Power and Climate

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SLIDE intro

I speak now because in 1977 I was among the first researchers to make a living from the question of how human activities change the climate. Work to which I contributed in the early 1980s was recognized with the 2018 Nobel prize in economics to William Nordhaus. In the past couple of decades my own work has concentrated on adjacent challenges such as how to measure ocean life and the quantities and origins of hydrocarbons. While I have not participated in the IPCC or other campaigns in the climate wars, I have remained informed about them. I offer perspective and proportion, not the latest gossip or squabbles.

Ten statements summarize my understanding. **SLIDE key points**

1) No one knows what will happen to emissions, how the climate will change, or the consequences.
2) Finally, the question is risk aversion.
3) Biases of stakeholders, whether business executives, environmental activists, or university professors, predictably color risk and environmental assessments.
   That said, I can offer my view.
4) Density of consumption, rising watts per square meter, drives the energy system.
5) Methane and uranium are the way through decarbonization to a hydrogen – electric economy.
6) Public policies to lift efficiency have not much affected long-term trends.
7) Public policies do strongly affect adaptation to hazards, or “Trailer parks causes tornadoes.”
8) Societies are anyway moving indoors and climate-proofing.
9) Nevertheless, seek to monitor environmental variability and change, objectively.

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10) Form a club of China, India, Russia, and the US if you aim to determine the global energy future.

Let me begin with the difference between the unknown and the unknowable.[2] A crucial factor is the level of detail; broad averages may be knowable, but rarely particular outcomes. A similar factor is that the rough hillsides of real life contrast with the smooth surfaces of mathematical models, and a small detail, unknowable, may change the behavior of a system. Moreover, as we complicate our models, they themselves may become unknowable. Researchers and analysts, whether on Wall Street or in natural sciences, tend to blur the distinction and over long periods of time things that were unknowable may become known. But the world and environment of 2050, much less 2080 or 2100, are largely unknowable. Hard limits impede predictability, so let's be modest.

In the year 2012 I led an exercise for the Office of the Secretary of Defense that examined foresight in 1987 for 25 years later, 2012. In 1987 few if any foresaw the explosion from a dozen to 5,000 television channels and from a few sources of news to many millions of individuals reporting and sharing news. No one tweeted in 1987.

Few foresaw the emergence of the Internet and the ability to search it. Facebook, Google, Amazon, and Netflix did not exist.

Few foresaw a boom in shale oil and gas extraction.

When a Bronx police station was called Fort Apache, few foresaw the rally of many central cities including New York,

Few bet on the stagnation of Japan, speedy collapse of the USSR, reunification of Germany, and vertical rise of India and especially China.

A NATO war in Serbia and Kosovo was not in the picture.

Obviously, few perceived a terrorism epidemic and formation of a US Department of Homeland Security.

Most underestimated changes in roles of women and acceptance of more forms of sexuality.

Many try to improve foresight, but anyone who confidently describes 2050 should also be required to put much of her or his personal wealth on the bet. Reports including the IPCC are prepared by people who risk nothing. Corporate directors take risks that the report writers cleverly avoid.

Future greenhouse gas emissions, the fraction of emissions that will remain in the atmosphere, how climate responds to changes in chemical composition of the atmosphere and other factors, how ice sheets respond, and how Ohio or Texas or Venezuela will adapt, each of

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[2]R. Gomory, **The Known, the Unknown and the Unknowable**, *Scientific American*. June 1995, pp. 120.

these questions offers a range of possibilities that jointly broaden into a spectrum from negligible to catastrophic. If greenhouse gas emissions rise 1% per year and plateau, if 40% remain airborne, if climate sensitivity is 1.5 degrees C, if the response of ice is slow, if carbon dioxide pleasures plants, if malaria is a solved problem, then climate change is just chalk on a white wall of successful global development. If emissions rise 3%, 60% stay airborne, sensitivity is 4.5 degrees C, ice sheets collapse abruptly, and public health around the world has reverted to norms of, say, 1900, then humanity faces a crisis, although the climate afflictions may be only a particular darkness in the night of failed global development. Some statisticians try to assign probabilities but the basis for the odds is very questionable – too many unknowables. We have no sure map of the future because no one who has been there has ever returned.

After 40 years of ever more head-scratching about climate, we are left with the broad truth that "Something terrible could happen." We do not know, and probably cannot know, whether Earth's climate system operates gradually like a dial or abruptly like a switch. We do not know whether among the very numerous feedbacks the positive or negative will prevail. The alarmists could be right, but so could the skeptics. In assessing the assessments, we come back to what anthropologists call the cultural bias of the forecaster.[3]

Importantly, cultural bias is quite stable. Humans choose risks in consistent ways. Some people use bicycle helmets and condoms, others do not. Some who use helmets, also rock climb or eat magic mushrooms. If you play cards with your friends, you come to know their risk preferences, and the same is true of investors. To exemplify with the dimension of time, some try to balance carefully between the short and long term, for some the long term dominates, for some the short, and some feel strategy is irrelevant and live fatalistically. Society as a whole usefully spans people who rank and choose risks differently. In fact, the heterogeneity of preferences and expectations is crucial for evolution.

For anyone with a lot at stake, understanding the biases inherent in assessments and forecasts is worth careful effort. It is predictable that the shoe industry is biased in favor of shoes and that energy industries tend to emphasize benefits rather than risks or costs of energy. You don't need professors to tell you this, and professors tend to perfume their own bias in favor of more money for research and education.

For the year 2000 – remember the Millennium Bug – I wrote a short essay titled Dis the Threat Industry[4]. The CIA for decades overstated the size of the Soviet economy and thus its threat to the USA. Worldwatchers have yearly forecast a food crisis from the exhaustion of soil or oil since the early 1970s. The Wall Street Journal editorial pages daily scare entrepreneurs with multiplying regulations stifling markets.

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[3] Thompson, Michael, Richard Ellis, and Aaron Wildavsky. "Cultural Theory." Routledge, 1990.

[4] http://phe.rockefeller.edu/dis_the_threat/

Diminishing a problem unemploys not only experts and their publicists. Threats beget threat removal industries. Fears about asbestos created the asbestos removal industry, which in turn needed to feed fear of asbestos. Environmental protection agencies feared to reverse themselves, even as evidence for the removal programs itself got removed. The CIA overstatements boosted the USA military, whose growth in turn justified the Soviet military's growth, which then further nourished the budgets of its USA counterpart. The Cold War shows how hard it is to break a threat cycle.

Of course, the USA and USSR did endanger one another. And I am not saying disbelieve global warming or ignore anthrax. But fears of germ warfare sustain military budgets. We now have a large industry built around fear of climate change. Members of the industry may entirely believe what they say but their own bias weighs heavily, even as they may rage about the bias of someone paid by an oil company. At issue is not only money but identity, status, and pride.

America tends to accept more risk than many other nations. The electric utility industry tends to accept less than other industries because of the importance of its services and the longevity of its infrastructures. Within the power sector, each firm needs to understand its own risk preferences.

That said, I offer my own view. I have the bias of someone keenly interested in the history, evolution, and diffusion of technology. I once wrote a paper called "Because the human brain does not change, technology must." That encapsulates much of my bias – more confidence in technical than behavioral change.

In my view, over the long run the spatial density of energy consumption at the level of the end user drives the evolution of the energy system. Think of Earth at night and the most brightly illuminated spots, those with the highest demand or usage in watts per square meter. These spots, basically modern cities, or one might say, data centers, proliferating in China and India, drive the overall system.

As the spatial density of energy consumption rises, only electricity and gases satisfy demands for precision, power, cleanliness, reliability, and other attributes. In turn, for generation, the sources that can achieve economies of scale win over the long run, and the firms that can capitalize and manage them. The compact and thus *scalable* sources of power generation are methane and nuclear.

Let's not let enthusiasm for small business, the famous family farm, obscure the continuing power of economies of scale. Microsoft, Amazon, Google, and Facebook, and a dozen or so other firms, including Chinese, run the global IT show. Electricity affordably and reliably meeting the enormous demands of Asian cities may favor power parks generating 5 GW or more and concomitantly large enterprises.

Methane has the greatest energy density of the hydrocarbons, measured for example as the kilos of fuel to produce a joule of energy. **SLIDE HC DENSITIES** The methane molecule's ratio of four hydrogen atoms to one carbon atom also gives it climatic and other advantages over oil, coal, and wood which burn more Cs for each H. At high temperature and pressure, it can also operate in highly efficient and very powerful but compact units. In the 1990s and early 2000s, I and my colleagues, with occasional support from EPRI, explored zero-emission power plants which capture and sequester the CO_2 in plants that use supercritical CO_2 as the working fluid (like the Turk plant). **SLIDE ZEPP** Our ideas, published in *Industrial Physicist* and elsewhere, have been developed, patented, and popularized by Rodney Allam in his ventures such as Netpower**. SLIDE NETPOWER** We wish him a great fortune. Carbon capture with coal rather than methane as the feedstock was always a clumsy idea.

Methane of course is booming. **SLIDE GLOBAL METHANE** Here you see the rising global use. The scale of investments is immense, for example, the $34 bn Icthys facility off northwestern Australia. **SLIDE ICTHYS** The investments reflect increased understanding of the astounding abundance of methane, both offshore and onshore, including in Ohio and Texas. Under the seafloor, 2018 saw huge gas discoveries, tens of trillions of cubic feet, off places as diverse as Northern Russia, Cyprus, and Guyana.

Atomic power of course is 10,000 times as dense as hydrocarbons, or one could say 10,000 times as powerful as TNT or dynamite, the reason for atomic bombs and for nuclear deterrence. **SLIDE HC WITH NUKE DENSITY** Contrary to many expectations, Earth has been safer for human during the atomic era. **NUCLEAR WEAPONS SLIDE**

The nuclear power industry worldwide is growing only slowly but there are some interesting developments involving Russia and China. The shipment of LNG from Siberia to China is already very attractive and would become even more attractive if climate warms and Arctic ice diminishes, but how to extract and transport all the polar methane? **SLIDE ARCTIC ice decline**. Russia is now putting into operation 300 MW nuclear barges to power the gas extraction and communities associated with it. In turn, nuclear ice breakers can navigate the Northern Sea Route now, year round, and in future winters, when ice will still persist. By the way, the Chinese are building their own ice breakers, including nuclear powered. **CHINA ICE BREAKER**

Importantly, small modular reactors already abound. Over 140 ships are powered by more than 180 small nuclear reactors, and more than 12,000 reactor years of marine operation have been accumulated with an almost perfect record. Most nuclear vessels are submarines but some are ice breakers and aircraft carriers.

Smaller units may become popular, fulfilling the wish for distributed generation. **SLIDE HOLOS** The Strategic Capabilities Office of the Pentagon and its counterparts in China and Russia are investing in mobile reactors to meet demands for power in remote and austere locations, like the Arctic. The US program aims for between one and ten megawatts of energy, weight less than 40 tons, portability by truck, set up in 3 days, and function of at least 3 years but potentially with operational life up to 60 years.

More generally, we need to watch growth of nuclear power in China, where 16 gigawatt units are under construction, and also India, where seven large units are under construction. Whatever they buy will enjoy learning curves and create excess manufacturing capacity that can lead to relatively cheap or affordable plants of similar design for many other parts of the world.

While the energy economy of 2050 is hard to foresee, LNG tankers sailing every few days from nuclear-powered Siberia to the South China Sea could be a lucrative part of it.

I continue to take keen interest also in large nuclear plants that can operate at high enough temperatures to fire cycles attractive for producing hydrogen as well as electricity. Hydrogen solves the problem of energy storage and transforms the economics of the nuclear industry. Just as electrification of mobility can more or less double the market for electricity, production of hydrogen can allow nuclear power to make something besides steam, something lucrative, if fuel cells continue to improve and proliferate. Hydrogen production and use keep growing nicely in the US. **SLIDE H2**

I despair about renewables. They may be renewable but they are not green. The true green credo is "no new structures." But renewables require immense acreage, because they produce few watts per square meter averaged over a year, and thus require hundreds or thousands of square kilometers to generate the total yearly kilowatt hours of, say a 1000 MW nuclear plant**.** **SLIDE WATTS PER SQ M.** At sea they may even require new islands. **SLIDE OFF SHORE WIND** They pollute seascapes and landscapes with moronic tall towers or dark metallic carpets and require immense amounts of concrete and steel. Comparisons of demand for space and materials with methane plants embarrass the renewables. **SLIDE DENSITY COMPARISON** Egypt's 14.4 GW Beni Suef and sister NGCC plants, completed in 28 months and serving 40 million people, would have required 900 sq miles of solar or 5000 of wind.

And they need batteries for energy storage that require hideous mines in Chile, Argentina, and Bolivia for lithium and other metals. Try opening a lithium mine in Massachusetts or California. **SLIDE LITHIUM MINE** And finally, the actual experience of renewables is that they do not reduce CO_2 emissions – Germany's are flat after spending $580 bn. Renewables may pay off influential stakeholder groups, provide tax benefits, and launder $C0_2$ emissions, but they do not reduce the emissions.

For all the decades of renewable noise, of global primary energy in 2017, solar PV, solar thermal, and wind provided about 7 exajoules of 566, or 1.2%. In 2016 they provided 5.4% of the world's electricity – wind 952 b kWh, solar 343 b kWh. Renewables of course are inherently inefficient, with capacity factors of 15%-20% for high-performing solar and about 35% for wind, so immense capital always sits on its hands, a reason their true cost will always be high. The flaws of these sources will magnify as they seek to multiply. The effect of blocking nuclear and favoring renewables for the last few decades has been to superannuate coal and stall a decarbonization trend that had proceeded nicely for 150 years without so-called energy policy. **SLIDE DECARB**

Of course, renewables attract us more if we can destroy demand and use much less energy in the first place. The good news is that energy systems have been getting more efficient since ever, whether chimneys and forges, lamps, or motors. US energy consumption per GDP exemplifies the trend. **SLIDE ENERGY GDP** The bad news is that public programs to accelerate efficiency through weather-stripping or whatever have had scant success. Higher energy prices and/or taxes do use up the energy budgets of consumers for a while and suppress consumption, but after a while cyclical forces come into play and bring prices down, and consumption grows again, if only at the general level of the economy in the rich countries.

A rising intensity of use of electricity per dollar of GDP up to the mid-1970s caused the US electric power industry to vastly overestimate future demand. **SLIDE PEAK** Intensity of use has gradually fallen since then. Demand continued to grow because of rapid population and GDP growth, but if population growth slows and intensity of use continues to fall, then America could be around peak electricity.

On the demand side, one mega-question is whether electricity will beat oil in the market for mobility. It could happen – but fuel cells and H_2 could also beat batteries. Many paths compete for the wells-to-wheels market**. SLIDE WELL TO WHEELS**

A more fascinating and important question is how IT and AI will alter demand. Siri and Alexa are hungry goddesses. I mentioned illuminated skylines of cities but consider that a square foot of a data center guzzles more than 100 times the electricity of a square foot of a skyscraper. More than 1500 skyscrapers of more than 40 stories now define the world's cities, but the population of enterprise-class date centers now exceeds 5000. The Switch Corporation's Citadel data center in Northern Nevada will be 7.2 m square feet, 0.25 square miles, and more than twice the area of the world's largest office building, the Burj al Khalifa in Dubai. It will consume 650 MW around the clock. In round numbers, one million square feet of a new data center demand about 100 MW to live, a density of about 1000 watts per square meter. The world's most powerful computer, the Summit Supercomputer in Oak Ridge, demands per square foot about 20 times a conventional data center. While efficiency gains continuously, the cloud is nevertheless a glowing cloud of electrons.

Connecting the clouds and all the devices that rely on the clouds also uses a lot of electricity. Per unit of data transported, wireless systems use about ten times the juice of a wired system. Each smart phone finally uses about the same electricity as a high-efficiency household refrigerator. The global population of smart phones may pass five billion in 2019. Meanwhile, Amazon has already sold an additional 100 million digital assistants such as Alexa. We are creating a world with hundreds or thousands of radios per person. The system now operates at 4G, which involves about 20 base stations per square km, globally about four million cell towers. Present information networking uses about 200-300 TW hours per year, about $20 billion worth.

5G, one hundred times faster and needed for high resolution streaming, virtual reality, and autonomous devices, may employ as many as 2000 base stations per sq km, and the Global

Small Cell Forum of the telecom industry anticipates for 2025 some 70 million base stations and networking demand for $90 bn worth of electricity. All this will come before autonomous vehicles and indeed is the prerequisite for the sensors and AI that will make autonomy safe and effective.

Whether or not the autonomous vehicles (AVs) use batteries or hydrogen for propulsion, they will use electricity to process their zettabytes and yottabytes of data. In effect each AV will be a high-level server. A fully connected car is expected to generate 25 GB of data per hour. If the car is used 2 hours each day, 60 such cars would generate a petabyte in a year, 60,000 cars an exabyte, and 60,000,000 cars a zettabyte. The present global annual market for servers is about 10 million units. Motor vehicle sales globally are an order of magnitude larger, about 100 million. No wonder software and hardware companies now read *Car and Driver*. Powering a global stock of one billion servers that also happen to be autos will be a good business, even apart from propulsion. IT can drive a new wave of global electrification, including for mobility. Keep an eye on energy use patterns in Northern Virginia, which hosts the world's largest concentration of large data centers.

Returning to the supply side, US power generation companies have decoupled sulfur from US GDP. **SLIDE SULFUR** The happy trajectory comprises more effective technologies, fuel-switching, and regulation. Companies such as AEP have decoupled NOx as well as SOx. **SLIDE AEP NOX SOX** And the trajectory of decoupling of CO_2 looks well-established for the US as well. **SLIDE CO2** The question is the rate, and whether a bit of capture and sequestration from methane is needed to ease worries.

The American worries in recent years about climate have tended to concentrate on storm surges, floods, and fires. Hurricane Harvey flooded the rich modern city of Houston. **SLIDE HOUSTON** Houston quickly absorbed the losses and is booming again. Ditto New York City for Sandy, whose traces disappeared in about five years. Looked at over decades and centuries, in fact, the American and global record for reducing lethality and damage is very good. Millions of people died in weather-related disasters in Russia in the 1920s and 1930s, in Bengal in the 1940s, and in China in the 1960s. These examples show the complexity of cause and effect. Nature pleads not guilty and blames Josef Stalin, World War II, and Mao Tse-Tung.

The same hurricane passing over the island of Hispaniola causes little harm in the eastern half called the Dominican Republic and disaster in the western half called Haiti. As former Martin Marietta CEO Norm Augustine liked to say, "Trailer parks cause tornadoes."

Every region of the world experiences natural hazards, whether earthquakes and volcanism, tsunamis, fires, heat waves and droughts, floods and storm surges, hurricanes and typhoons, or ice bergs and ice storms. Whether or not their frequency or intensity has risen, satellites, cell phones, and the Weather Channel have lifted awareness and made disasters a source of high ratings.

The dollar damages tend to keep rising, including in the US, even if the hazards are more or less the same. The chief causes are more humans, more wealth, and more of us choosing to reside in hazardous regions. Programs of national flood insurance in the US have encouraged risky behavior, and so do TV programs about beachfront living. In January PG&E filed for bankruptcy associated with billions of dollars in exposure for recent California wildfires. However, US rates for super-cat (or super-catastrophe) insurance have fallen in recent years and stayed low, a fact suggesting that an upward trend in occurrences has yet to establish itself.

A big question for climate change is whether or how much it is accelerating rise of sea level and salt water intrusion. Sea level has been rising about the thickness of a nickel each year for many centuries. A couple of recent analyses find an acceleration during the past 10-20 years, but the data are not yet strong. Moreover, not everyone will experience the same rise – it will rise higher in areas where we also pump gas and oil from the ground and less in areas where land rebounds from compression during the last ice age. Do Americans want to wait until we know whether the actual sea level rise will be one or two or three feet by 2100? Here we come back to risk aversion. We can lessen worries by investing in both defense and retreat.

Much of the discussion about adaptation is about fresh water, and here, as with energy, we must think about managing both supply and demand. **SLIDE US WATER** It shocks most Americans to learn that water use efficiency has improved greatly in the US over the past 50 years. According to the USGS, utilities cut fresh water withdrawals for thermoelectric power by about one-third, 50 billion gallons per day, between 2005 and 2015. Since 1975 the USA has absolutely reduced water withdrawals while adding 118 million residents and quadrupling corn and soy production. Yet here and in most of the world water use efficiency is far from its limits. If we can continue improving our water use efficiency a few percent per year, then it may matter little if rainfall declines.

In general, one can make the argument that while numbers of people and quantities of natural resources were extremely important well into the 20th century, humanity has now entered an era when, rather than labor and tons of minerals or acres of land, what matters most are information and capital. **SLIDE FOOD GDP** At the global level, rising GDP elicits only modest increases in calories and protein. People buy little more rice as their income rises.

In fact, the agricultural sector astonishes in decoupling production from land and other inputs. **SLIDE CORN ACRES** Up until 1940, more American corn required more American acres. But since then, other inputs including irrigation, fertilizers, herbicides, and pesticides but increasingly more information in forms such as better seeds, smarter spacing of plants, and more accurate weather forecasts account for rising yields. Precision agriculture does not need as much land or water or other inputs. While professors who cannot tell corn from soy keep prophesying the end of yield growth, American farmers have relentlessly lifted yields for 80 years.

The result is vast overproduction globally in agriculture which causes ethanol for cars, hamburgers, and obesity. Moreover one-third or so of global food production is either thrown away as waste or lost because of poor storage. People who worry about climate and agriculture need to realize that global agriculture could be reduced by a third or more and do a better job of feeding humanity while also sparing land for nature, including forests. The world's challenge is too much, rather than too little agriculture.

More generally, contrary to the expectations of most ecologists, the total global biosphere has been growing, not shrinking, since about 1990, in a phenomenon known as global greening. **SLIDE GREENING** Some of this owes to longer growing seasons that could be associated with climate change and with more CO_2 in the atmosphere, which speeds the growth of most plants. Between 2000-2010, the continents added a Pennsylvania of forests by subtracting a Pennsylvania of forests in the tropics but adding two in the temperate and northern regions.

A lot of ink also describes indoor agriculture. After the US, by dollar value the Netherlands export the most agricultural produce. They accomplish this feat by enclosing about 36 square miles, one and a half times the size of the island of Manhattan, in greenhouses. Precision agriculture operating day and night year-round enables the Dutch to grow more than 140,000 tons of tomatoes per square mile. One has to ask with an open mind how climate will matter for food in 2050 or 2100.

Whether or not much more agriculture goes indoor and vertical, more and more activities are climate-proofed. Think of football stadiums in Indianapolis, Detroit, and Minneapolis. At 173,000 square feet, Ohio's Kalahari indoor water park near Sandusky is the largest in the United States (and uses about 7 million kWh a year). Germany has created a sunny tropic domed island not far from Berlin. **SLIDE TROPICAL GERMANY** Thinking of shopping via Amazon, which does not require a trip even to the air-conditioned mall. The fraction of the economy directly sensitive to climate change is small, a few percent.

A simple thought experiment verifies the lack of sensitivity for the US. USA cities, say Tampa, Dallas, Chicago, and Seattle, have very different climates but very similar GDP per capita. Medical care is similar in Houston and Boston. One reason is that in reality humans on average spend only about one hour per day outside exposed to the elements.

To the extent Americans are relocating to new caves, they are also choosing warmer locales. The increase of population in California, Nevada, Arizona, Texas, and Florida means that the average climate that a person resident in the USA experiences has already warmed several degrees over the past fifty years. The average climate of Texas is more than 10 degrees C warmer than Michigan. A person moving merely from Columbus (52.9F annual average temperature) to Nashville (59.2F) is choosing a warming of 3.5 degrees C, a bit more than the central projection for a doubling of CO_2. In a profound sense America has already adapted to a warmer climate. Similar migration toward warmth has occurred within Canada, Sweden, France and numerous other countries

This leaves the question of what we really should worry about, and the answer is ecological, rather than economic. Some species on land and in the sea can migrate as human snowbirds do, but a lot cannot. Moreover, humans are emotionally attached to many landscapes and associated cultural heritage.

And, as said at the outset, something terrible that we cannot foresee could happen. One specter is abrupt increases in asylum seekers and migrants. But who knows what the baseline global situation for migration will be in 2050. Perhaps every person will already have a global ID based on iris or DNA and a social score that permits movement or not. When I see how obsessed young people are with smart phones, I wonder whether future humans will seek only virtual experiences. Riding spin bikes with video screens affords people the chance to tour the world without the headaches of travel.

The global warming industry tends to assign every woe and misfortune from higher beer prices to more heart defects to climate change. But a lot good has happened in the world as well, even just in 2018. I have mentioned astonishing rises in agricultural yields. Scientists and journalists such as Steven Pinker, Gregg Easterbrook, and Hans Rosling have written powerful books about recent progress achieved in human well-being. By almost every measure, life for most humans has improved since climate worries began. Levels of war and violent conflict are at or near historic lows, lives are longer and healthier, incomes are higher, the fraction of poor keeps falling, women have won greater equality. Stoop labor whether for income or the household is much rarer. Simple conveniences, most powered by electricity, have made life almost imaginably easier than for the families who simulated an 1880 Frontier House in the 2002 reality TV show.

Maybe climate change and CO_2 should even get some of the credit for the good things that have happened since 1990 or so when most experts think human-induced climate change became detectible, including the amazing success of farmers. I work next door to a hospital, and when I read the climate literature it reminds me of the reports only of admissions, not of those successfully treated and departing.

Alternately, how do we think human history and global ecology would have differed over the past century if CO_2 had remained at the 1910 level of 300 ppm rather than rising to 400ppm? In truth, not much has happened. The problem is still, Something terrible could happen.

To earn timely warnings, let's make sure that the environmental monitoring is really good and as objective as we can make it. My father was a professor of European history. When I began my career and explained to him that my work would involve forecasting decades ahead, he remarked, "There is more disagreement about the past than about the future." In this city, think of the endless rewriting of the arrival of Columbus in the New World.

Still, we can bring to bear more or less evidence. A particular concern is the under-sampling of the oceans. While the atmosphere has Alzheimer's and cannot even remember its temperature from earlier the same day, the ocean has a good memory and is key to knowing whether climate is changing. Some recent papers have made big claims about finding the heat of global warming in the oceans. But if we divide the ocean into 10,000 boxes of equal volume, 9,000 of them have no measurements. **SLIDE OCEANS** Analysts are trying various tricks to squeeze new insights from old, scant data sets. It is time America and other science-rich nations get beyond sensing in salt water like an abstract Russian painting of the 1930s and invest in a comprehensive global ocean observing system that could much more reliably tell us year by year and decade by decade what is happening to heat storage in the oceans.

My last point is about actors. Climate is surely global but including every national flag in the international attempts to foster actions to lessen worries has made the job less tractable. In truth, the paths that China and India follow will largely determine Earth's future atmosphere and climate. The USA matters also, because we have a large economy and capacity to develop and market technologies and services to reduce emissions. Russia matters because of its gas resources and nuclear technologies. These four nations, if they can set aside Great Power rivalries, could form a Climate Club powerful enough to achieve strong objectives. Forming and operating the Club would require skillful diplomacy as well as domestic political craft to build and sustain support within each nation. The Club could act while the 25,000 diplomats now making a living from climate keep agreeing to agree.

To re-cap **SLIDE RE-CAP**

1) No one knows what will happen to emissions, how the climate will change, or the consequences.
2) Finally, the question is risk aversion.
3) Biases of stakeholders, whether business executives, environmental activists, or university professors, predictably color risk and environmental assessments.
4) Density of consumption, rising watts per square meter, drives the energy system.
5) Methane and uranium are the way through decarbonization to a hydrogen – electric economy.
6) Public policies to lift efficiency have not much affected long-term trends.
7) Public policies do strongly affect adaptation to hazards, or "Trailer parks causes tornadoes."
8) Societies are anyway moving indoors and climate-proofing.
9) Nevertheless, seek to monitor environmental variability and change, objectively.
10) Form a club of China, India, Russia, and the US, if you aim to determine the global energy future.

Finally, what about a firm making and distributing electricity? First, one need not take a side in the falsely polarized climate issue. Maintain some humility about times as distant as 2080; the integrated circuit and the word software were invented only in 1958, 61 years ago. Much we would like to know will stay unknowable. We do need to assess our own risk aversion and make some investments accordingly. The investments should foster decarbonization via methane and nuclear, and efficiency and reliability. Consider carefully whether to promote pictures of wind turbines and solar roofs as images of the future. Keep climate-proofing and reducing threats from related hazards, many of which people induce or amplify. Give away 5G smart phones and digital assistants if you want to promote electrification. Support and share in the costs of global environmental monitoring systems. Forego the big multilateral blah-blah and support careful relationships among China, India, Russia, and the US to understand and shape the evolution of the global energy system and our climate. And stay profitable. Red ink is not green.

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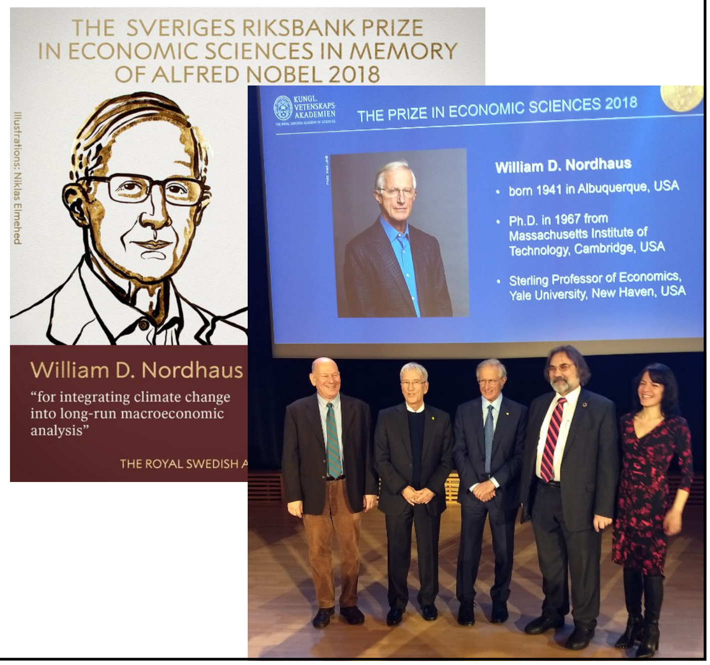

Key points

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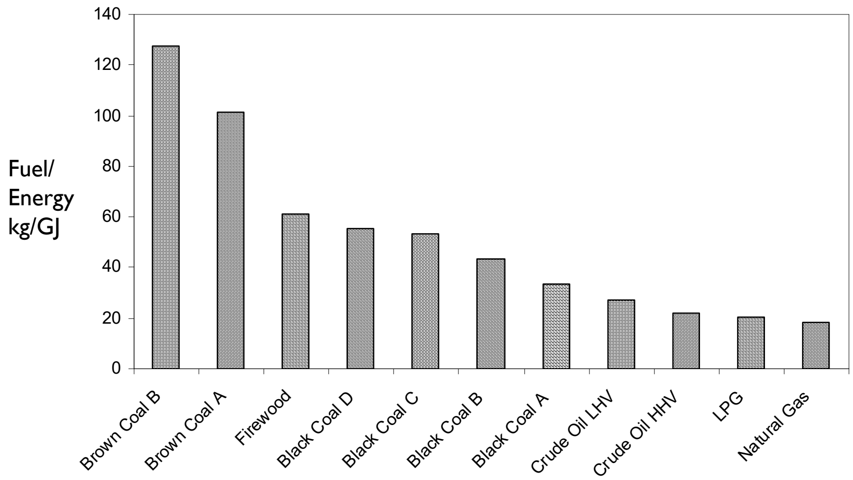
10) Form a club with China, India, and Russia, to determine energy future.

Fuel mass per energy of hydrocarbons

Economies of scale favor fuels suited to higher power density and thus decarbonization

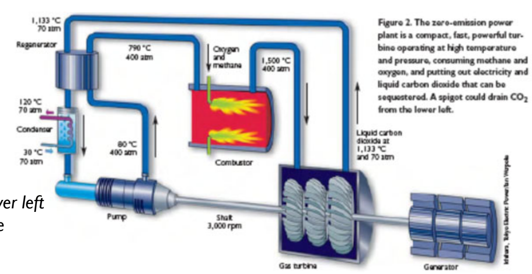


Source: N.Victor & J.Ausubel, 2003

Methane-fueled Zero Emission Power Plant (ZEPP)

temperatures to 1,500 Celsius, pressures to 400 atmospheres

A spigot in the lower left might draw off the carbon dioxide.



Credit: Tokyo Electric Power, from Ausubel, 2004

NET Power LLC natural gas power plant, La Porte, Texas

Rodney Allam, designer

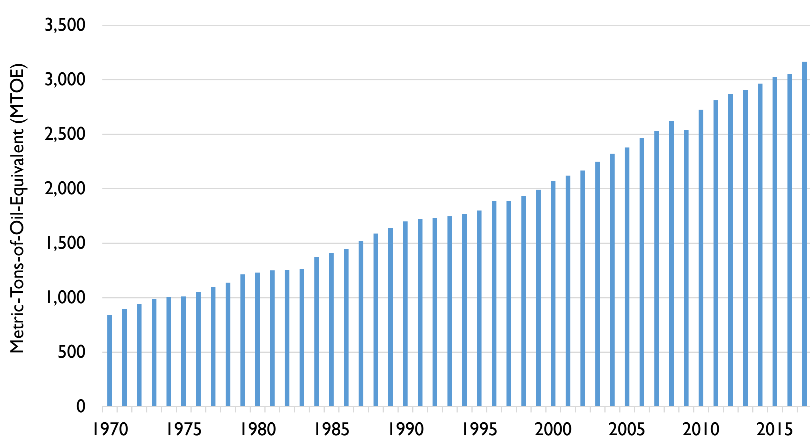
Feb 21, 2017

Revolutionary Power Plant Captures All Its Carbon Emissions, At No Extra Cost

…The best part is that it makes electricity at the same low cost as other modern gas-fired turbines – about 6 cents per kilowatt-hour… The so-called working fluid that turns the turbine is carbon dioxide itself. The CO_2, under pressure and heated to a manageable 1,000 degrees, is kept in a supercritical state, in which it can expand to fill its container like a gas, yet has the density of a liquid. Instead of pouring into the sky, that CO_2 gets cycled in a loop, spinning the turbines that power the generators. Combustion continually adds additional CO_2 while excess CO_2 is directed off into a pipeline.

Source: Christopher Helman, Forbes
(https://www.forbes.com/sites/christopherhelman/2017/02/21/revolutionary-power-plant-captures-all-its-carbon-emissions-at-no-extra-cost)

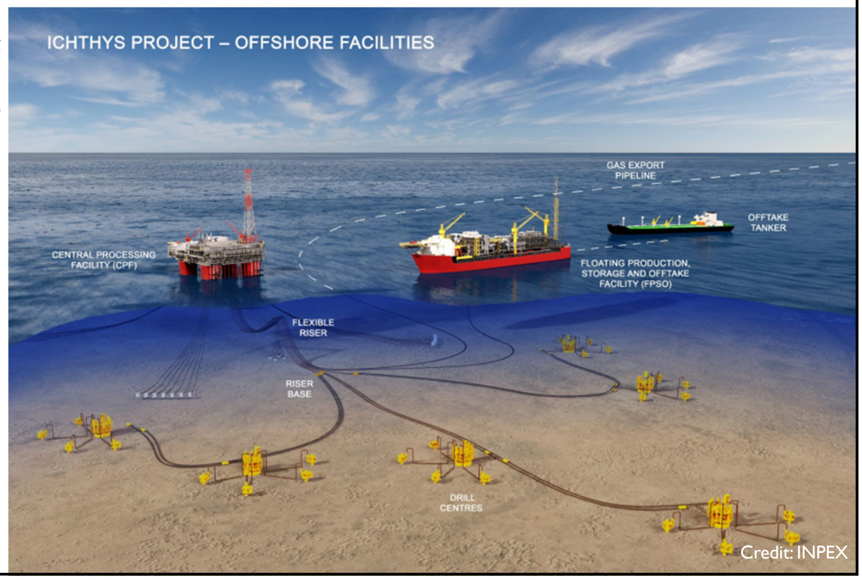
Global natural gas production



Source: BP Statistical Review of World Energy 2017
(https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html)

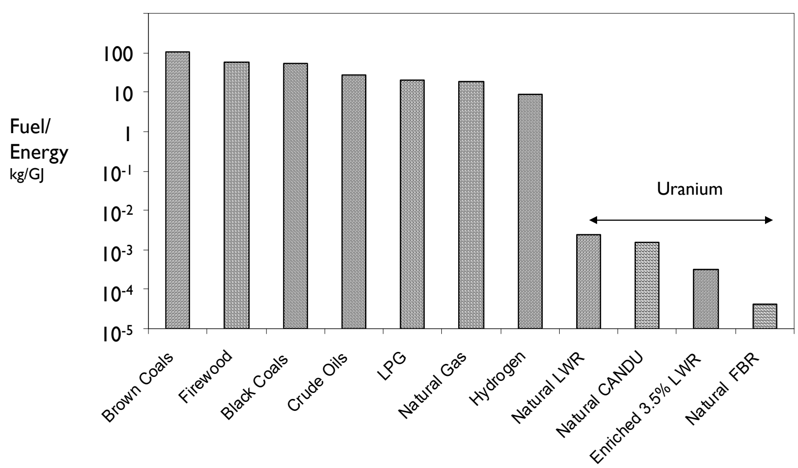
Natural gas: extremely large projects, mostly sub-surface

Ichthys (Japanese-led):
$34bn natural gas project in Timor Sea
200 km off NW Australia,
900 km pipeline to LNG plant in Darwin



Fuel mass per energy including nuclear fuels

economies of scale favor fuels suited to higher power density, thus decarbonization & thus finally nuclear sources 10,000x more compact than hydrocarbons



To produce with solar cells the energy generated in 1 liter of core of a nuclear reactor, one needs ~1 hectare (10,000 square meters) of solar cells

Source: N.Victor & J.Ausubel, 2003

Nuclear weapons era: so far, deterrence has worked

Wartime fatalities as % of world population (civilian+military)

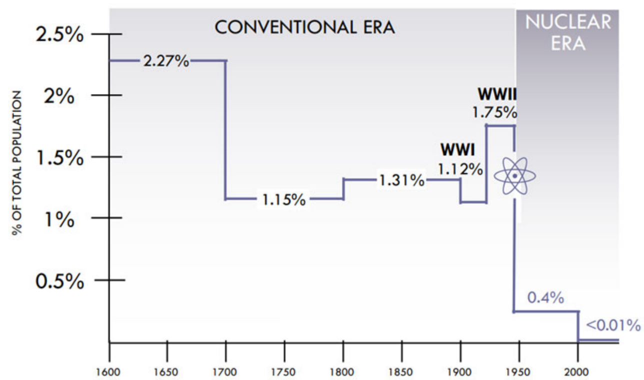


Figure 2. Wartime Fatalities Percentage of World Population
Data from the DoD Historical Office

Non-nuclear forces also play essential deterrence roles. Alone, however, they do not provide comparable deterrence effects, as reflected by the periodic and catastrophic failures of conventional deterrence to prevent Great Power wars throughout history. Similarly, conventional forces alone do not adequately assure many allies and partners. Rather, these states place enormous value on U.S. extended nuclear deterrence, which correspondingly is also key to non-proliferation.

Credit: Office of the Secretary of Defense, 2018

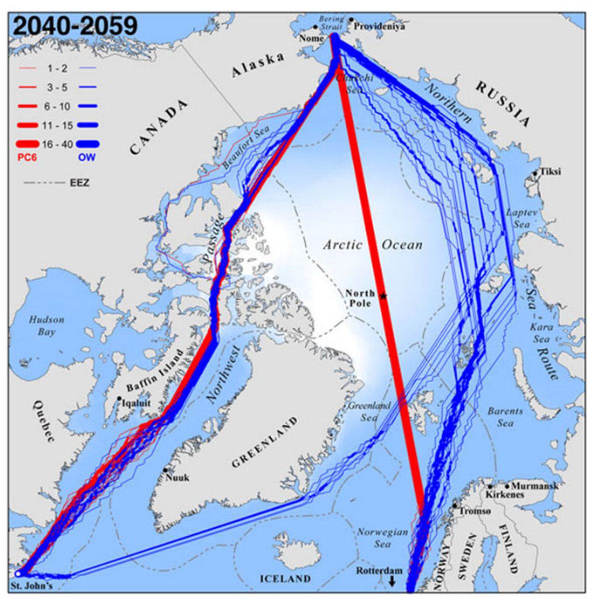
Projected decline in Arctic sea ice, 2040-2059

Red lines indicate fastest available trans-Arctic routes for Polar Class 6 (PC6) ships; blue lines indicate fastest available routes for common open-water (OW) ships.

Line weights indicate successful transits using same route.

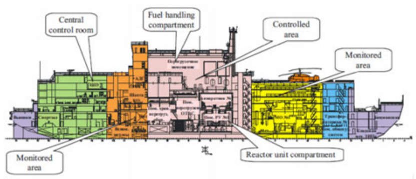
Dashed lines reflect currently existing (200 nautical mile) national Exclusive Economic Zone boundaries.

White backdrop indicates period-averaged sea ice concentration.



Credit: Laurence C. Smith and Scott R. Stephenson, 2013, *New trans-Arctic shipping routes navigable by midcentury.* PNAS 2013 March, 110 (13) 4871–4872.

Naval reactors finally repurposed for floating civilian power



Russia launched Akademik Lomonosov, world's first floating (70 MW electricity, 300 MW heat) nuclear power plant, out of St. Petersburg shipyard; destined for Pevek, in Arctic, where it will begin generating power in summer of 2019; no propulsion of its own; will provide electricity to 100,000 people; will also power oil and gas mining rigs and access to fossil fuels in what used to be impassable parts of Arctic.

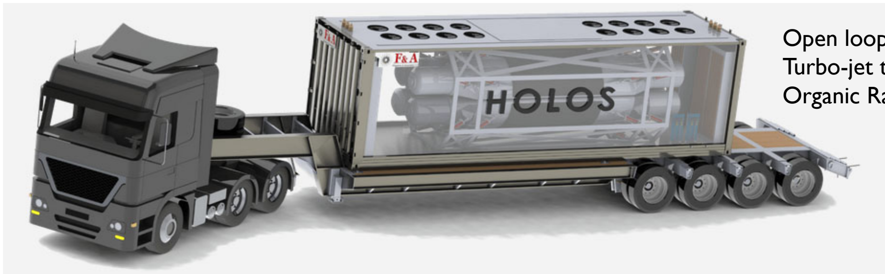
Credits: IAEA; Alexander Galperin, AP

China adds icebreaking capacity

China's first domestically built polar icebreaker *Xuelong 2*, or Snow Dragon 2, at shipyard in Shanghai, September, 2018

Credit: Reuters

Nuclear generators in a shipping container



Open loop
Turbo-jet technology
Organic Rankine Cycle

Technology Features

- Subcritical power modules coupled with ORC components
- Fits inside single ISO container
- Generates 13 MWe of uninterrupted power for 12-20 years
- Depending on application, fuel cartridge uses up to 15% enriched fuel
- Refueling includes replacement of all spent fuel cartridges
- Refurbishing components during refueling
- Can be refueled twice to reach a total operational life of 60 years

Projected NOAK Costs

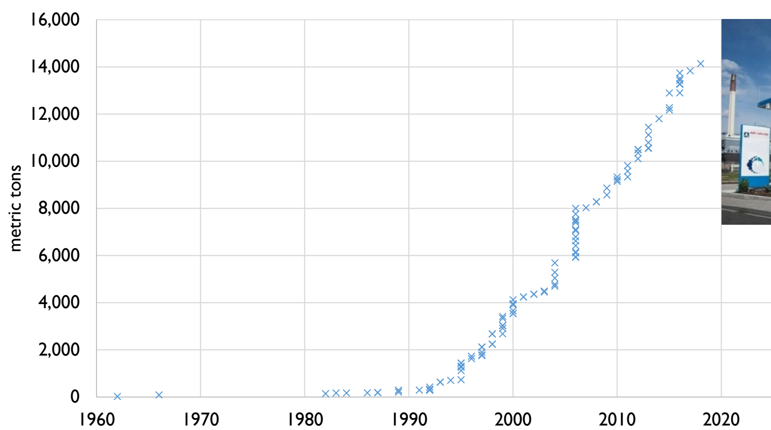
- Capital construction costs: ~$40M
- Other costs (fuel, licensing, operations & maintenance costs): ~$54M
- Total Investment: ~$94M
- Overnight cost of electricity: $5,761/kWh
- Average levelized cost of electricity: 5.19 ¢/kWh*
- Payback period: less than 7 Years*
- Return on investment: 234% (20 year life)
- Return on investment: 1243% (60 year life)

*Calculated using Energy Information Administration's 2018 U.S. Year-to-Date Average Price of Electricity

Credit: HolosGen

Hydrogen: long used in refining vehicle fuels; now preparing to marginalize them?

Merchant hydrogen plant capacities in North America
production capacities (1000 kg/day or larger)



Source: Pacific Northwest National Laboratory
(https://h2tools.org/hyarc/hydrogen-data/merchant-hydrogen-plant-capacities-north-america)

Renewable energy production intensities

oil and natural gas produce about 25 to 30 watts per square meter
as rule of thumb, an oil or gas well equals about 20 large wind turbines.

	watts/meter^2	km^2 to produce 1000 MW
Hydro		
-Hoover	***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***
PVs	***6***	***150***

Sources: Ausubel, Hayden

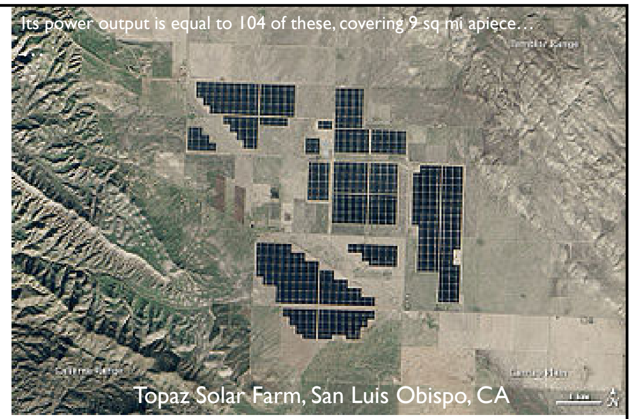
Offshore wind farm infrastructure

Credit: Inhabitat (https://inhabitat.com/european-firms-eye-artificial-island-for-north-sea-wind-and-solar-farms/)

Tale of two energy densities

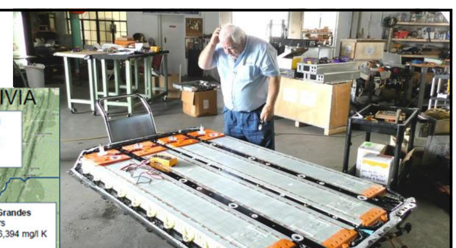
Siemens >1/3 of way through contract that will deliver 14.4GW of NGCC to Egypt by 2018. Big bet on natural gas supply that will come via pipeline from Israel giant offshore fields.

Equivalent to installing 900 sq mi (2,400 sq km) of solar farm, or almost 5000 sq mi of wind, plus at least 400 GWh of battery storage.



Source: TA Kiefer, 2017

Batteries: rechargeable, not green

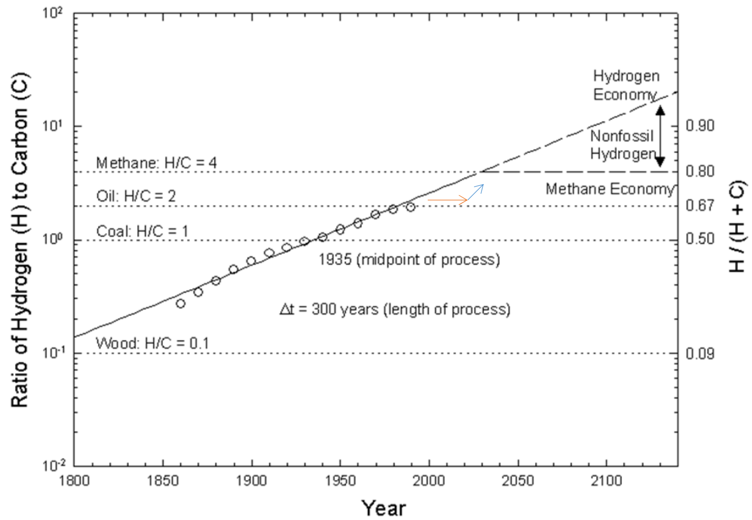


Tesla Model 3: 4,416 cylinder cells in four modules that weigh 1,054 lbs / 478 KGs combined

Average battery-electric vehicle stores ~40 kWh.

Running New York City for two average days would require over 100 million such battery packages, about a dozen/person.

Decarbonization: deferred a generation by "policy"??

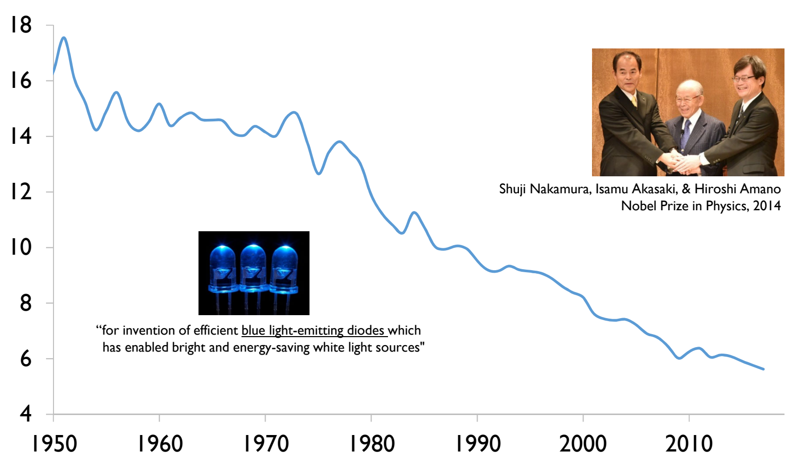


Source: JH Ausubel, Resources and Environment in the 21st Century: Seeing Past the Phantoms, *World Energy Council Journal*, July 1998, pp 8-16.

Decoupling of US economy & energy consumption

changes in structure of economy, better generation & transmission, better end-use devices

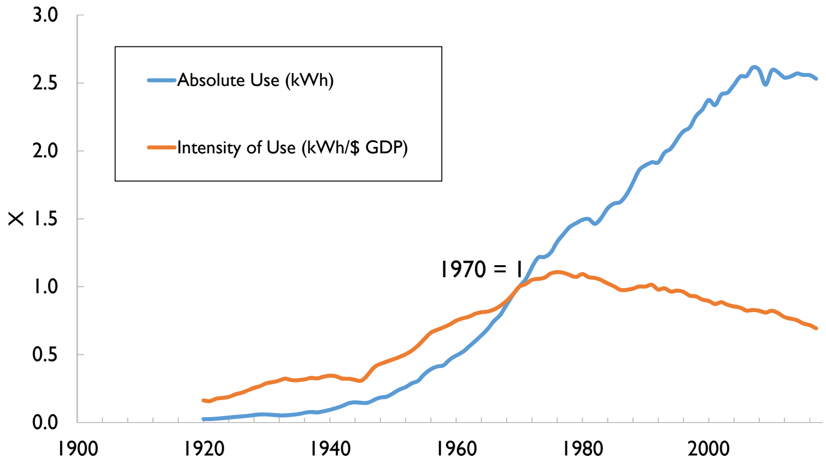
US energy consumption (thousand BTUs) per dollar of GDP, 1949-2017



Source: EIA, https://www.measuringworth.com/datasets/usgdp/

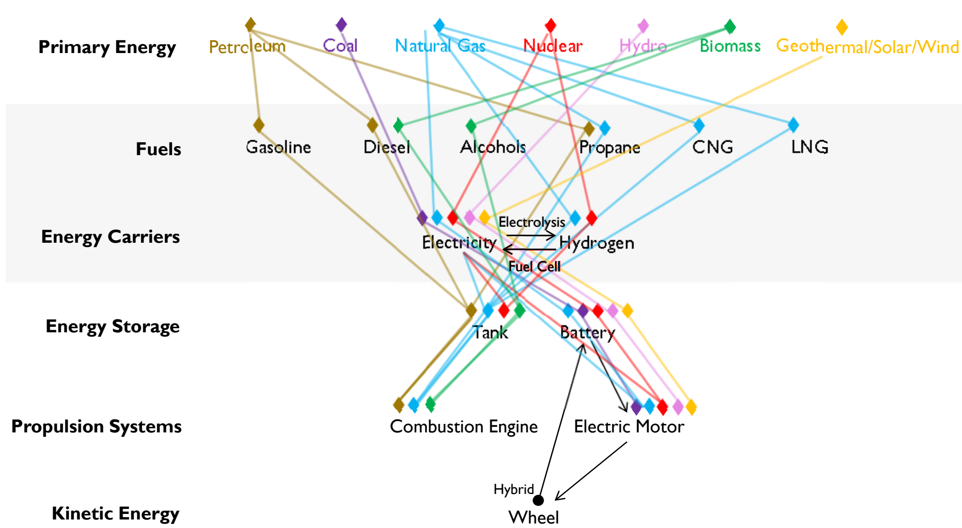
Peak electricity in US?

Use (kWh) to 2017: no longer grows in tandem with economy ($ GDP)
Could information technology cause another upward wave?



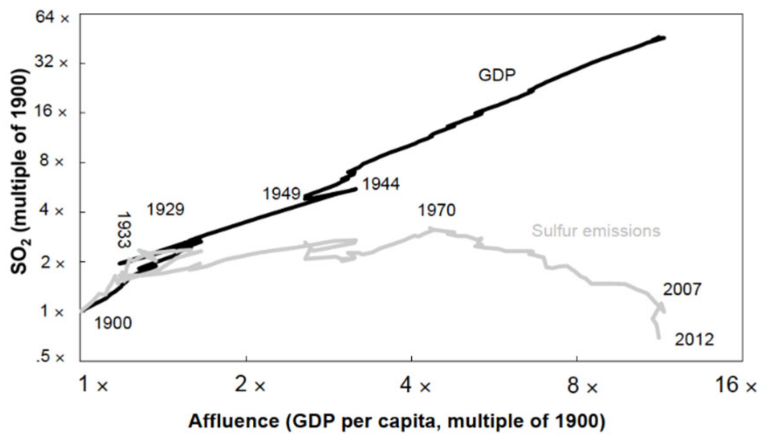
Source: EIA

Many routes "well to wheel": Will tanks or batteries win for storage?



Credit: Alan Curry

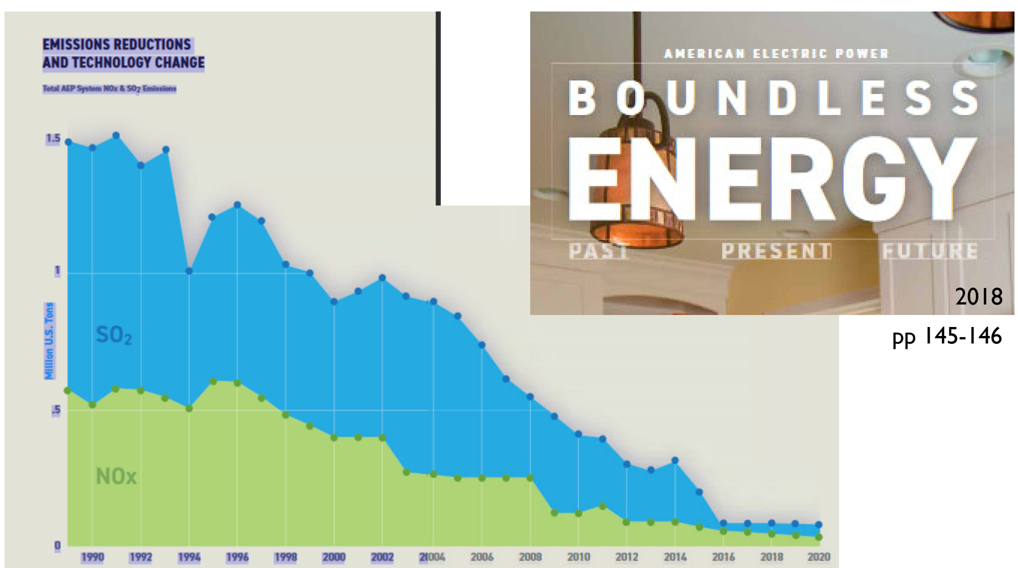
Decoupling of US economic growth & sulfur dioxide emissions



Gray curve of sulfur emissions, which peaked in 1970, contrasts with black straight line of growth of GDP. Economic slumps in 1929 &1944 reverse growth for 5-10 years but do not affect longer term trends for GDP or emissions.

Source: EPA Credit: P.Waggoner and J.Ausubel, 2009; updated I Wernick 2015.

AEP's massive SO_2 and NO_x reductions

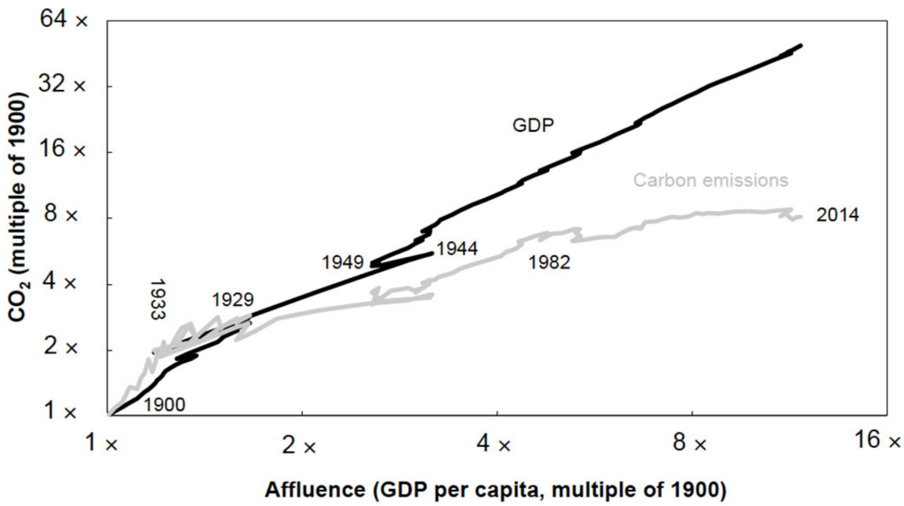


2018

pp 145-146

2007 peak carbon dioxide?

Decoupling of US economy & emissions – 2017 ~14% below 2005, owing to decline of coal



Carbon emissions seem around their peak, especially by analogy with sulfur emissions

Sources: CDIAC, EPA   Credit: P. Waggoner and J. Ausubel, 2009; updated I. Wernick 2015.

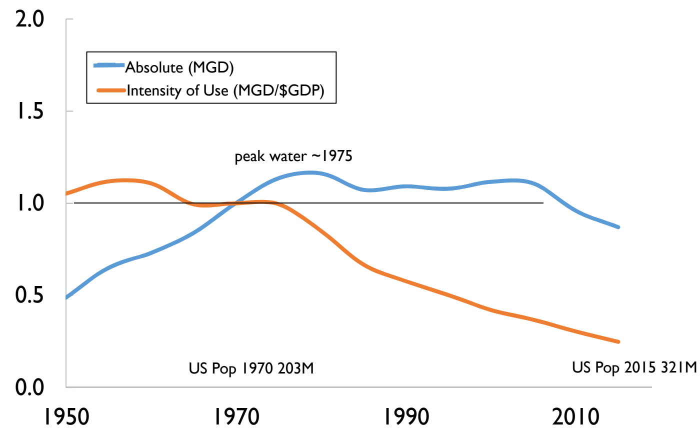
Risky siting, poor defense, in a stormy world

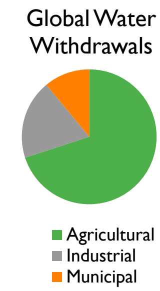
A wastewater treatment plant in Houston, Texas, flooded during Hurricane Harvey.

Credit: Karl Spencer/iStock/Getty Images

US water withdrawals flat 1975-2000 & now falling

while tons of corn & soy +>300%, wheat +>60%, potatoes +25%; +118 mn Americans

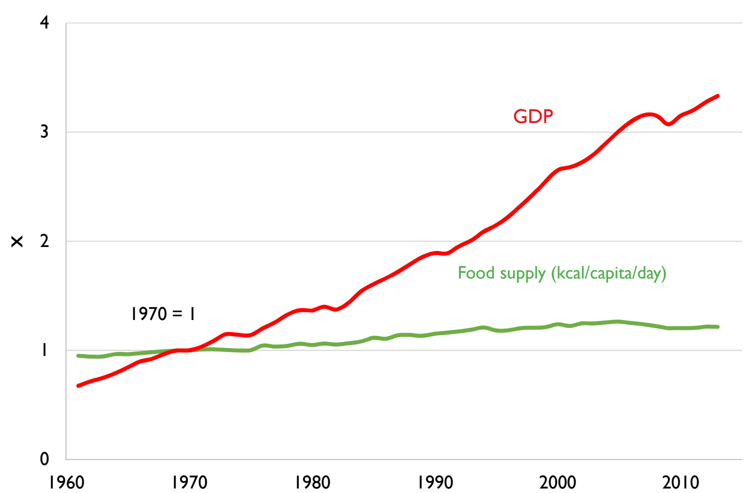




Source: USGS, Ausubel & Wernick (2014)

Decoupling of economy & natural resources

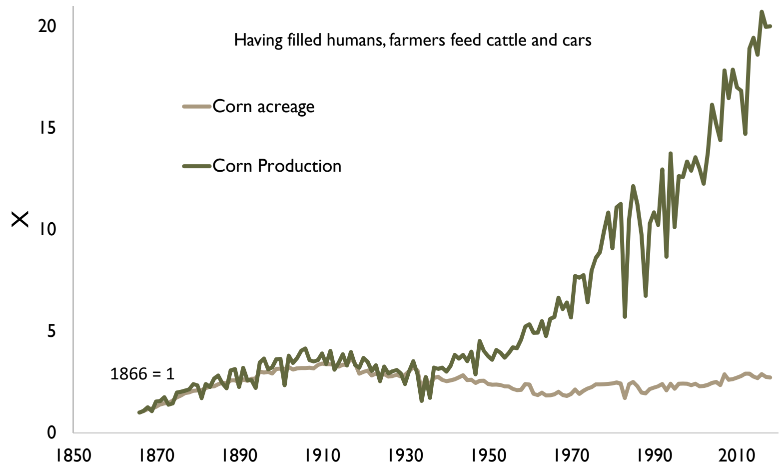
More affluent people do not demand more food.
World calorie & protein production far exceed demand.



Sources: UNFAO, Angus Maddison, Ausubel & Wernick (2015)

Precision agriculture allows bushels to decouple from land

David Hula, record holder for corn yield
542 bushels/acre, 2017

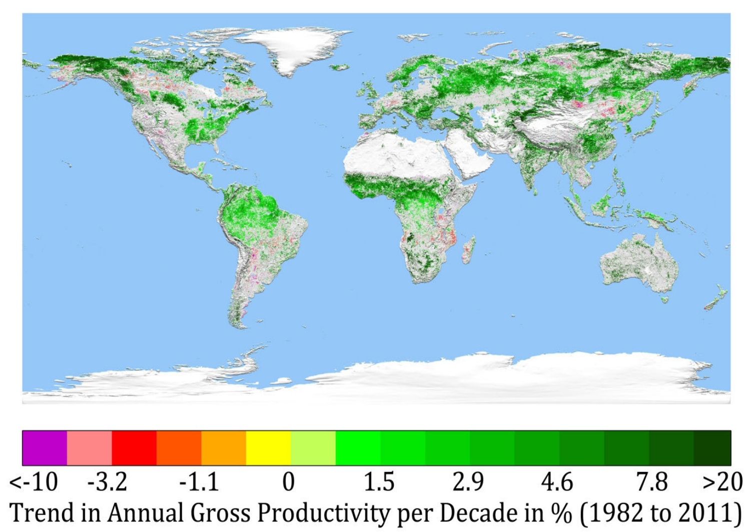


Source: US Department of Agriculture

Global Greening

more vegetation, all types, almost everywhere

- 31% of global vegetated area greened
- This greening translates to 14% increase in gross productivity
- Greening is seen in all vegetation types



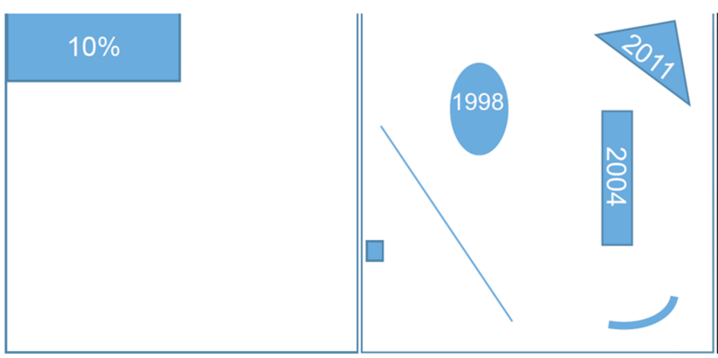
Source: R. Myneni
Note: Productivity measured as integrated $NDVI_{3g}$ using Vogelsang (1998) method

Tropical Islands Resort near Berlin, Germany

Credit: Tanjong PLC

Ocean still known by sticks, boxes, circles

five to 10 percent of the cubic volume of ocean has been characterized, often not contiguously in space or time



In the Black Square, Wassily Kandinsky, 1923, [Public domain], via Wikimedia Commons

Lines and forms in an artist's work suggest state of monitoring and observation of the world's oceans.

Re-cap

1) No one knows what will happen to emissions, climate, or the consequences.
2) Finally, the question is risk aversion.
3) Biases of stakeholders predictably color risk and environmental assessments.
4) Rising watts per square meter, density of consumption, drives the energy system.
5) Methane & uranium are the way of decarbonization to H_2–electric economy.
6) Public policies to lift efficiency have not much affected long-term trends.
7) Public policies strongly affect adaptation - "Trailer parks causes tornadoes."
8) Societies are anyway moving indoors and climate-proofing.
9) Nevertheless, monitor environmental variability and change, objectively.
10) Form a club with China, India, and Russia, to determine energy future.

Thanks
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