The Next 100 Years of Global Energy: Part V
Density, Key to Fake and True News about Energy and Environment*

Jesse H. Ausubel[1]

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[1]Director, Program for the Human Environment, The Rockefeller University, New York, NY (jesse.ausubel@rockefeller.edu)

Abstract

Fake news is that renewable forms of energy are green. True news is that mobility, the great gift of petroleum, is more precious than prices usually tell. Reducing mobility cruelly limits access to education, mates, and jobs. Humans want low-cost speed, with minimal fallout. Petroleum has excelled for a century in this role. The hard news is that it will likely be surpassed soon by natural gas, and geologists must urgently think further than petroleum, though it abounds. The long-term driver of the evolution of the energy system is rising spatial density at the level of the end user. As humans concentrate in ever larger, taller cities, watts per square meter rise, and finally only electricity and energy gases meet the specs for 21st century cities.

Introduction

I will tell you the fake and true news about energy and environment over the past and next 100 years. Fake news is that renewable forms of energy are green. Hydro, biomass, solar, and wind are renewable but not green at scales that power billions of people. True news is that mobility, the great gift of petroleum, is more precious than prices usually tell. Reducing mobility cruelly limits access to education, mates, and jobs. Humans want low-cost speed, with minimal fallout. Petroleum has excelled for a century in this role. The hard news is that it will likely be surpassed soon, and you must urgently think further than petroleum, though it abounds.

The heart of the story is energy density, exemplified by the 400 horsepower of a 1960s muscle car. The long-term driver of the evolution of the energy system is rising spatial density at the level of the end user. For simplicity, think of watts per square meter. As humans concentrate in ever larger, taller cities, watts per square meter rise, and finally only electricity and energy gases (basically methane, or natural gas, and hydrogen) meet the specs for 21st century cities. Think of the voluminous Houston convention center and the high-rise hotels in symbiosis with it, almost totally electrified. The kitchen may still use natural gas.

Finally to supply electricity and gases to the end user, fuels that benefit from economies of scale will win on the supply side. Cords of wood and heaps of coal lost out to denser sources of supply that flow through grids that go from aortic to capillary.

Old-fashioned magnets lost too. Metallurgical "vitamins" called rare earths allowed magnets of equal force to shrink in size by more than an order of magnitude and thus proliferate. Density and miniaturization bestow power and grow markets, as the ubiquity of computers shows us.

Like wood and coal, petroleum has also lost markets for most energy uses. Oil has retreated to motor vehicles, where tanks rather than grids have made and still make sense.

Electricity and Natural Gas

The well known global challenge for electric generation is decarbonization. The power industry's desulfurization already shows the way. Consider the trajectory of U.S. sulfur emissions peaking about 1970. America achieved desulfurization through a blend of means. Geologists found and produced less sulfurous coal and oil. Engineers made the same coal or oil emit less sulfur. Firms added sulfur-free gas, nuclear, and hydro to the generation mix. Now sulfur is essentially a solved problem. Along the way, legislation and regulation sometimes led and sometimes followed. America found strategy to conform to our fate, that is, the preset trajectory.

For carbon dioxide, data suggest that 2007, or so, flagged the year of peak American emissions (Figure 1). I am amused by the huffing and puffing of politicians and nongovernmental organizations, many of which I support. America is right on schedule for decarbonization, regardless of Clean Power Plans and elaborate Paris costumes, whose main benefit may be to make sinners feel virtuous. The U.S. economy decoupled from carbon during the 1940s, long before congressional hearings about it. For deeper reasons the country shifted to natural gas and nuclear power, and these, together with relentlessly rising efficiency and changing industry composition, will carry us to a low-carbon economy in another 50 years or so.

While sulfur is overwhelmingly bad stuff to pump into the air, carbon dioxide is a much more complex story. Plants love it, and good evidence suggests that Earth is experiencing a "global greening" associated with increased CO_2 as well as other factors. Since the early 1980s, Earth's biosphere has been expanding, rather than shrinking, which humans had caused it to do since the start of agriculture and land-clearing about 10,000 years ago. The factors include not only higher atmospheric CO_2 but also longer growing seasons, perhaps more nitrogen around, more productive management of farms and forests, and, crucially, soft demand for products of the biosphere. Email and ebooks spare forests from cutting for pulp and paper, and larger forests enjoy the difference. Coal and gas did and still do spare forests from logging for fuel.

While some commentators focus on bad weather news, in fact, recent years have brought record yields for most crops and food surpluses, not shortages. The steady brilliance of farmers lifting corn yields first forced Americans to eat hamburgers and now our cars to drink ethanol (Figure 2). Global agriculture is a good deal larger than needed, taking into account the 30 percent or so of all food that is wasted, grain diverted to ethanol, excessively meaty diets, and obesity.

Now some geologists might like biomass fuels because they are essentially recycled natural gas called fertilizer and oil called tractors. We pour one unit of energy on the land to extract perhaps 1.2, a sad return, and a vicious use of acreage. The acreage in America for biofuels equals Iowa or Alabama, greater than the size of all the national parks in the lower 48 states.

The cause of insanity such as ethanol is not only the Iowa primary and clever lobbying by farm interests, but the abiding fear, not fake, among many people that something terrible could happen to this magnificent planet, and Earth's climate has become the focus of the fear. We simply do not know, maybe we cannot know, whether the climate operates like a dial or a switch. If further global warming meant merely that my home city of New York (annual average temperature 55.1°F or 12.8°C) were to become a couple of degrees warmer and have the climate of Baltimore (annual average temperature 58.4°F or 14.6°C), a risk-benefit analysis would probably not call for much action. Does anyone really believe that global well-being and GDP would differ importantly from today if the average atmospheric concentration of CO_2 had magically stayed at the 300 parts per million that prevailed a century ago when the AAPG began? In the 1910s the global mean annual temperature averaged 13.7°C (56.7°F), while in the 2000s it averaged 14.5°C (58.1°F) (GISTEMP Team, 2017; Hansen et al., 2010).

The danger is still in what could happen, that perhaps we will abruptly let loose a lot of weird weather and ice, for which our immense investments in water supply and coastal living are poorly prepared. Harmful feedbacks could amplify bads, and a disaster movie results with more sequels than *Fast & Furious*. Finally, I know of no objective basis on which to calculate precisely how risk averse Houston or Texas or America or the world should be. But let's agree for now that if geologists, engineers, and businessmen can cheaply sequester some carbon as well as decarbonize, let's do it, to lessen worries and perhaps probabilities.

Helpful leverage comes from the opportunity to operate mighty methane power plants with CO_2 as the working fluid at very high temperatures and pressures that also allow CO_2 to be separated, captured, and later sequestered. A 5 GW cluster could fit in the footprint of a power park now producing one-tenth that power. And the Houston region shows the way, more precisely the firm Net.Power, which uses a variation on the cycle that I and my pals in Austria and Japan first described about 25 years ago. Net.Power shows that methane can generate gigawatts compactly while conveniently providing CO_2 that petroleum geologists know how to reinject into the crust and store.

Renewable Lies, Fake News

I mentioned watts per square meter at the outset. During my career, and I accept some responsibility for this, decarbonization has become synonymous with clean or green energy. But this is a harmful fallacy. The core of green is not zero or low carbon. The core of green is No New Structures or at least Very Few and Compact Structures, ones that fit into existing footprints, or whose footprints can be readily covered.

And here the renewables are heartbreakingly, destructively evil. Table 1 summarizes the amount of land that each renewable devours. For reference, oil and natural gas produce about 25 to 30 watts per square meter, and nuclear 50 or more. As a rule of thumb, an oil or gas well equals about 20 large wind turbines. Variance depends on the stage of life of the well, horizontal drilling, and other factors.

I use watts per square meter as a common denominator and will refrain from adding facts about dead bats or rivers without salmon. For a thriving nature beside human nature, sparing land (and sea) is green requirement number one. Without habitat, life has no chance to adapt or migrate to warm or cool, wet or dry.

For meager return, windmills industrialize the landscape with concrete and steel and use an order of magnitude more such material per megawatt than methane. Consider that each windmill is constructed on site from gargantuan subassemblies transported at great cost over public highways. If small is beautiful, wind is ugly.

Of course, if you like wind, you better love transmission. The cables turn the sky into laundry lines for invaders from Jupiter. The net result is what Bill McKibben called the End of Nature over immense acreages. Consider an example from California. To replace the kilowatt hours of the 1.5-square-mile, 2200-MW Diablo Canyon nuclear power plant would require a 250-square-mile wind farm (Figure 3). Or consider examples from the Middle East and India. The 14 GW development of natural gas off the coast of Israel operated from a few platforms and a compact onshore facility would require 900 sq mi (2400 sq km) of solar farm, plus at least 400 GWh of battery storage; or 90 copies of what India expects will be the world's largest solar plant at Kamuthi in Tamil Nadu.

Solar offers more watts per square meter than wind, but finally all the renewables fail the crucial test of economies of scale. A larger wind turbine may have four times the power of a smaller one but uses four times the land. Wind turbines can extract only so much power from a given area, no matter their size. And operators aim to use the best sites first and then move to feebler.

The largest offshore wind farm contemplated so far (300 square kilometers of state-of-the-art turbines) would deliver only 1.2 W/m^2, assuming a generous 50 percent capacity factor. 1.2 W/m^2 is the same as wind farms 30 years ago. A larger plant is neither more productive nor cheaper, it just spans more land and uses more material. As I said at the outset, renewables may be renewable, but they are not green. And their touted learning curves mostly report effectiveness in learning to garner subsidies and to do deceitful accounting that ignores the full cost of a reliable energy system.

That leaves us with atomic nuclei, disproportionately powerful and compact. Tell me when Jason Bourne leaping across rooftops is actually engaging in industrial espionage about solar panels. In fact, the U.S. is trying to give solar technology to North Korea, a good way to set them back a hundred years or more.

On nuclear, at the AAPG, let me comment only that geologists have provided several good solutions for the vexing problem of waste disposal. My own preference is self-sinking capsules of waste, hot and heavy enough to sink through the crust, reach the mantle, and dissolve there. Think of the China Syndrome as a solution rather than a problem.

Petroleum and Mobility

At the outset I hinted that humans are territorial animals. We maximize our range subject to a budget constraint of about 15 percent of disposable income and a time constraint of about an hour per day of pure travel or exposure. The game is to increase range within the constraints, which means we seek higher income and lower cost speed. Raising the cost of vehicles or fuels reduces our range and thus punishes us, especially the poorer among us.

The paramount contribution of petroleum geologists has been provision of low-cost speed. Cars multiplied our range from 5 km/hr on foot and thus a territory of about 20 km^2 to about 35 km/hr and thus about 1000 km^2, a revolutionary 50-fold increase. Money and prices barely begin to give fair value to this increase of range. Bossard's classic 1932 study of 5000 marriages in Philadelphia before cars diffused widely found that more than half of all matches occurred between couples who lived within 15 blocks of each other. Externalities include more than pollution.

As many films and songs testify, modern love owes a great deal to petroleum geologists. Indeed, when scholars in future centuries ponder the 20th, the car may well symbolize our civilization. As the 21st century dawned, cars still provided Americans about seven times as much total mobility as planes and about four times as much for intercity travel. Figure 4 shows a few of the glorious machines that AAPG has fueled, including the 1970 Chrysler Plymouth Road Runner, whose horn sounded like the beep-beep of the popular cartoon, and guzzled gas. Such vehicles have become icons of automotive art and command fabulous prices at auction among collectors.

During AAPG's first century, a lot of tinkering took place on cars, but until now most cars would impress but not surprise Henry Ford and John D. Rockefeller. Now we face overhauls of propulsion and energy storage. We of course honor petroleum. Liquid hydrocarbon fuels offer peak volumetric energy densities, excellent gravimetric energy densities, and are optimal for storage, transport, volatility, and temperature tolerance. Members of the AAPG ingeniously fracked countless reports of the demise of the resource. Yet, already in the time of the Road Runner, about 1970, Americans hit saturation in per capita petroleum consumption (Figure 5).

The saturation mainly reflected that Americans used up their daily travel time budget with cars, and while cars added new energy-consuming features, such as air-conditioning, they also became more efficient, so that petroleum consumption remained stable. But finally, as our task is to look forward another century, we must admit that in the long run electric motors have many advantages over internal combustion engines. They convert fuel to motion more efficiently with more power density, and they do so quietly with instant torque and no emissions. The problem is the difficulty in storing electrons, and then the question becomes basically batteries or fuel cells.

Despite a torrent of press releases, I am skeptical about the progress of batteries. While their volumes have shrunk, their weight improves only very slowly. We still need to carry around nearly a ton of batteries in a Tesla, inherently inefficient.

Moreover, batteries, though rechargeable, are not green. Visit a lithium mine in northern Chile. Texas would not permit such a facility, and consider trying to open one in California or Massachusetts. And keep in mind, that lithium, like lead and cadmium, also popular for batteries, is a poisonous heavy metal. This is another aspect of the fake news about new renewables. And consumers need a lot of mines and batteries. A new battery for a full-size car stores 1 kWh. Running New York City for two cloudy, windless days would require about 530 million such batteries, about 62 per person.

Meanwhile, progress on fuel cells, operating on hydrogen looks good, and companies such as Toyota and Honda, bet heavily on it. I believe that General Motors has it right in their brochures that forecast vehicle and fuel evolution through increased energy density over time as improved vehicle fuel economy displaces petroleum and reduces emissions. We need to take very seriously the combo of hydrogen and fuel cells. Today's package of a fuel cell and a hydrogen storage tank weighs one-third to one-quarter of a comparable battery package.

The energy gas, the hydrogen, to power the fuel cell will come first from steam reforming of methane and later possibly from other methods. By mid-century, high-temperature nuclear power plants could manufacture the hydrogen.

What of the hope that growth in markets in China and India will save the car and thus petroleum? My group at The Rockefeller University has studied the demand in Japan and Korea as well as China and India. Japan and Korea saturated their petroleum demand, like the USA, but with about one-third less per capita. Projections for China suggest consumption will saturate at one-third of Japan and India at one-seventh (Figure 6). Our Austrian colleague, the geographer Arnulf Gruebler, has calculated that total vehicle population in China will plateau about 0.2 per person, which means the total number of vehicles in China will max out about where the USA is today. After all, although China has four times as many residents, it has about the same area.

How could the demand for fuel and cars peak so low? First, engineers of internal combustion engines could fight back and double their efficiency. Inevitably, part of the story will be cars operating on fuel cells or batteries. Part of the story is GPS, or more broadly sensors, autonomy, and precision. If GPS means no one is ever lost, that saves a bunch of fuel.

And there will be fewer cars per capita. The auto industry needs to take seriously the share economy, made famous by AirBnB. The average car operates only about one hour per day. If companies like ZipCar can cause the average car to operate just two or three hours per day, we will need less rubber, steel, and glass for the same mobility and fewer parking spaces. Traffic can move better, also saving fuel. In 2013 alone, the UPS company estimates it saved 8 million gallons of oil by smart operations research that made its fleet travel more efficiently.

So, markets in China and India and other developing countries will grow but not enough to alleviate the squeeze on petroleum, and they will saturate in 2040 or so, just a generation from now. From an environmental point of view, this is good news. The average vehicle will be much cleaner, as Delhi and Beijing desperately need. Another nasty problem that could diminish is the global bloodbath called traffic. An estimated 1.25 million people per year die globally in traffic accidents, about three times the deaths from malaria (World Health Organization, 2017). Humans are dangerous drivers. It is hard to see how self-driving vehicles, once trained, could do worse.

If we could leap to 2040 from today, we might say a revolution has occurred. In practice these changes will evolve at something like 3 percent per year, but compounding over a generation causes a very different system of motor vehicles and fuels.

Importantly, the reason for saturation of motor vehicles is not that phones substitute for cars. Communication and travel are complementary goods. The more we travel the more we communicate, and the more we communicate the more we travel. Airports are full of people talking on phones, and airplanes are full of passengers now sending emails. Here we return to the travel time budget. To range farther, we need to shift from cars to a much faster mode of transport, namely planes.

Aviation will grow, and jet fuel can help geologists thrive for a while. The average American flies about 70 seconds per day, much less than the average member of the AAPG, and much more than the global daily average (excluding the USA) of about 12 seconds. Of course, hydrogen powers rockets, and could power planes too, directly or through fuel cells.

Societies could also build a new wave of faster transport using linear motors, a sequence of electromagnets, so-called magnetically levitated trains. For the past couple of centuries, societies have invested sequentially in great waves of infrastructure: canals, then rails, then paved roads, and then airways (Figure 7). Linear motors give us the technology for a new wave. In low-pressure tubes, maglev trains rival planes in speed. They require very little energy, in part because unlike a horse or car or train or plane, a maglev does not need to drag around an engine and fuel weighing a ton per passenger. A maglev can consist of just a light envelope, say of aluminum, containing the valuable cargo. Density again. Elon Musk's battery-powered cars are a poor idea, but his maglev trains now popularized as the Hyperloop are a rich one.

The basic point is that increasing energy density drives humanity toward electricity and hydrogen, and along a progression of hydrocarbons that extends from soft coals and wood (~ 10 MJ/kg) to hard coals (20-30 MG/kg) and oils (35-45 MJ/kg) and methane (~55 MG/kg). Perhaps it is time for AAPG to call itself the American Association of Methane and Petroleum Geologists. The growing gas market is a lucrative arrow, rising to about 3.2 billion metric tons of oil equivalent globally in 2015 from less than 1 billion in 1970 (Figure 8).

And hydrogen, much of it processed and used near Houston by industrial gas companies, is a formidable competitor and a great form of energy storage. This light, immaterial material, about 140 MJ/kg, mainly used now in refining present vehicle fuels, appears destined to marginalize them. U.S. production of hydrogen has grown from about 50 million cubic feet in 1971 to 1.2 billion in 2014 (Figure 9).

But we need to keep an eye on nukes. Atomic density, 10,000 times as great as hydrocarbons (Figure 10, note the logarithmic scale), is something to fear or ally with. Thermochemical production of hydrogen from water with nuclear power should one day compete with steam reforming of methane, and requires no capture and sequestration.

Summation

My task has been to speak about the fallout from energy systems. When I began my career, this grim task focused on smog, absence of seatbelts, and tanker spills. More recently, the success of offshore exploration and production properly elevated the responsibility of the oil and gas industries for broad protection of the marine environment. My predecessors worried about the great fogs, and sadly London and Paris suffered bad air quality this winter because of the regression to diesel.

The recent decline in air quality in European cities makes me wonder if the greatest disaster has been energy policy, or making the system conscious of itself, reflexive. The reflexivity seems to have helped cause stasis, as basically every interest fights not to lose its absolute and relative position. A mature person who looks in the mirror commits to try to stop aging. We abhor social Darwinism and thus also provide aid to every newborn. Growth of the system allows some shifts but not to the extent that might be normal evolution. We have created a planetary hospital for energy technologies. We put weights around the ankles of the strong and give growth hormones to the weak. The result is that the march of decarbonization, steady over centuries, has plateaued for the last generation (Figure 11). Fortunately, we see signs that the gas and hydrogen are gaining again.

Meanwhile, I have trouble to think of a subject on which there has been a larger supply of fake news than renewable energy. The lies and exaggerations extract the subsidies, which become an addiction, and addicts are terrible, thieving liars. Renewables are renewable but not green.

But evolution works relentlessly. The density of energy consumption at the level of the end user finally drives the system. People keep moving into cities, and the energy consumption per square meter keeps rising. Finally only electricity and gases really thrive in cities. Petroleum is incredibly great stuff. It gave all of us amazing freedom of movement and satisfied our most basic instincts. It gave every Texan the chance to have 400 horses and ride low. But the oil market is gated and attacked by richly armed electricity and energy gases, which have powers and attributes petroleum struggles to match.

Let us make the next and likely final generation of the petroleum economy brilliant, including restoration of landscape that it may have damaged, so that future humans grow ever more nostalgic for the golden age of the auto and bid up the value of its mechanical treasures. Let us grow and operate carefully and tightly an efficient methane economy that spares land and sea, air and water, while providing both power and mobility. Prudently reinjecting carbon, let us discover and produce cleanly and safely the methane that will be the signature fuel of the 21st century.

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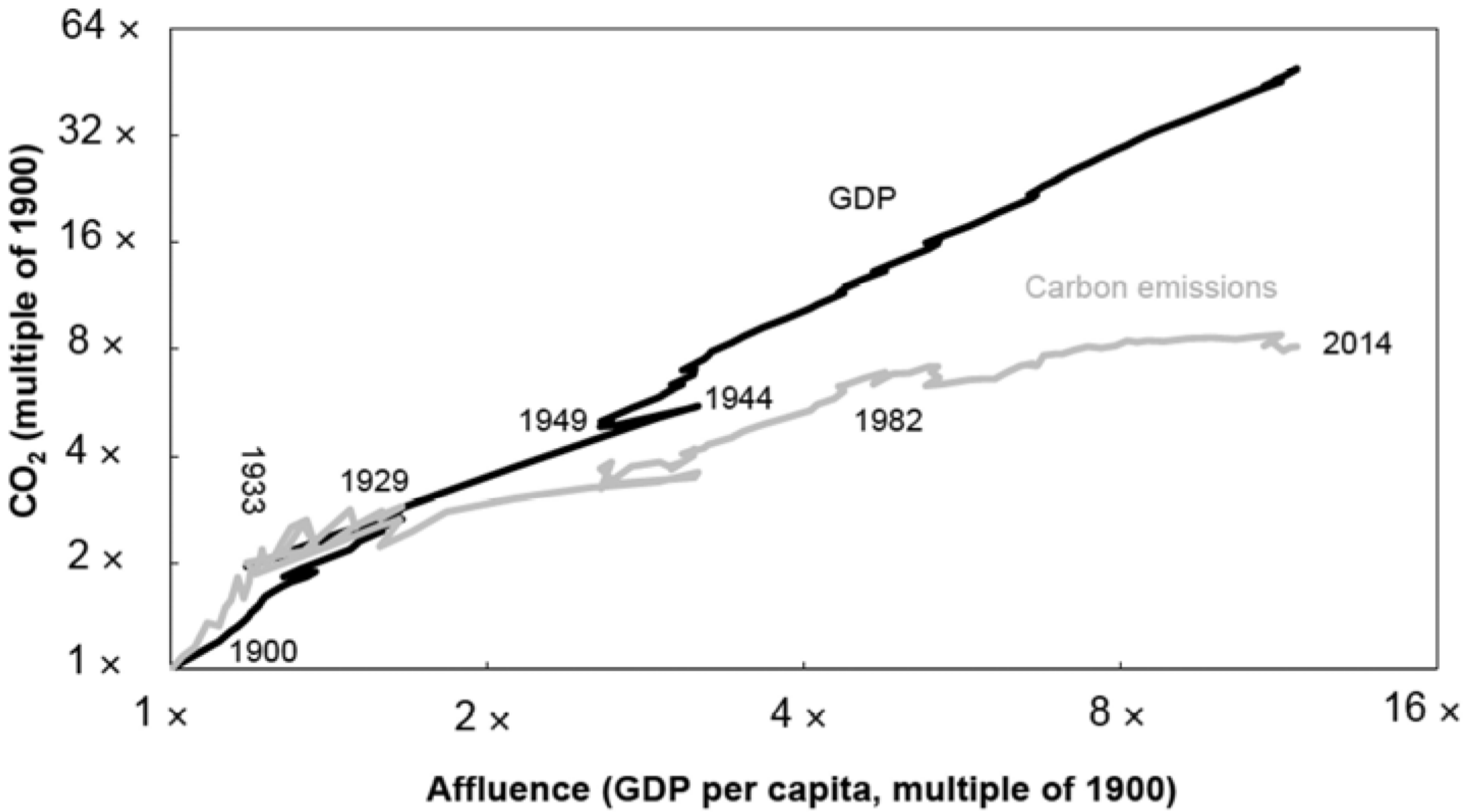

Figure 1. Carbon emissions seem near their peak. If the fall is symmetrical, about 75 years are needed to return to a very low level of emissions. Data sources: Carbon Dioxide Information Analysis Center; Environmental Protection Agency. Credit: Ausubel (2015a).

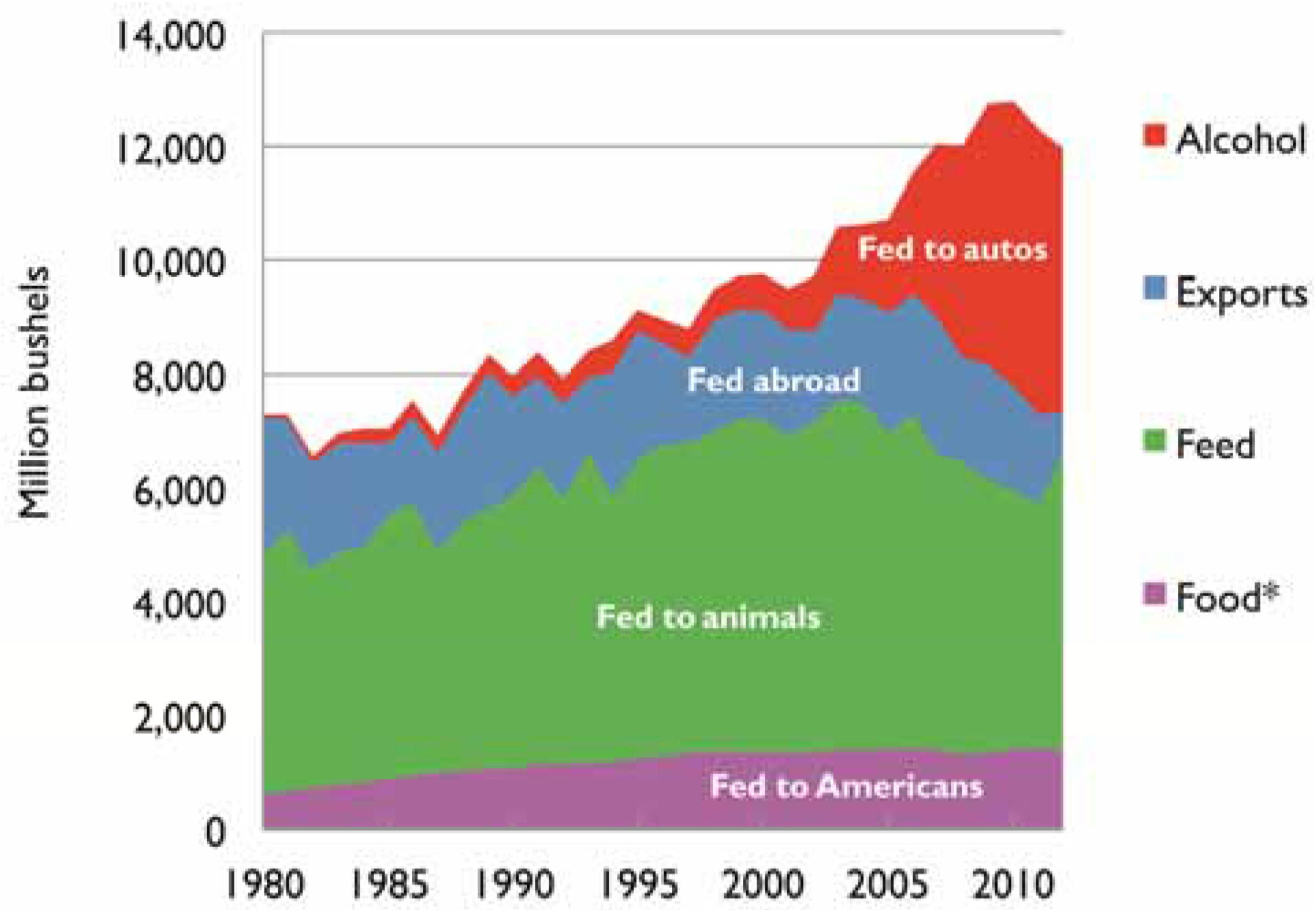

Figure 2. U.S. uses of corn. *Food uses include production of high-fructose corn syrup (HFCS), glucose and dextrose, starch, alcohol for beverages and manufacturing, seed, cereals and other products. Source: USDA Economic Research Service. Credit: Ausubel (2015a).

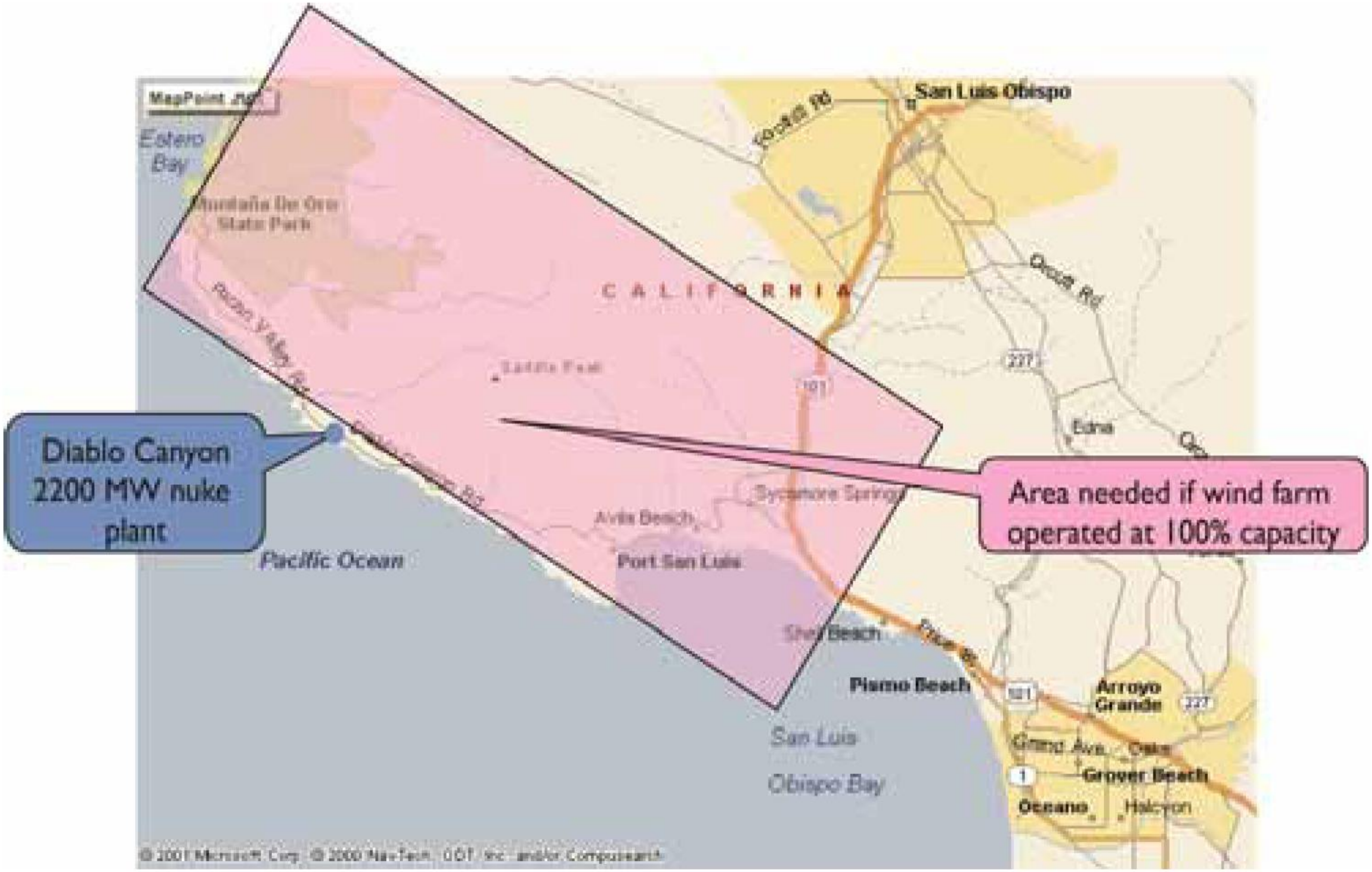

Figure 3. Spatial scale of nuclear and wind power. California coast 2200 MW wind farm based on 1 MW towers spaced 1000 feet apart. Area covered ~75 square miles, assuming 100% capacity factor; i.e., wind blowing at peak velocity 24 x 365 hr/yr. A more realistic 30% capacity would require ~250 square miles. Source: Grant (2004).

Figure 4. Automotive art with recent auction prices. Clockwise from top left: 1936 Delahaye Type 1355 Teardrop Coupe ($2,420,000); 1958 Oldsmobile Ninety-eight Convertible ($258,500); 1956 Aston Martin DB2/4 MK II Supersonic ($2,310,000); 1970 Plymouth Road Runner Superbird ($363,000); 1938 Talbot-Lago T150-C SS Teardrop Cabriolet ($7,150,000). Photo credits: Sotheby's 2013.

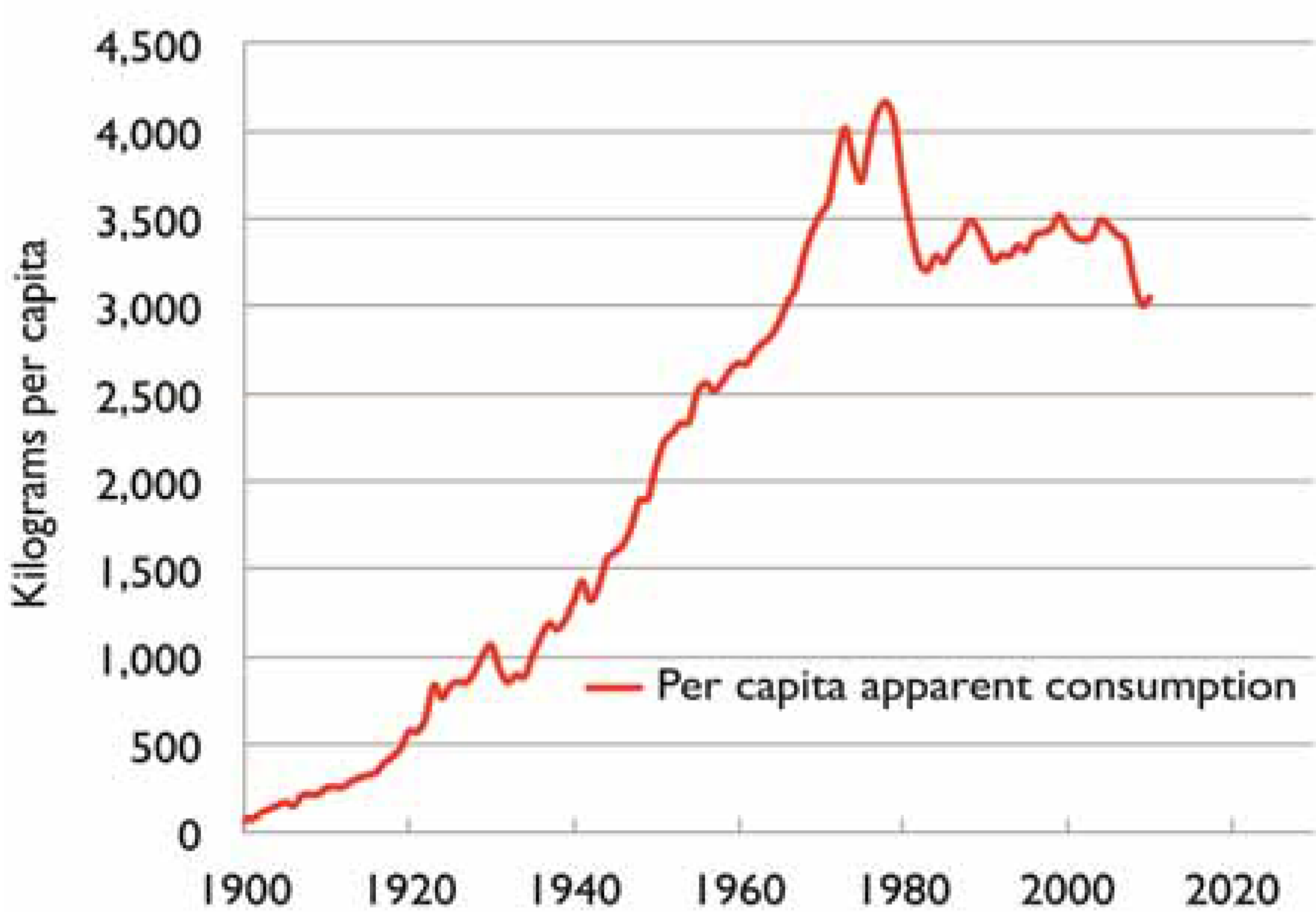

Figure 5. U.S. petroleum consumption 1900-2012. Source: USDOE Energy Information Administration 2013. Credit: Wernick and Ausubel (2014).

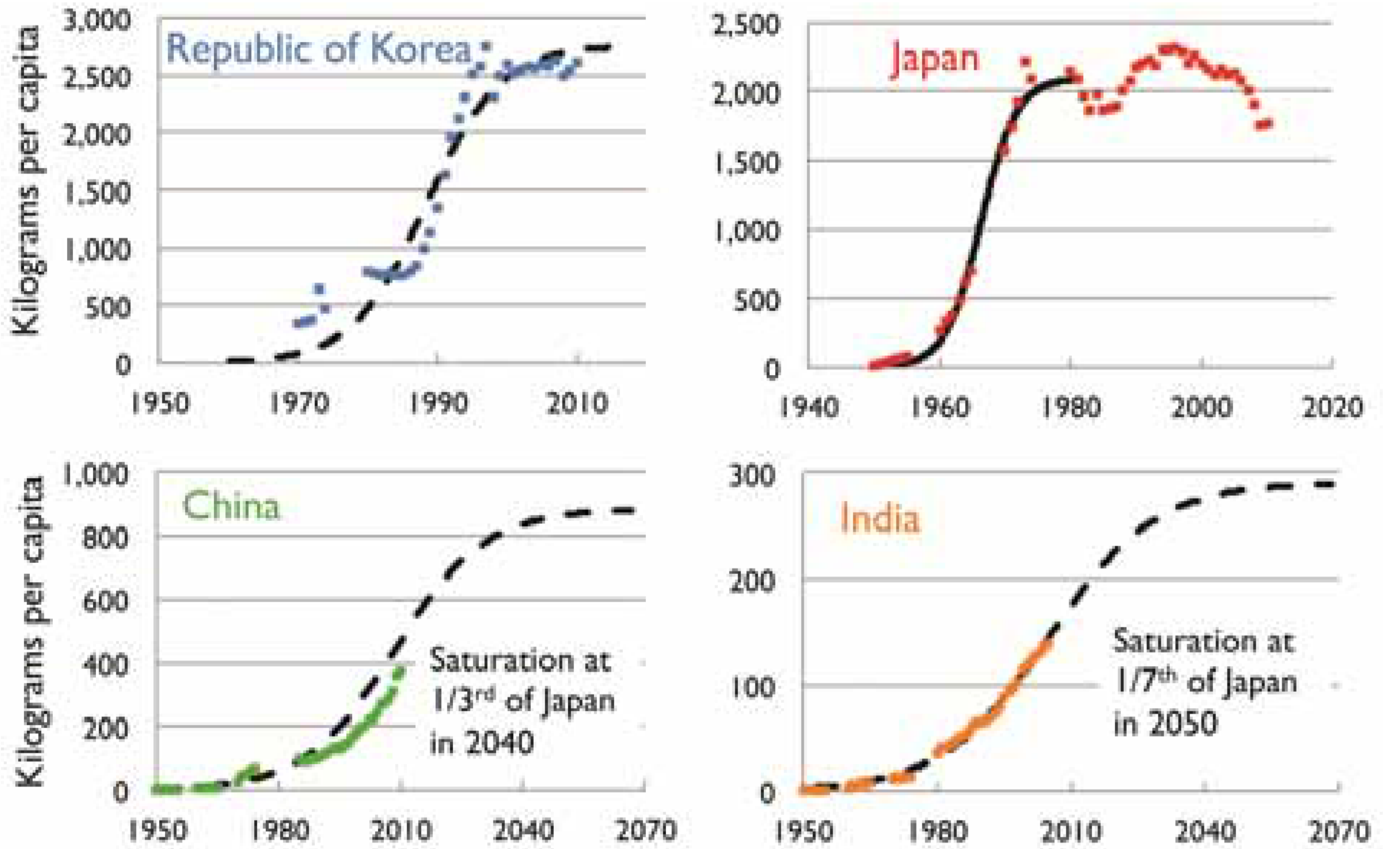

Figure 6. Time and level of estimated petroleum saturation in four Asian nations. Data sources: U.S. Energy Information Administration; British Geological Survey; International Energy Agency.

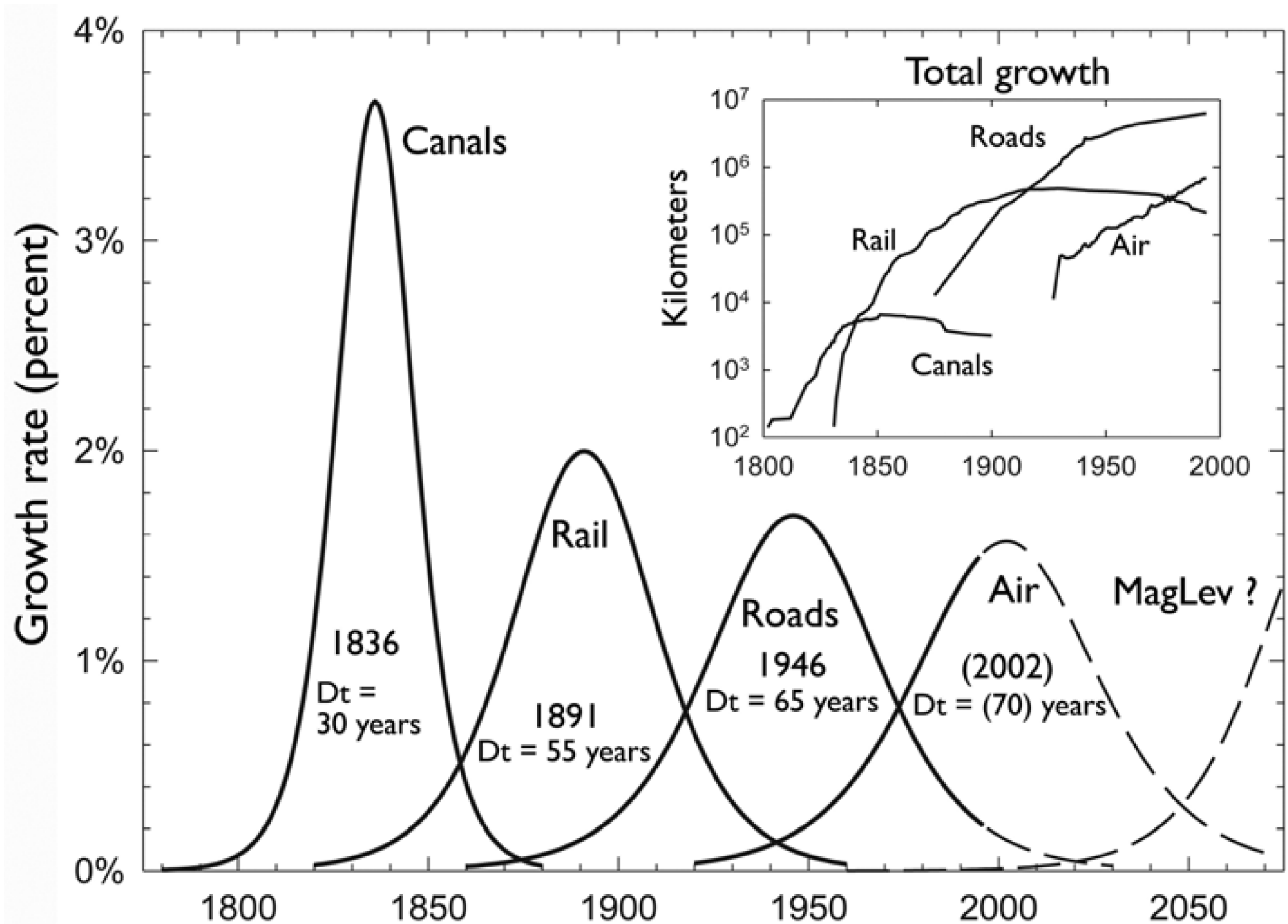

Figure 7. Idealized growth of U.S. transport infrastructure. Credit: Ausubel et al. (1998).

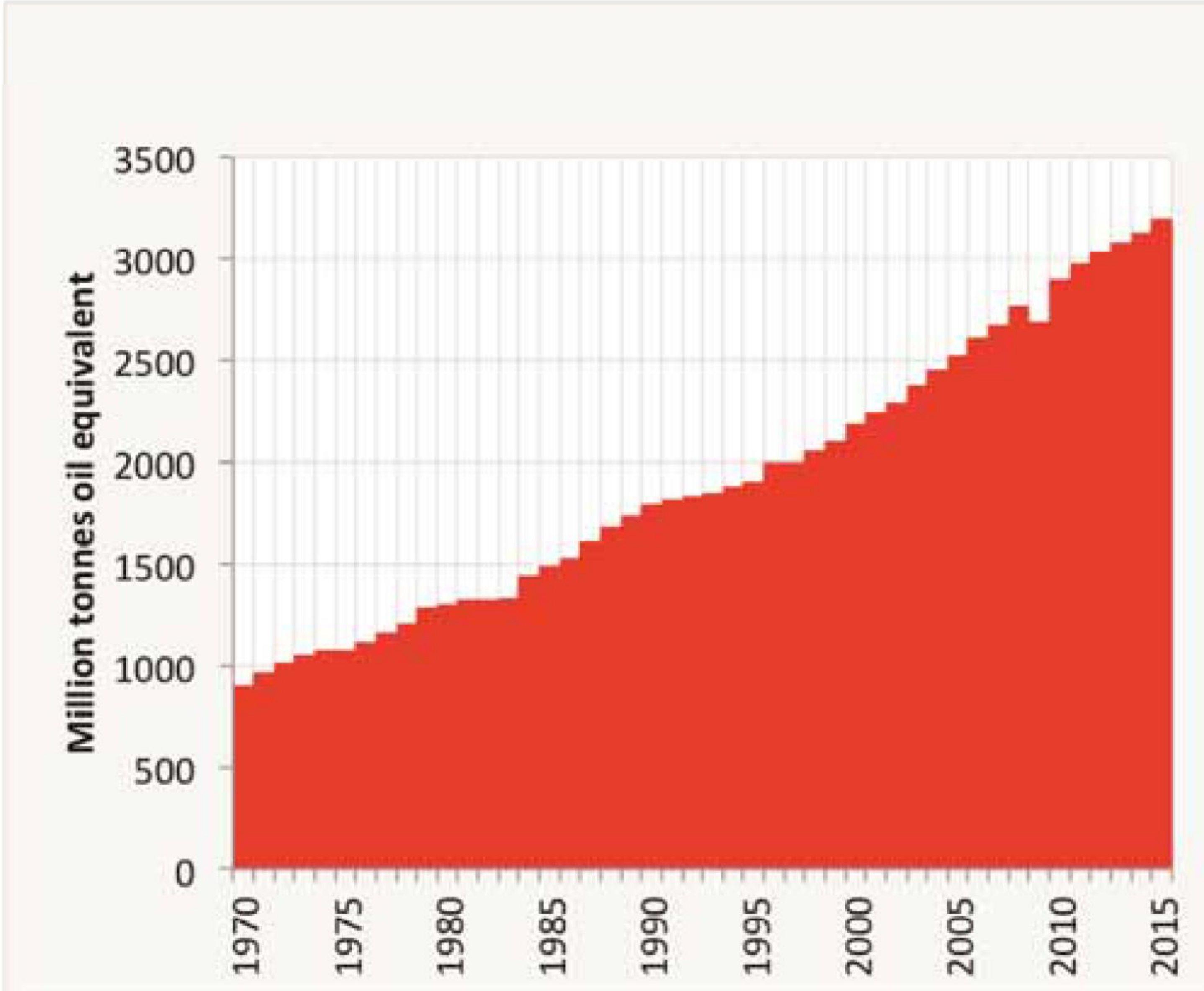

Figure 8. Global natural gas production. Source: Energy Matters, euanmearns.com. Data: BP Statistical Review of World Energy (2016).

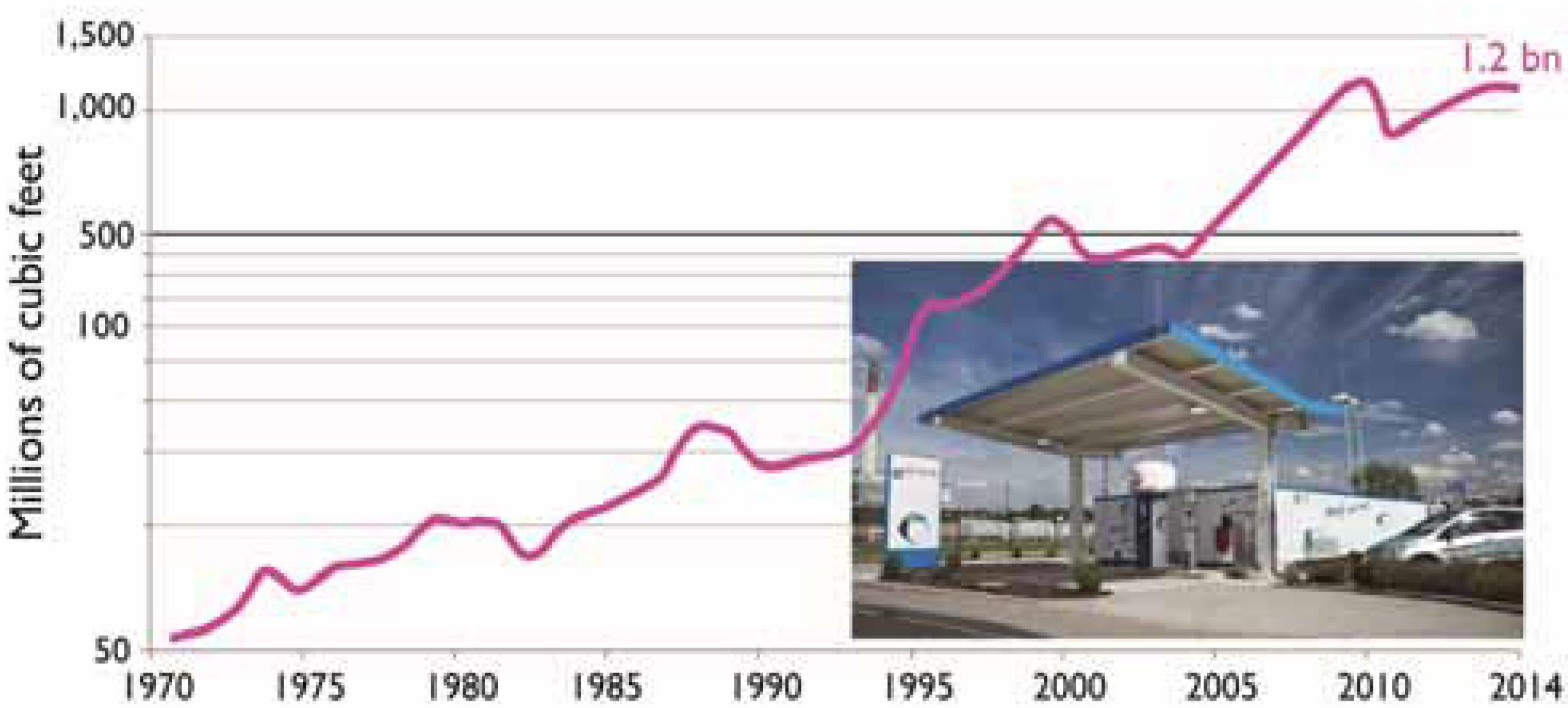

Figure 9. U.S. hydrogen production, 1971-2014 (millions cubic feet). Data sources: U.S. Census Bureau, 1971-2004; U.S. Energy Information Administration, 2005-2013. Photo credit: Air Liquide.

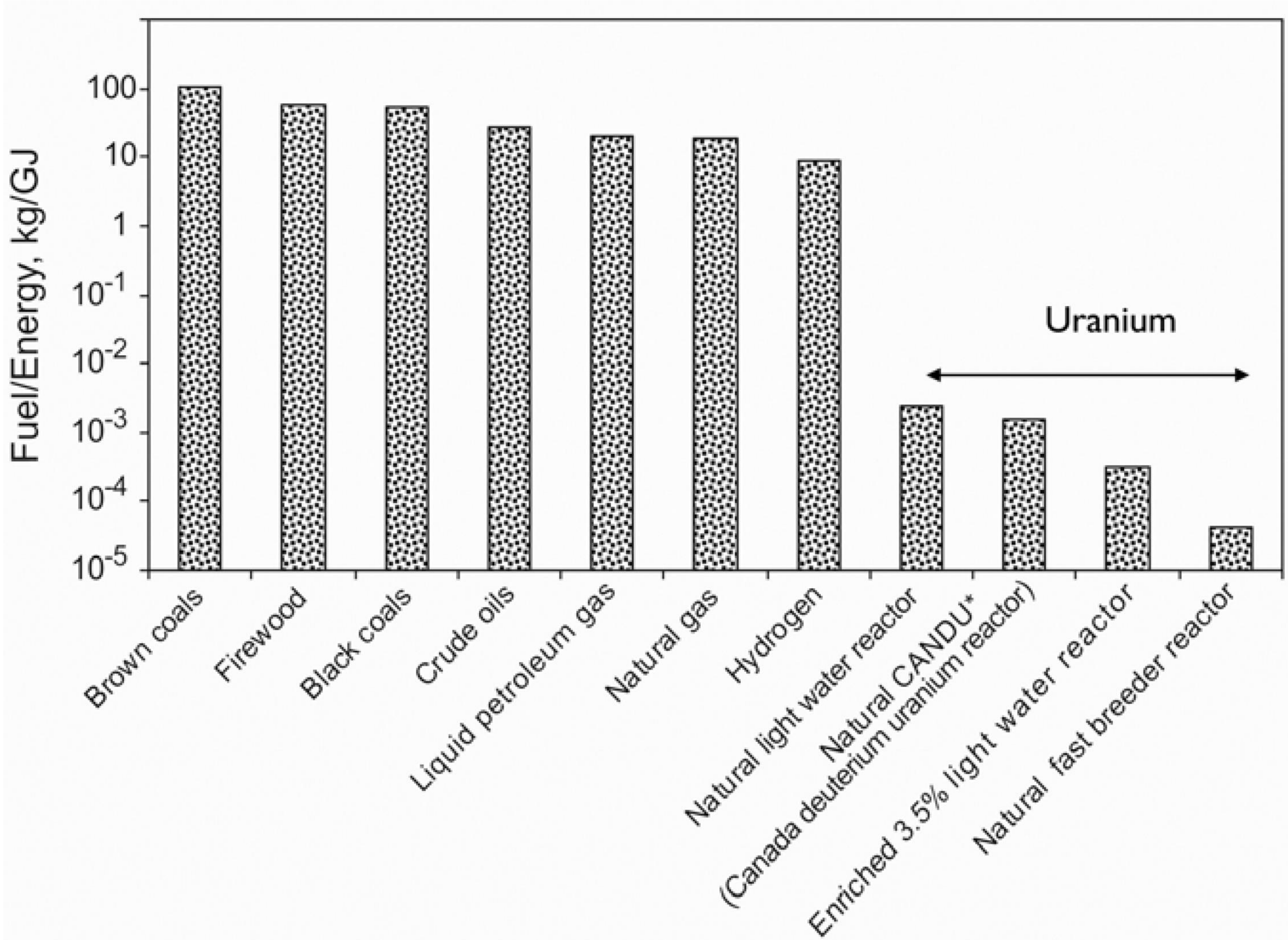

Figure 10. Fuel mass per energy, including nuclear fuels. Economies of scale favor fuels suited more compact than hydrocarbons. Source: Ausubel (2015b).

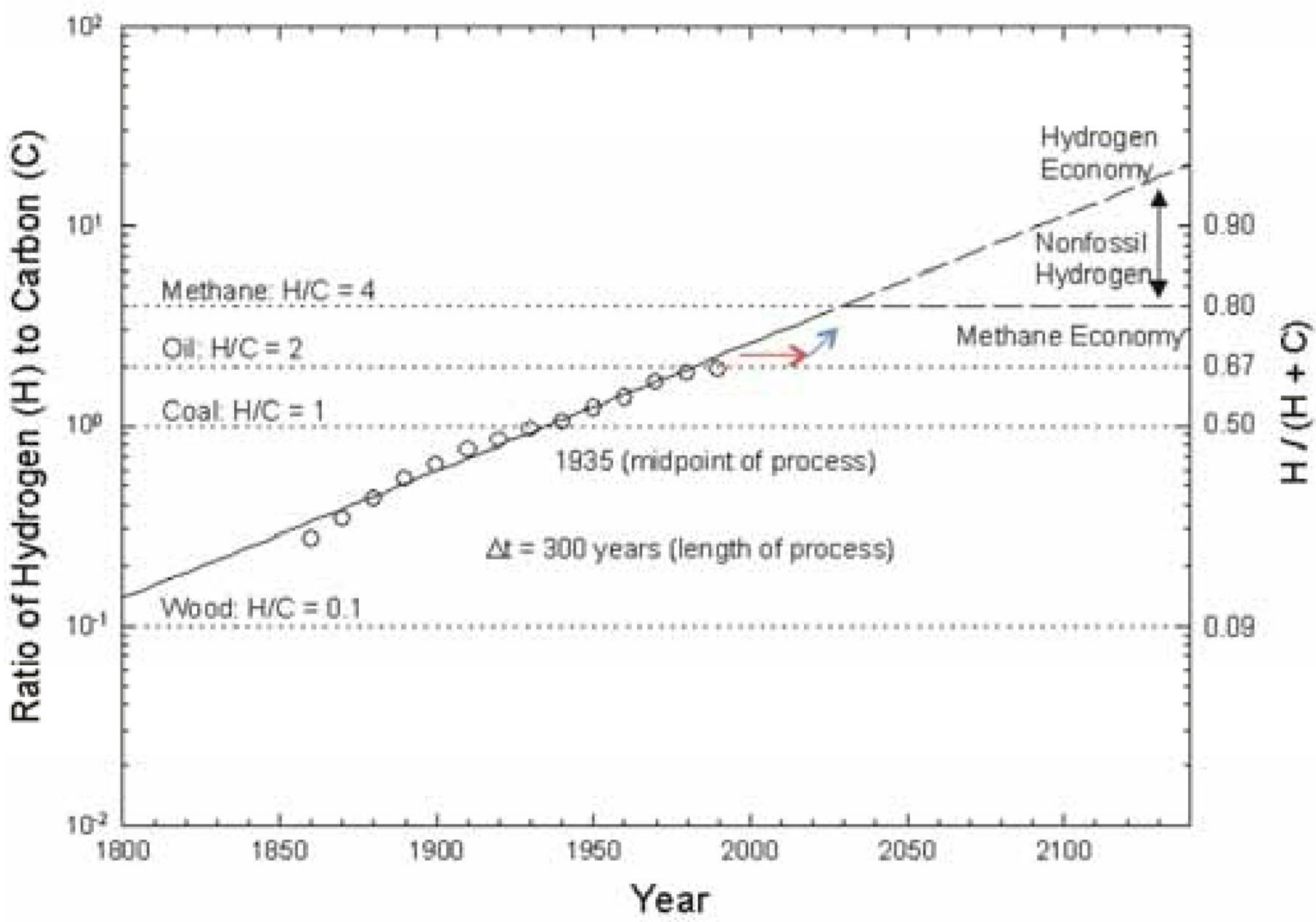

Figure 11. Decarbonization: Deferred a generation by "policy"? Source: Ausubel (1998).

	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

Table 1. Renewable energy production intensities. Data sources: Hayden (2004), J.H. Ausubel and others.