity and of hydrogen, in turn with two routes to hydrogen, through electrolysis or thermochemical manufacture. The opportunity is huge. America has used about 700 million motor vehicles, and so far only about 100,000 electric cars and 1,000 hydrogen cars. About 1.2 billion motor vehicles now populate the continents.

Going to basics, electric engines beat internal combustion engines in many ways. They are more efficient and emissions free. They recover kinetic energy in braking, and they are quiet. But because we still can't store electrons well, gasoline beats batteries. I have been reading press releases from the US Department of Energy about batteries for 38 years. Lots of promises, not much delivered. The real progress has been in shrinking the power demanded of the battery, not in strengthening the battery itself. Ear buds replaced boom boxes, and solid-state memory replaced the energy-hungry mechanical drive of cassette tapes. Non-rechargeable batteries have improved more in density than the rechargeables (**Figure 6**). The rechargeables improved about 1.5%/yr, doubling in 25 years, hardly the biennial doubling of Moore's Law.

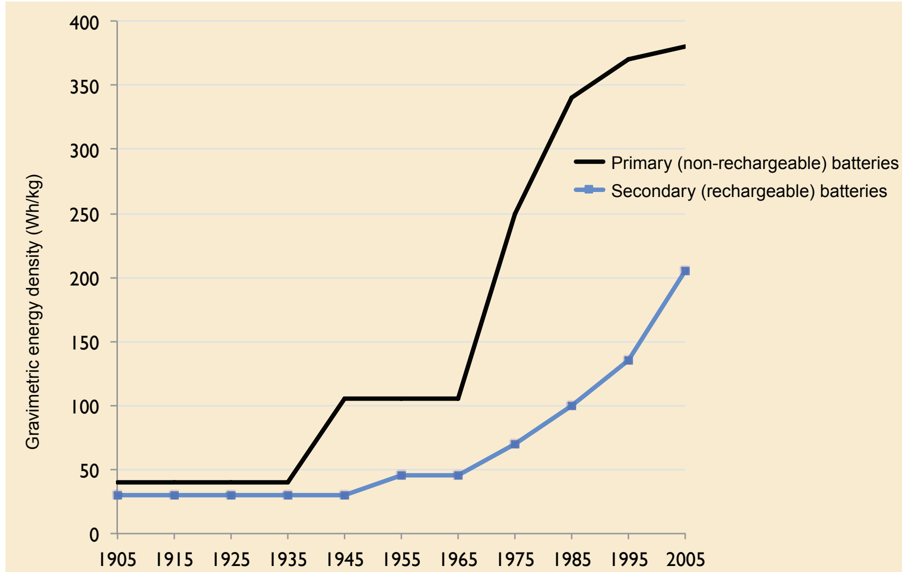

Figure 6. Battery performance does not follow Moore's Law of semiconductors (doubling every two years) despite huge investments.
Data source: *Energy & Environmental Science*, 2011, 4:2614.

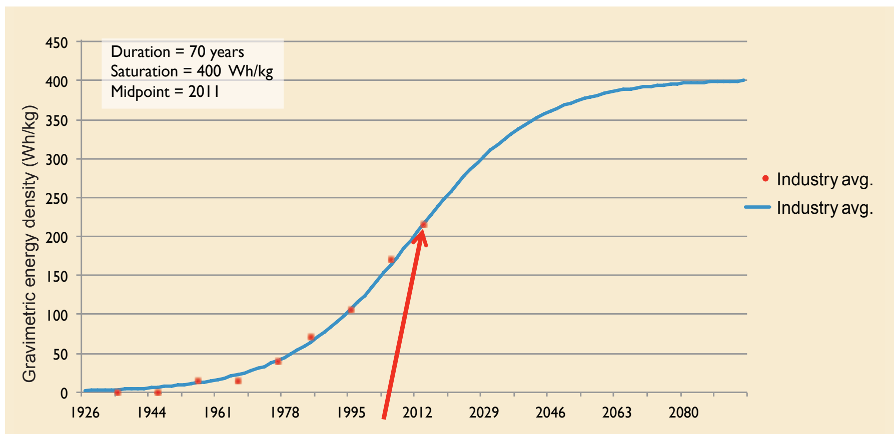

Figure 7. Rechargeable batteries will improve, but very slowly.
Data source: *Energy & Environmental Science*, 2011, 4:2614.

My group's projection is that the rechargeables will continue to improve, but slowly and to a rather low or heavy gravimetric density (**Figure 7**). Battery proponents tend to emphasize volumetric density improvements, which are good (as much as 10%/year during 1990–2005) but less important for the mobility market. The weight of the trunk of batteries matters more than the size of the trunk. Meanwhile, proton exchange membrane fuel cells are improving steeply in ratio of power to weight, as well as by volume (**Figure 8**).

I believe Toyota, Honda, and other car makers are right to place their main bet on fuel cells rather than batteries. Fuel cells are overtaking batteries. Both GM and Hyundai have indicated that hydrogen fuel cells have time and performance on their side to displace petroleum. Simple, sturdy, cheap fuel cells capable of many years of unattended operation remain a major engineering challenge, but the trends look good for meeting it.

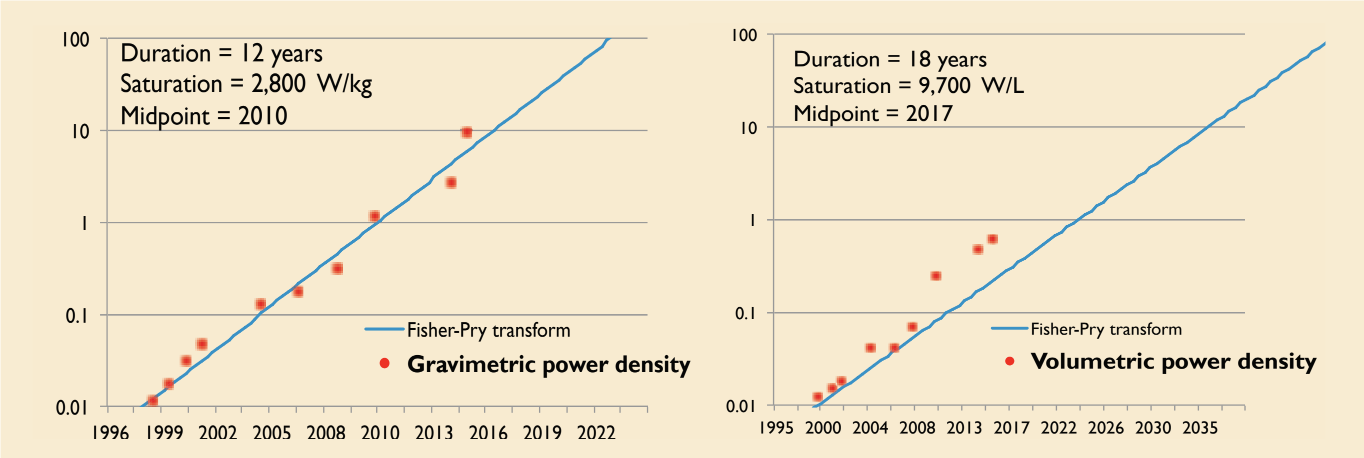

Figure 8. PEM fuel cells on steep trajectories. Current surge to max power/weight is near top, while packaging still shrinks by half. New pulses of improvement could follow.
Data sources: GM, DaimlerChrysler, Honda,Toyota, Hyundai, National Renewable Energy Laboratory.

Where does the hydrogen for the fuel cells come from? First, recognize that the hydrogen industry is growing nicely, in the USA (**Figure 9**) and worldwide. The global hydrogen generation market was estimated at $103 billion in 2014. The refining industry consumes the biggest share of hydrogen, about 48% of total consumption in 2014, to convert low-grade crude oils into transport fuels. The ammonia industry follows a close second with a 43% share. World production capacity in 2014 totaled about 80 million tons, or about 300 GWt, not so different from nuclear electricity. So hydrogen is already a significant chemical product that firms have experience handling on a large scale. Prices are coming down, too (**Figure 10**). Most of the hydrogen, of course, comes from natural gas reformed in the steamy Haber process.

Can nuclear power compete with methane as a source of hydrogen? Let's go back to basics. Nuclear reactors are essentially large sources of heat, but the energy market splits into a host of small customers, like cars, and heat is not easily stored or transported to each customer. The solution is a flexible intermediary, producible in large blocks, in which nuclear heat can be stored as chemical energy and economically distributed. Hydrogen can become the main energy mediator between nuclear energy and human society, avoiding most of the political, ecological, and other problems associated with fossil fuels.

Hydrogen can be produced from water and reverts to water. Pipelines can transport it overland at low cost and tankers by sea as liquid hydrogen (LH_2). It can be readily stored, particularly in ground structures, like exhausted gas fields. It has extreme flexibility in how it can be used, with great advantages in many cases over current fuels, for example, not only for fuel cells but for airplanes, too. In fact, H_2 can cover nearly all

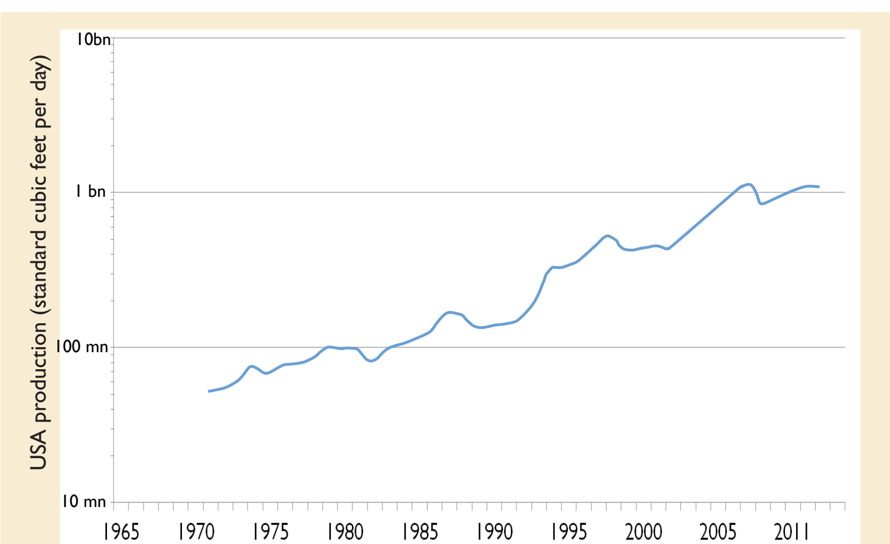

Figure 9. Hydrogen, the immaterial material, becomes a big industry.
Data sources: US Census Bureau, 1971–2004; US Energy Information Administration, 2005–2013.

the market for energy not directly covered by electricity. And it can be produced in large units benefiting from economies of scale.

So, the challenge is to find the best process to produce H_2 from water using heat of the grade available from commercial nuclear reactors, now 300 degrees C from water-cooled reactors, but perhaps soon 500–800 degrees C from the high-temperature gas-cooled reactor under construction in China. A range of 800–1000 degrees C might open up a lot of attractive two-step recipes with various catalysts (Naterer et al., 2013).

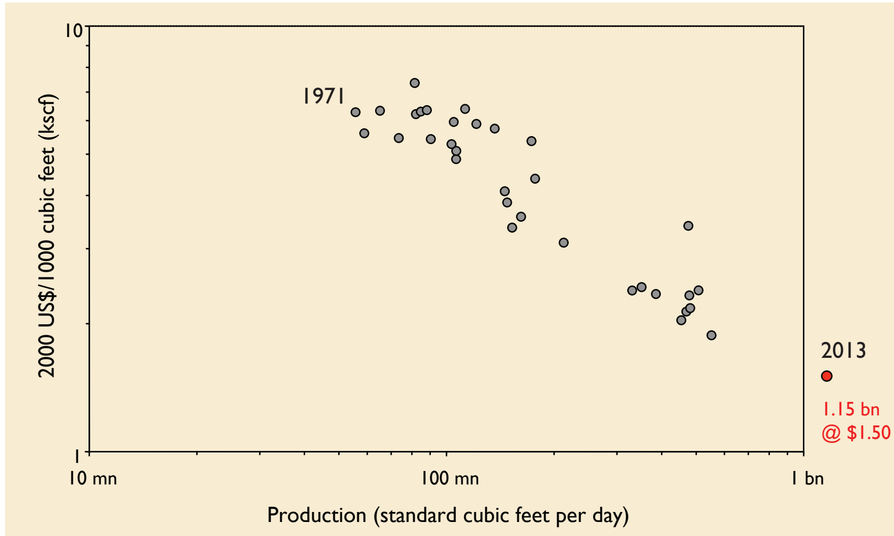

Figure 10. Falling hydrogen price versus USA hydrogen production, 1971–2003, 2013. Hydrogen becomes price competitive.
Source: Ausubel, 2007, with 2013 data point added.

Electrolysis sounds straightforward but is in fact twisted: the energy is handled many times, in the boiler first to make steam, then in the turbine for mechanical energy, then in the generator for electrical energy, which is rectified, and fed to the electrolyzer. All that piles up costly capital and cascades inefficiencies. The outcome may be a watt per square centimeter of plant. No economies of scale, and thus vast facilities.

So, let's return to a dream from 50 years ago, a black box containing chemicals where the inputs are heat and water, and the outputs are oxygen and hydrogen, plus some degraded heat. Inside operates a thermochemical processes for water splitting. Chemical engineers have readied some good candidates, and the context finally seems right.

Hydrogen still faces problems at the consumer end, but these seem en route to solution. Carrying an amount of H_2 giving the same range as a tankful of gasoline is a tough problem. Liquid hydrogen has three times the volume of gasoline for the same energy content. Progress may come from air transport, which tends to use the best in available techniques, puts a premium on weight, and takes an increasing share of the energy market. While three times bulkier than jet fuel, LH_2 is 2.5 times lighter, and we see progress in light cylinders for carrying the hydrogen. Both gravimetric and volumetric density matter. On many planes, the fuel carried is two to three times heavier than the payload. The Tesla Model S batteries weigh more than 500 kg, six to seven times a typical driver.

Summary

The electric grid has been a mixed blessing for nuclear energy. The preexisting market made life easy but in the rich parts of the world its capacity seems saturated for now around 400 GWyr per year. In spite of efforts to make nuclear small and cozy, the only viable variety seems big and distant.

Nuclear energy is produced as heat, but heat is not transportable easily because it is diluted. If you heat a gas or liquid, the energy density is very low. Moreover, the pipes leak energy through heat losses. We have to find a stable form for nuclear energy. Stable form means putting the heat into a chemical form. The only product alternative to electricity seems to be hydrogen.

Happily, hydrogen is a fat market, a chemical for which people are willing to pay large sums. And it scales up. The hydrogen on a rocket from a space shuttle or moon rocket would fuel about 15,000 cars. The nuclear industry can solve the problems we have identified and make that hydrogen and much more.

Let's not worry about wind and solar. The fact is that they provided about 2% of Europe's primary energy in 2014. They do not enjoy economies of scale. Acreage and concrete and steel rise in tandem with production. In truth, wind suffers from diseconomies of scale; to gather more wind one must go to less desirable sites. But good energy density makes natural gas a serious, durable competitor. Its vulnerability is the C that accompanies each quartet of Hs.

Finally, let's see the energy system as it is, huge and hierarchical. A mere 36 people crew a vessel of 76,500 gross tons carrying 8,500 hydrogen-powered Toyota Mirai automobiles, boasting 67 miles-per-gallon-equivalent and a commercially viable price tag, due in part to nanotechnology allowing 80% reduction in costly platinum within a fuel cell. Small may be beautiful, but big is cheap; economies of scale still count.

Let's grow a safe nuclear industry that provides the big increments of power that will provide electricity for India and China and other fast-growing regions, and the hydrogen for all. The opportunity starts with supreme density, which is finally the genius of atomic power.

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