Lecture 8: Energy Economics—Nuclear and Nonnuclear

QUESTIONS TO BE ADDRESSED:

I. **Why bother with energy economics?**

II. **What are the basics of electricity production, consumption, distribution, and storage needed to assess the costs of different electrical options?**

III. **How do nuclear and non-nuclear forms of energy perform economically at home and abroad?**

I. Why bother with energy economics?

Energy economics is a relatively dry topic. Yet, it is difficult to understand international relations without knowing what drives countries to export and import trillions of dollars' worth of energy commodities to produce electricity, power transport, and fuel industry without some familiarity with electricity supply system economics. Also, states control their own energy and electrical systems to varying degrees for political, environmental, and economic reasons, through direct ownership, subsidies, and regulation. Understanding the actual costs of an energy option, therefore, provides insight into how sound various countries' energy policies might be.

More important, energy economics informs nuclear nonproliferation policy. As explained in earlier chapters, in some instances, civilian nuclear activities and materials can bring states to the very brink of acquiring nuclear weapons. Frequently, these nuclear materials and activities are also among the most uneconomical means to produce electricity.

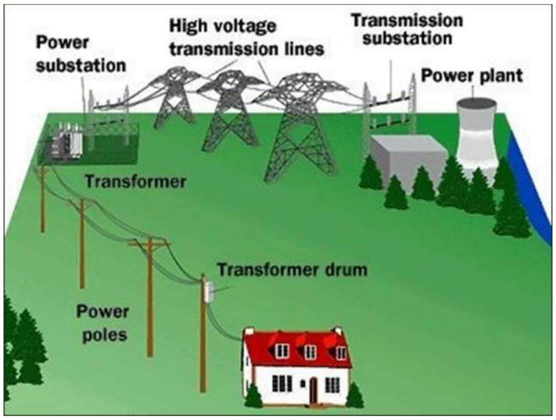
Under the NPT, activities or materials that might have some civil application, though, are generally viewed as being legitimate and "peaceful." The treaty stipulates that states have an "inalienable right" to all forms of peaceful nuclear energy. These are to be shared "without discrimination," in the fullest possible fashion, including nuclear fuel making (enrichment of uranium, chemical nuclear separation of plutonium from spent reactor fuel, and nuclear fuel fabrication), as long as they have some conceivable civilian application and are occasionally inspected.

In the real world though, economics is a major factor in determining what nuclear technologies companies and countries seek. Even though the NPT's preamble speaks about sharing the "benefits" of civilian nuclear energy, it rings hollow if the nuclear technology or materials in question cost far more than nonnuclear alternatives.

This then brings us back to countries' inalienable right to "peaceful" nuclear energy. If a state would lose money investing in a particular nuclear activity, it would be far less likely to insist on its right to pursue it. Thus, Article V of the NPT stipulates that states have a right to enjoy the potential benefits of peaceful nuclear explosives (PNEs). In the 1950s and 1960s, many believed such explosives would prove helpful for civil engineering projects (creating canals, ports, excavations, mines, etc.). However, experts determined that the costs of cleaning up the radioactive debris associated with nuclear detonations rendered any such project uneconomical. As a result, no state ever asked to receive the "benefits" of these explosives under the NPT.[1]

This raises the question what nuclear activities and materials now are so uneconomical that states would be foolish to insist on their "rights" to acquire them. Because nuclear power is primarily used to produce electricity, investigation of this matter requires understanding the essentials of electrical production, consumption, distribution, storage, and what current energy economic trends (both nuclear and nonnuclear) are.

II. The basics of electricity production, consumption, distribution, and storage



Above is a cartoon of a typical electrical supply system. Some of the pictured items are easily recognizable—the house, the power plant, the cooling tower, and the power poles. Some of the other pictured items you might have seen before as well—transmission lines, towers, and transformer stations.

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1. Henry Sokolski, "The NPT's Untapped Potential to Prevent Proliferation," in Henry Sokolski, ed., Reviewing the Nuclear Nonproliferation Treaty (Carlisle PA: Strategic Studies Institute, 2010), available at http://npolicy.org/article.php?aid=195&rt=&key=untapped%20potential&sec=article&author=

The generation of electricity is generally accomplished with fossil-fueled, hydro-powered, wind-driven, or nuclear reactor powered electrical generating plants. All these plants spin a set of magnets in an electrical turbine generator to produce electrical voltage. Hydro plants spin turbine generators using water and gravity while wind-powered plants use sophisticated blades to catch the wind. Fossil-fueled (e.g., natural gas, coal, oil, diesel, propene-fired plants, etc.) and nuclear power reactors do so by heating water to produce steam, which, in turn, is used to spin turbines that produce electrical voltage, which is transmitted to residential and commercial customers. Yet another way to produce electrical voltage directly without spinning an electrical generator is photovoltaic solar power.

The next challenge is to move the generated voltage as far as possible to the largest number of customers. If you try to transmit low-voltage, it won't go as far as high voltage. More important, electrical voltage "leaks" proportionate to the distance that the voltage is pushed over transmission wires. For this reason, alternating electrical current, the most popular form of electricity, is bumped up periodically at transformer stations (how this is accomplished is explained below). Finally, power lines and poles are used to get the electricity to the customer and transformer drums are employed to reduce the voltage so residential and commercial users need not fear blowing out the electrical fuses and circuit breakers in their homes or commercial establishments.

This brings us to the issue of grid stability. If more electrical voltage is delivered to customers than they can use, it can trip commercial residential voltage regulators (fuses and circuit breakers), and the house or store fronts will go without any electricity until the fuse or circuit is fixed and the excess electricity cut back. Sometimes an electrical voltage surge is caused by electrical storms (e.g., lightning) that strike local power lines. Electrical surges also occur when transformers break down. On the other hand, if too little electrical voltage is available to meet demand—if, for example, everyone operates their air conditioners and other electrical appliances full blast on a hot day and there's not enough electricity to power them—blackouts and brownouts occur.

This puts a premium on keeping supply and demand on any electrical grid in balance. It is not well appreciated but roughly two-thirds of the price we pay for the electricity in our homes is to cover the cost of "balancing" the grid; only a third is dedicated to covering generating the electricity (i.e., the costs of building, maintaining, fueling, and operating electrical generation stations).[2]

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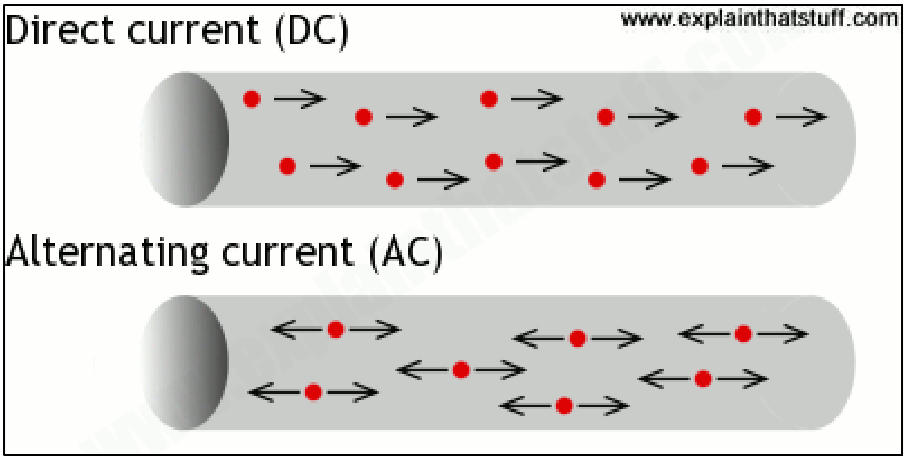
2. See Energy Watch, "Transmission & Distribution and Supply – Utility Expenses Explained," accessed November 8, 2019, available at https://energywatch-inc.com/utility-expenses-transmission-distribution-vs-supply/.

Finally, every electrical system operates at a specific frequency—the spin speed of the electrical generators. Most frequencies are either 50 hertz (Hz) or 60 Hz. The latter is popular in North America; the former in Europe, Africa, and Asia.

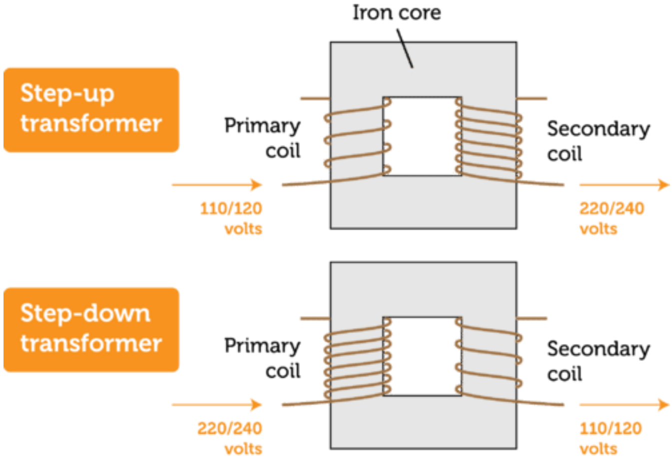
Alternating and Direct Current

There are two ways to move electrical voltage or current: Direct current (DC) and alternating current (AC). Direct current is easy to explain: It moves electrons through wires like water runs through a pipe, i.e., in a single, linear direction (see illustration below). With alternating current, the electrons oscillate forward and backwards within the wire at a given frequency (again, see the illustration below). Almost all appliances operate with alternating current. As a result, direct current transmission systems need to convert direct current to alternating current before it can be used by most customers.



https://www.explainthatstuff.com/electricity.html

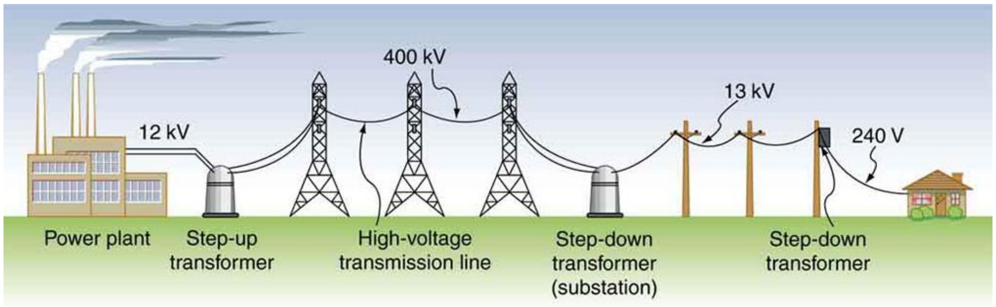
Why are there two systems? The short answer is history. At the turn of the Century, Thomas Edison developed direct current systems. The voltage leakage over transmission lines was significant. It also was difficult and expensive to convert direct current to appliance-popular alternating current. George Westinghouse bested Edison's direct current electrical systems by buying Nikolai Tesla's patents for producing and transmitting alternating current, which had the clear advantage of not having to be converted to alternating current for customers' appliances. Tesla's patents included transformers, which made it possible to increase voltage to extend the distance electrical voltage could be transmitted over power lines. Transformers also could be used to decrease the voltage before it was delivered to customers to avoid tripping residential and commercial fusing systems.[3]



https://www.ck12.org/book/CK-12-Physics-Concepts-Intermediate/section/21.4/

The essentials of a transformer are displayed above. By utilizing windings around an iron core, it is possible to double or "step up" the incoming voltage simply by doubling the outgoing windings over the number of windings at the input. Conversely, voltage reductions or "step downs" are possible by decreasing the output windings in relation to the input windings.

As already noted, transformers are used to increase voltage to extend the range of electrical transmission and to decrease voltage to make its reception by residential and commercial customers sufficiently low to be safe. Most 20th Century electrical supply systems employed alternating current technology.



https://courses.lumenlearning.com/austincc-physics2/chapter/23-7-transformers/

Director current transmission systems that use high voltage (HVDC systems), though, are now making a comeback. There are three reasons why. First, electrical transmission losses over long distances are no longer so high: It is now possible to transmit direct current many hundreds of miles with only minor voltage losses. Second, with the development of cheap micro circuitry, the costs of converting direct current to alternating current have plummeted. Finally, direct

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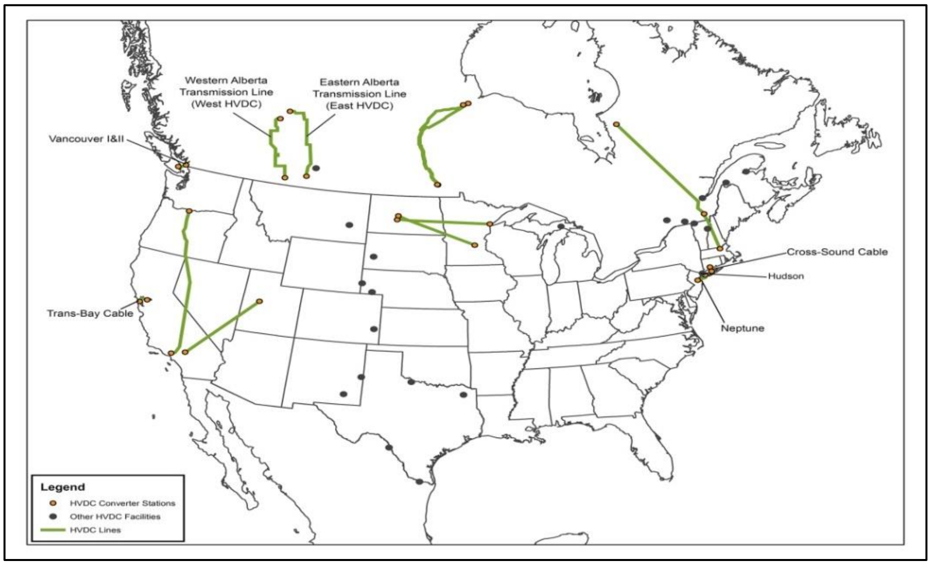
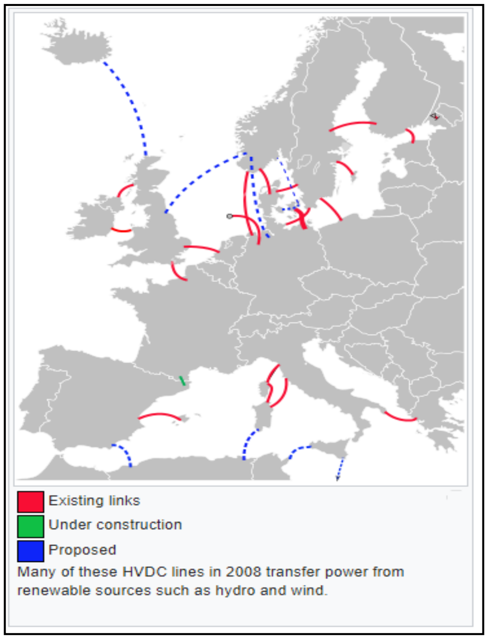
[3] See US Department of Energy, "War of the Currents: AC versus DC Power ," November 18, 2014, available at https://www.energy.gov/articles/war-currents-ac-vs-dc-power.

current transmission systems obviate the need for transformers, which can break down or be targeted. All of these attributes of HVDC transmission systems are attractive for moving large amounts of power, such as wind, hydro, solar power, or other forms of surplus electricity from one distant region to another. Below is a map of direct current transmission lines in the U.S. and Europe (see the illustrations below). Even more ambitious direct current systems are being planned for the Middle East and China.



https://en.m.wikipedia.org/wiki/High-voltage_direct_current



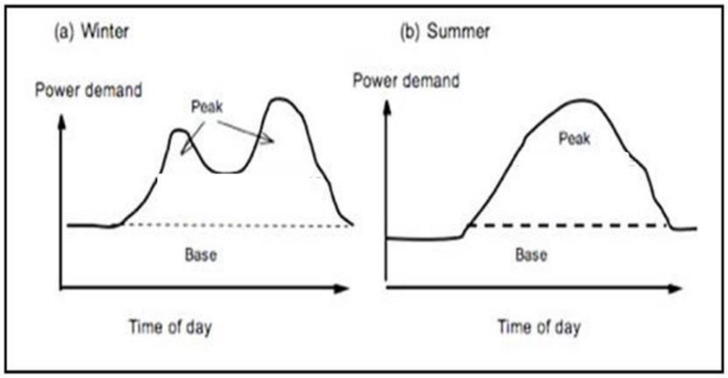
Many of these HVDC lines in 2008 transfer power from renewable sources such as hydro and wind.

https://en.m.wikipedia.org/wiki/High-voltage_direct_current

Base and Peak Load

Besides the different kinds of electrical transmission systems — direct and alternating current systems — there are different kinds of electrical power generating plants. Some electrical generators are fired by oil, natural gas, propane, diesel fuel, others are powered by nuclear energy, hydropower, and wind. Electricity can also be generated from solar energy. Why are there so many different kinds of electrical generators? One answer is economics: In any given location, it may be cheaper to use one type of electrical generator (e.g., a coal-fired generator) over another (a gas-fired one). Yet another reason, though, is that electrical demand has historically been divided into at least two different types — peak and base load demand — which require very different kinds of generating systems to supply.

Peak load electrical demand is reached when the consumption of electricity in a given market hits some of its highest levels. For example, on hot, summer days electrical demand spikes upward as more and more customers turn on their air conditioners. Electrical demand varies each hour of the day. It is relatively low at night; rises as people wake up in the morning and start using their home appliances; rises further to a maximum at mid-day as businesses go into operation. In the winter months, electrical demand generally declines during lunch time. In the summer, however, it continues to rise as air conditioners are left on at virtually all locations. It then declines in the summer and winter as businesses close in the evening (see the illustration below).



Most of the highest electrical demand levels are met with the help of dedicated peak load electrical generating plants. These plants can ramp power up and down quickly and easily. In contrast, base electrical demand hardly varies at all. It is the minimum electrical output required to service a given market 24/7. Because base load requirements are large and constant, base load generators are all relatively large. They include big coal plants, hydro plants, nuclear power reactors, and big oil and natural gas-fired plants.

These base load generators, though, do not run continuously year in year out. Coal plants need to be shut down for periodic cleaning. Hydro plants must occasionally be cleaned to eliminate debris and algae. Natural gas plants have to be serviced routinely and nuclear power plants have to be shutdown roughly every 18 months to be refueled. As a result, you need hold several base load generators in reserve to substitute for generators that must periodically be taken off line for servicing.

Peak load generators are much smaller and more numerous than base load generators. They are generally fueled with natural gas, diesel fuel, and propane. They operate as a "spinning reserve," like a car idling at a stop light. If you want to make sure you can move from the stop light quickly, you keep the engine running and on the ready. Similarly, if you want to make sure that you can meet anticipated peak demand for electricity, you keep your peak load generators operating (or "idling") in spinning reserve so they can be dispatched quickly to meet a spike in demand. Again, because these plants, like base load generators, break down and need to be routinely serviced, you need many more peak load generators than the minimum needed to supply what peak demand there is at any given time.

One way to compensate for local base and peak load generator failures or servicing downtime is to have local, spare generating capacity to fill any supply gaps that might arise. Yet another way that often is cheaper is to buy and import surplus electricity from outside of one's locality.

Electrical Transmission Systems: Domestic and International

In economically developed regions of the world, such as North America and Europe (see the illustrations below), the electrical transmission systems (or grids) are large, mature, and complex. They also are internationally integrated: The systems connect adjacent states (e.g., Canada and Mexico) and include both direct current and alternating current lines rated at a variety of voltages. This allows the sharing of electrical generating capacity and for the relatively easy rerouting of electricity if a portion of the grid fails due to technical failures, severe storms, earthquakes, vandalism, or sabotage.

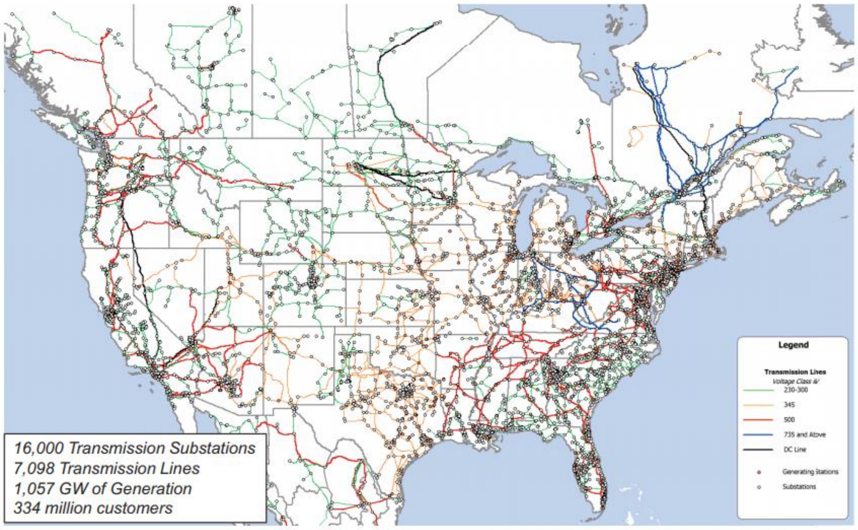
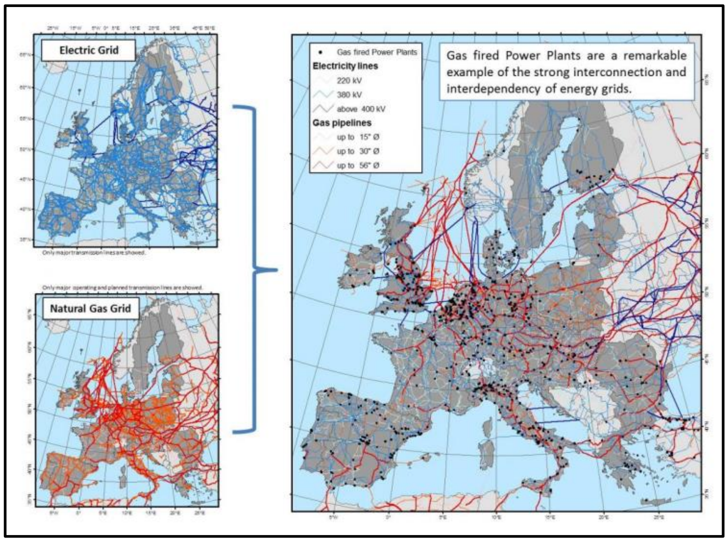


FIGURE 2.4 The North American transmission system.
SOURCE: This information from the North American Electric Reliability Corporation's website is the property of the North American Electric Reliability Corporation and is available at http://www.nerc.com/comm/CIPC/Agendas%20Highlights%20and%20Minutes%202013/2015%20December%20Compiled%20Presentations.pdf.



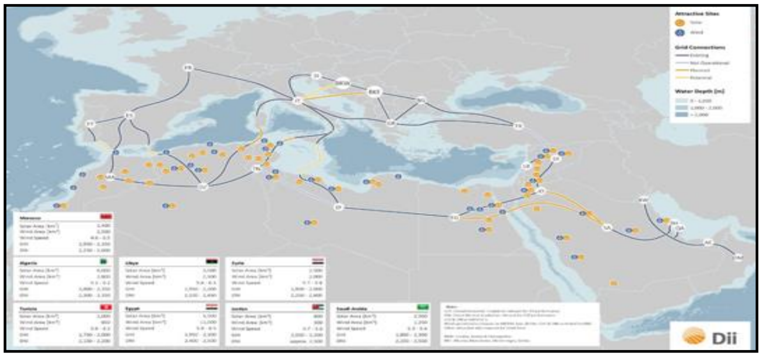
https://ses.jrc.ec.europa.eu/gas-and-power-modelling, Image Permission: https://ec.europa.eu/info/legal-notice_en

In the Middle East, Africa, and Latin America, there are plans to create electrical transmission interconnections across country borders (see maps below). The cost to complete these plans are steep and the lack of regional political consensus to allow and to finance these projects is also significant.

It remains to be seen how much of what has been proposed for developing regions will be built and how soon. Some energy analysts argue that building smaller, less grid-dependent micro distributed electrical systems would be quicker and cheaper to build.

http://solarey.net/african-nations-will-interconnect-power-grids-2020/

https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0173820



https://dii-desertenergy.org/our-activities/

With regard to East Asia and electrical transmission systems, the best known image is that of North and South Korea (see illustration below). North Korea generates very little electricity compared to the South. Its grid transmits electricity locally at a different voltage and lower frequency than that of South Korea. As a consequence, it is difficult to transmit any surplus electricity (of which there is plenty) from South Korea to North Korea. One is tempted to dismiss this as a function of unique, contentious politics and the economic disparity between the North and South.

Yet, when we look at Japan's electrical transmission system, there is a stunning disconnect there as well. The eastern section of the country operates on a different frequency (50 MHz) than the western section, which operates at 60 MHz. Originally, the difference in frequencies was due to the historical adoption of European electrical appliances in Japan's western regions and American standards in the eastern regions. This historical accident has been perpetuated by private local utilities who naturally want to capture and control the markets they have traditionally served. Because these frequencies are so different, though, it is difficult to transfer more than one gigawatt of electricity from western Japan to eastern Japan or vice versa. This has only increased the electrical supply problems facing Japan since so much of the grid and generating capacity in the east was damaged by the earthquake in 2011. If the country operated on a single frequency, the economic harm inflicted by the 2011 earthquake would have been far less as more electricity from western Japan could have been imported to the disaster-struck, eastern region.[4]

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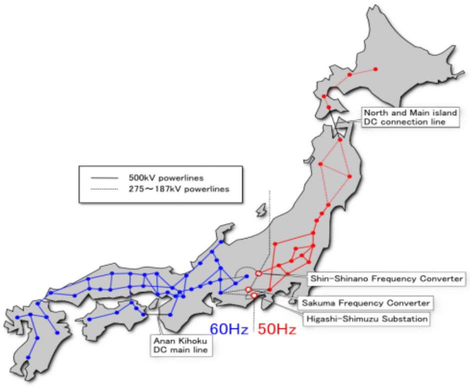
[4] See Alice Gordendeker, "Japan's incompatible power grids," *The Japan Times,* July 19, 2011, available at https://www.furniture-rental-tokyo.com/useful_info/electricity.html



https://en.m.wikipedia.org/wiki/Minami-Fukumitsu_Frequency_Converter

China's grid is also less than optimal. Almost all of China's transmission systems currently are located in its eastern provinces and run north to south. There is far too little transmission of electricity from east to west. To remedy this, Beijing is expanding its grid dramatically with extensive investments in high voltage direct current (HVDC) transmission systems both to import solar and wind power from the country's western regions to its more industrialized and populous eastern provinces and to further develop its more remote provinces in the west.

China's investment to build this east-west transmission system far exceeds the cost of building China's fleet of nuclear reactors. It views these grid investments as critical in ensuring its energy future and to secure greater political control over its western provinces.[5]

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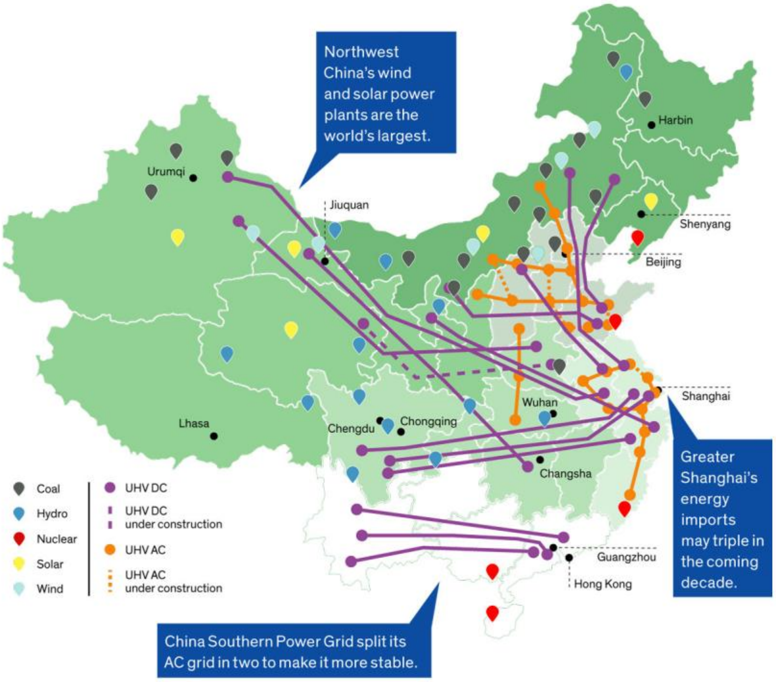
5. See Peter Fairley, "China's Ambitious Plan to Build the World's Biggest Supergrid," *IEEE Spectrum*, February 21, 2019 available at https://spectrum.ieee.org/energy/the-smarter-grid/chinas-ambitious-plan-to-build-the-worlds-biggest-supergrid.



Northwest China's wind and solar power plants are the world's largest.

Greater Shanghai's energy imports may triple in the coming decade.

China Southern Power Grid split its AC grid in two to make it more stable.

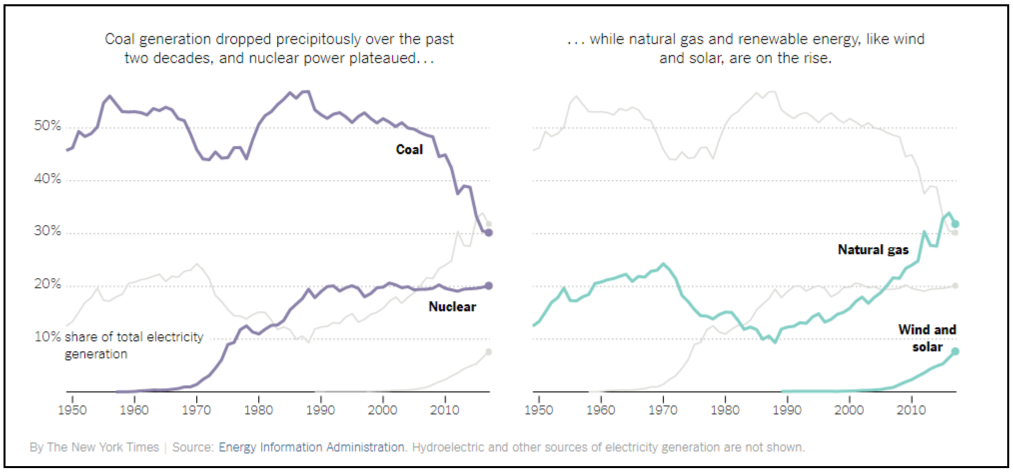
https://spectrum.ieee.org/energy/the-smarter-grid/chinas-ambitious-plan-to-build-the-worlds-biggest-supergrid

Like North America and Europe, Asia's electrical demand is high, but unlike North America or Europe, Asia lacks electrical transmission connections between the region's major nations. This is due, again, not to technical or economic factors (which strongly favor such interconnections being built), but rather to political differences between North and South Korea, and Japan, and China and its neighbors. Freed of these political constraints, a rational electrical transmission system would connect all of Asia from India to Japan and with Russia as well. South Korea, in fact, has proposed connecting their electrical grid with that of North Korea, Japan, and China. China also is proposing to connect its grid with several Central and South East Asian neighbors.

III. How do nuclear and non-nuclear forms of energy perform economically at home and abroad?

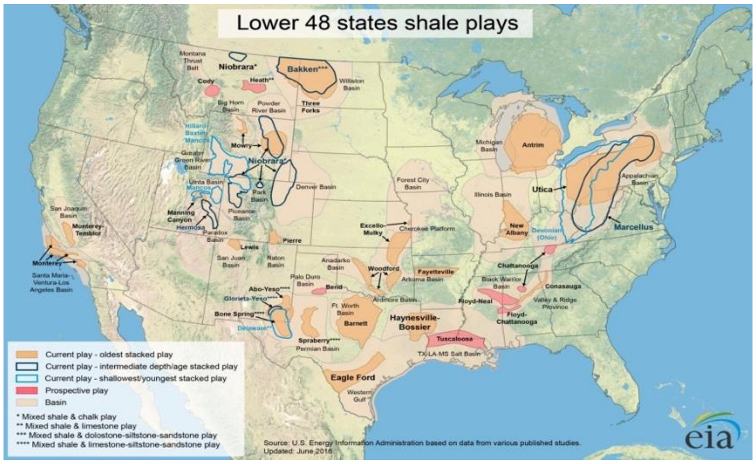
Lower Natural Gas Prices, More Coal-fired Generator Retirements

With these electrical system basics mastered, we can better understand recent and emerging electrical production trends. Over the last two decades, the most important trend has been the discovery of massive new reserves of natural gas as well as the development of new natural gas extraction techniques (including fracking) and the steady improvement in gas turbine technology. With these advances, natural gas prices have dropped along with the capital construction and operation costs of natural gas-fired electrical generator plants. This, in turn, has resulted in ever more electrical generation in America and abroad being fired by natural gas. Below is a set of charts showing how, in the last decade, natural gas use has increased to become the top fuel source for electricity generation in the US. Coal use, meanwhile, has declined dramatically:[6]



By The New York Times | Source: Energy Information Administration. Hydroelectric and other sources of electricity generation are not shown.

This trend is unlikely to change anytime soon. First, the U.S. now produces more natural gas than any other country.



Source: U.S. Energy Information Administration based on data from various published studies.
Updated: June 2016

https://www.eia.gov/todayinenergy/detail.php?id=20852

Since 2009 (and the popular advent of fracking), natural gas prices in the United States have been relatively low and stable (i.e., generally well below six dollars per million British thermal units (MBTUs):

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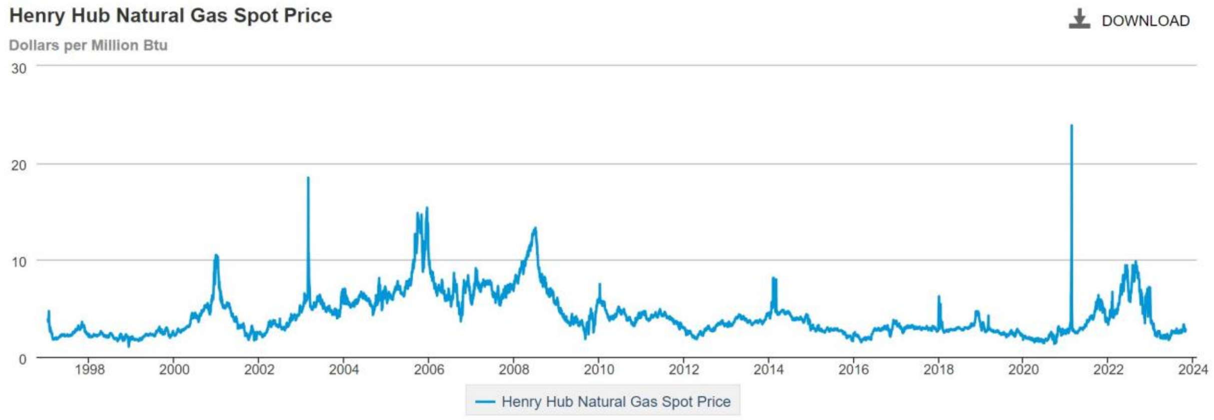
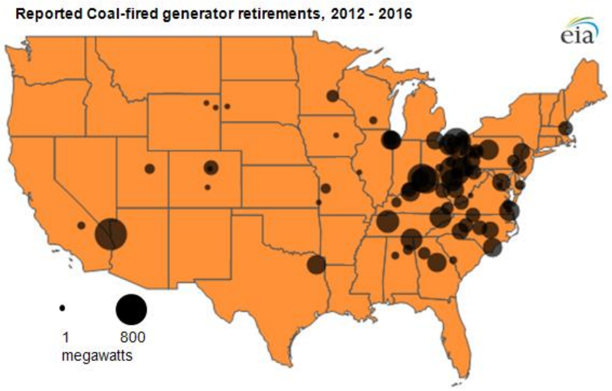
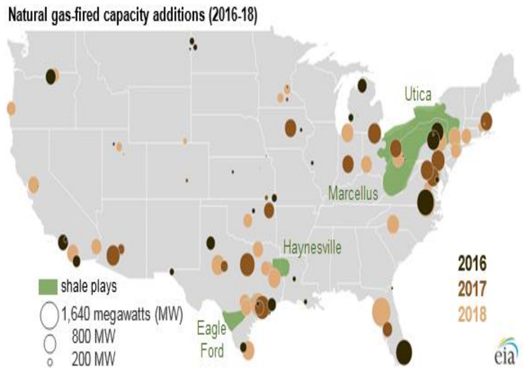
[6] Brad Plumer, "As Coal Fades in the U.S., Natural Gas Becomes the Climate Battleground," *The New York Times*, June 26, 2019, available at https://www.nytimes.com/2019/06/26/climate/natural-gas-renewables-fight.html.



https://www.eia.gov/dnav/ng/hist/rngwhhdd.htm

Second, natural gas burns much more cleanly than coal. If properly prospected to prevent methane releases, natural gas-fired electrical generators can produce up to 60 percent less greenhouse gases than coal-fired plants and far fewer pollutants (sulfur, arsenic, mercury, etc.). Combined with its lower capital construction, staffing, and operational costs, current natural gas-fired electrical generating turbines have become extremely popular replacements for older coal-fired plants. This has resulted in the retirement of coal fired-generators (See illustrations below)[7]:





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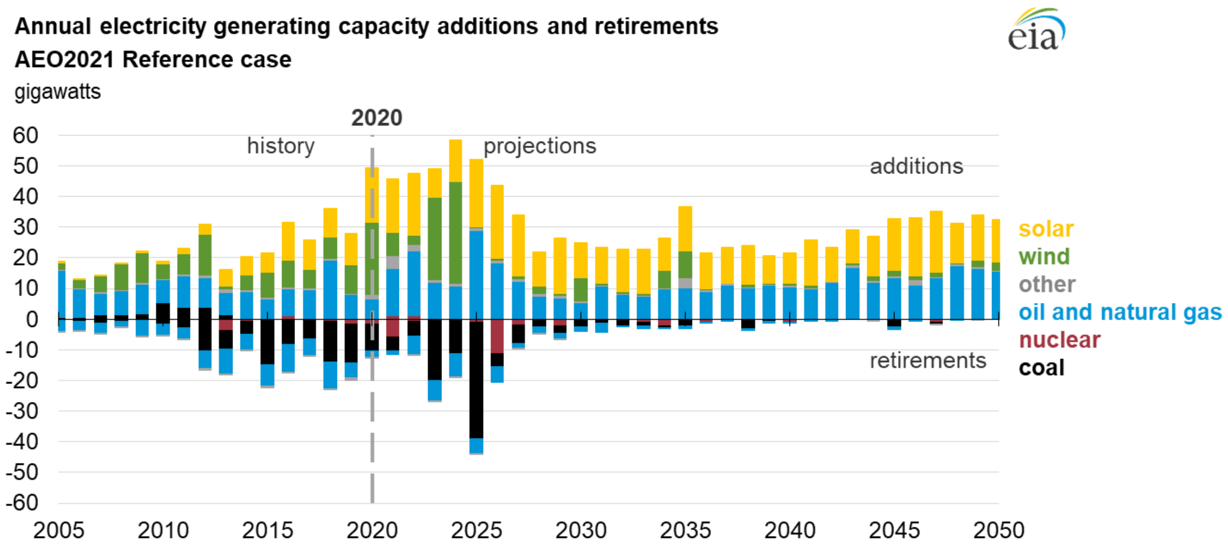
7. See US Energy Information Administration, "New Electrical Generating Capacity in 2019 Will Come from Renewables and Natural Gas," January 10, 2019, available at https://www.eia.gov/todayinenergy/detail.php?id=37952#; "Many Natural Gas-fired Power Plants under Construction Are Near Major Gas Plays," May 19, 2016, ton available athttps://www.eia.gov/todayinenergy/detail.php?id=26312; and "27 Gigawatts of Coal-fired Capacity to Retire over the Next Five Years," July 27, 2012, available at https://www.eia.gov/todayinenergy/detail.php?id=7290.

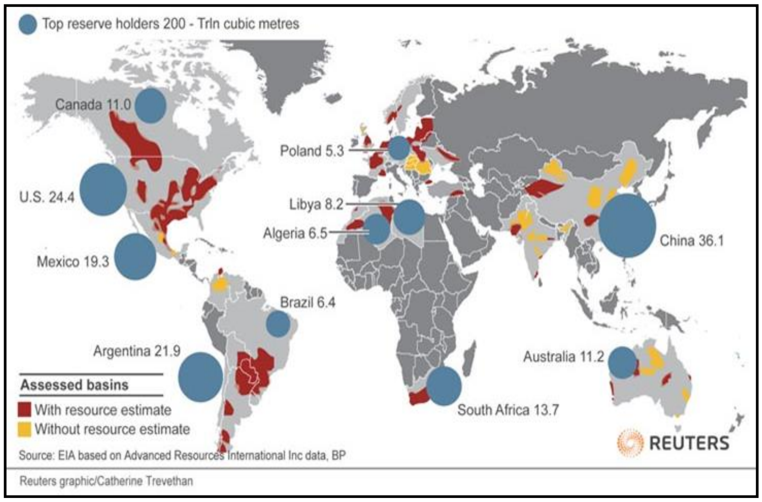


Annual electricity generating capacity additions and retirements
AEO2021 Reference case

Source: U.S. Energy Information Administration, *Annual Energy Outlook 2021* (AEO2021) Reference case and July 2020 Form EIA-860M

https://www.eia.gov/outlooks/aeo/electricity/sub-topic-02.php

Discovery and extraction of natural gas is also occurring at increased rates internationally. Part of the reason is that until the 1990s, prospecting for natural gas alone was rare. Instead, natural gas was found and tapped only when oil was discovered. This has changed. As a result, massive new reserves of natural gas have been discovered in just the last two decades (see illustration below):



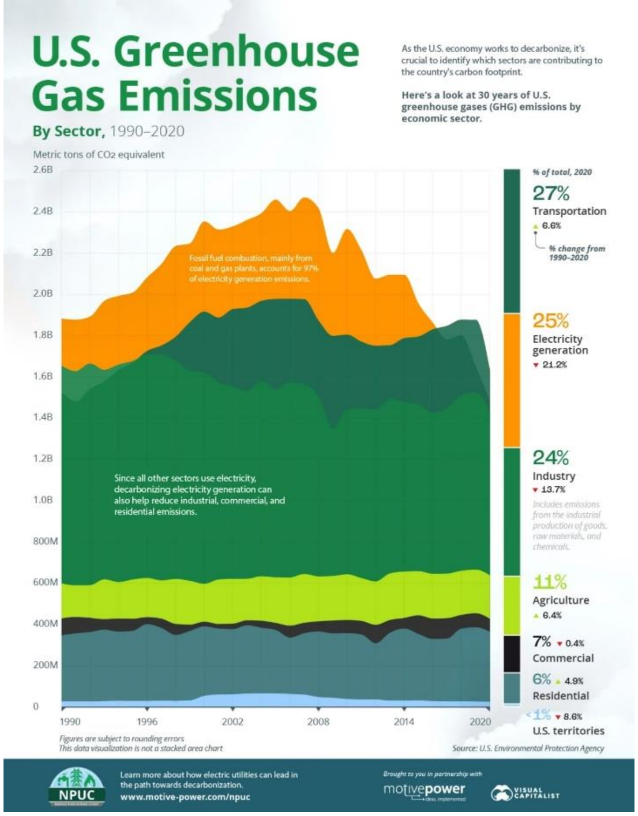
Source: EIA based on Advanced Resources International Inc data, BP

Reuters graphic/Catherine Trevethan

https://www.researchgate.net/figure/Global-Shale-Gas-Reserves-source-ARI-2013-EIA-via-Reuters_fig4_267705286

Increased Interest in Reducing Carbon Emissions, Substituting Coal with Natural Gas-Fired Plants

These natural gas developments and the retirement of coal-fired electrical generators are largely responsible for the decline in U.S. carbon emission over last decade (as reflected in the blue band portion of the chart below):

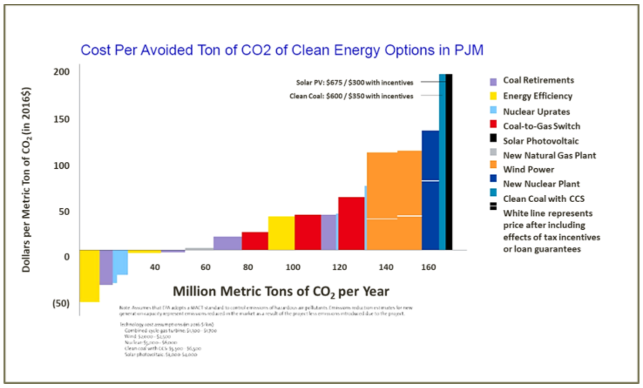


https://www.visualcapitalist.com/sp/visualizing-u-s-greenhouse-gas-emissions-by-sector/

Again, cleaner natural gas-fired plants are replacing coal-fired electrical plants because the latter are so much cheaper. How much further might market forces support such reductions is unclear but global demand for this fuel remains quite high. This and other renewable trends will have a direct impact on the future of nuclear power.

Just days before the Fukushima nuclear accident March 11, 2011, John Rowe, a nuclear engineer and then the Chief Economic Officer of Exelon, the world's largest merchant nuclear utility, argued that it did not yet pay to reduce carbon by building new nuclear power plants. As a nuclear engineer, he said he wished he could build such reactors but noted it didn't pay to build any now and probably wouldn't for at least a decade or more. The reason why, he noted, was that there were quicker, cheaper ways to reduce carbon.

Mr. Rowe demonstrated this point with the following chart (below). Using a model called the McKinsey Green House Gas Cost Abatement Curve,[8] Exelon analysts concluded that there were cheaper, quicker ways to reduce carbon than building new power reactors. These methods included encouraging increased electrical efficiencies so less electricity is consumed to produce a given product or service; retiring old coal plants; substituting coal-fired plants with gas-fired ones and renewables; and making existing nuclear power plants more efficient. In the chart below, the dark blue bar, which comes after nearly 16 other steps (see graph below), represents when and how much building new nuclear power plants would make sense. All of the other previous steps were determined to be both quicker and cheaper in reducing carbon.[9]



Since nuclear power has nearly zero carbon emissions, this conclusion seems counterintuitive but It actually tracks commonsense. Consider the following two options. Option one: You could eliminate a given amount of carbon emissions by retiring a set of coal fired plants and building two gas-fired plants in 24 months producing two gigawatts of electricity at total capital coast of $2 billion as substitutes. In this case, you could secure a return on your investment in a few short years. Option two: You could eliminate roughly the same amount of carbon by retiring the same coal plants and building a single, large one-gigawatt nuclear plant in 13 years at a cost of more than $13 billion and secure a return on your investment measured in decades. In this case, to reduce a given amount of carbon, going with the natural gas option would make more ecological and economic sense because it produces the same ecological result quicker, for less investment and returns a profit sooner.[10] Some experts project that it will eventually make

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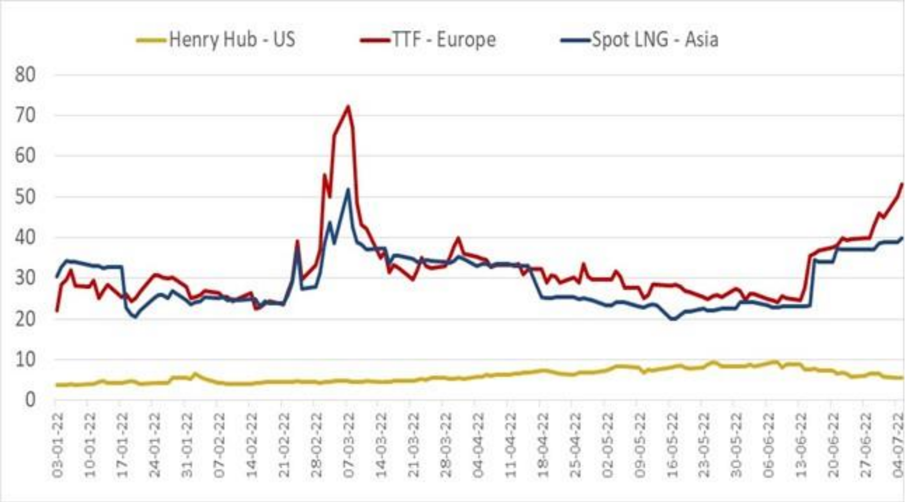
[8] McKinsey & Company, "Greenhouse gas abatement cost curves," accessed August 19, 2016, available at https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/greenhouse-gas-abatement-cost-curves.

[9] See John Rowe, "Energy Policy: Above All, Do No Harm," transcript of a presentation at the American Enterprise Institute, Washington, DC, March 8, 2011, available at http://web.archive.org/web/20110409151541/http:/www.exeloncorp.com/assets/newsroom/speeches/docs/spch_Rowe_AEI2011.pdf.

[10] See Peter Schwartz and Spencer Reiss, "Nuclear Now: How Clean, Green Atomic Energy Can Stop Global Warming," *Wired* 13, no. 2 (February 2005), available at https://www.wired.com/2005/02/nuclear-2/?pg=1&topic=nuclear&topic_set=; Sharon Squassoni, "The Realities of Nuclear Expansion" testimony for "Nuclear Power in a Warming World: Solution or Illusion?" hearing before the Select

more ecological and economic sense to substitute natural gas-fired plants with solar and wind generation backed with battery storage.[11]

Where does this put nuclear power? Building more nuclear power plants could make economic sense if natural gas prices rise significantly ***and*** carbon emissions are taxed heavily. John Rowe spoke to both points in his 2011 talk. His staff concluded that when natural gas prices rose above $19.58 per MBTU (in 2023 dollars) ***and*** carbon taxes rose above $44.50 a metric ton (in 2023 dollars), then building new power reactors would make economic sense. In the U.S., there is no national price placed on carbon emissions.[12] Regarding domestic natural gas prices, in the last decade, they have never been above $7 per MBTU. The current spot price is $2.85. Meanwhile, the cost of building new, large nuclear reactors has increased significantly over the last decade. All of this suggests that the time to build new, large power reactors in the United States has not yet arrived.



https://www.cedigaz.org/quarterly-report-q2-2022-international-natural-gas-prices/

Committee on Energy Independence and Global Warming, House of Representatives, 110th Congress, 2nd Session, Washington, DC, March 12, 2008, available at http://carnegieendowment.org/files/squassoni_testimony_20080312.pdf; and Peter A. Bradford, "Wasting time: Subsidies, operating reactors, and melting ice," *Bulletin of the Atomic* Scientists 73, no. 1 (January 2017): 13-16, available at https://www.tandfonline.com/doi/full/10.1080/00963402.2016.1264207.

11. See Charlie Block, James Newcomb, Sarita Shiredar, and Madeline Tyson, *Breakthrough Batteries: Powering the Era of Clean Electrification* (Boulder, Colorado: Rocky Mountain Institute, 2019), available at https://rmi.org/wp-content/uploads/2019/10/rmi_breakthrough_batteries.pdf and Will Wade, "Cheap Gas Is Killing Nuclear, Green Power May Finish the Job' *Bloomberg*, September 21, 2019 available at. https://www.bloomberg.com/news/features/2019-09-21/cheap-gas-is-killing-nuclear-green-power-may-finish-the-job .

12. See note 4 above.

The case for building such plant in Europe is different. There, there are carbon prices and these are currently at $130 per metric ton.[13] Meanwhile, the spot price for natural gas in Europe is now at roughly $11.55 per MBTU. As a result, interest in building large nuclear plants in Europe has increased. If natural gas prices drop, as is expected, with increased supplies from Russia and elsewhere, however, interest may wane.

As for Asia, natural gas prices also are on the rise, running at roughly $13.35 per MBTU. Like Europe, though, these prices are abnormally high. Unlike Europe, Asia also lacks carbon prices. As a result the economic case for building new, large reactors largely depends on what these plants will cost. In Japan, Taiwan, and South Korea, new construction of large plants is on hold (with Taiwan being committed to going nonnuclear by 2025). Only in China, whose economy is driven less by market signals, are large power reactors still being built.

Increasing Nuclear Costs

Certainly, the greatest impediment to nuclear power's economic expansion is the daunting costs to build them. One way to calculate these costs and to compare them with nonnuclear electrical generators is to measure what it would cost to build a given amount of generating capacity, excluding the finance or carrying costs associated with that capacity's construction. Excluding such costs favors large, expensive construction projects that take a long time to complete, such as nuclear power plants and is referred to as "overnight costs" — what it would cost to construct the plant if you could do so "overnight." What is striking is that the overnight costs of new U.S. nuclear plants are now several times higher than most of their nonnuclear alternatives.[14]

That said, these costs should decline as one builds more and more plants and develops a "learning curve" for making them more efficiently. Unfortunately, for at least the last two decades, this rule of thumb has yet to be realized with nuclear power plant construction.[15] Instead, the reverse has occurred. As one wag put it, over the last few decades, there has been

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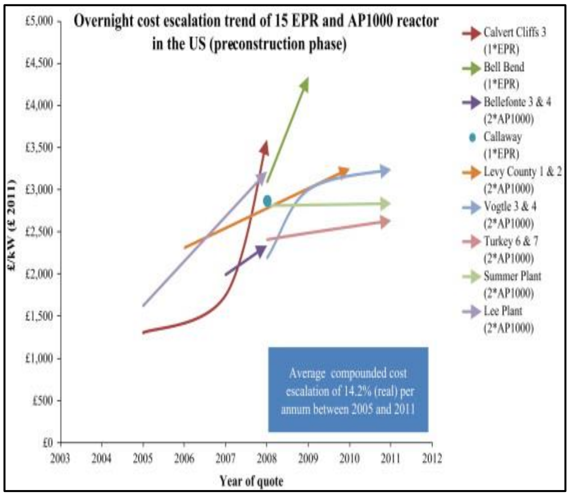
[13] Ember, *Daily Carbon Prices*, November 2, 2021 available at https://ember-climate.org/data/carbon-price-viewer/.

[14] See U.S. Energy Information Administration, "Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2019, " January 2019, available at https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf.

[15] See J. Portugal-Pereira, et. al., "Understanding Cost Escalation in Nuclear Reactor Construction Projects," a paper presented at 3rd International Conference on Project Evaluation ICOPEV 2016, Guimarães, Portugal, available at https://pdfs.semanticscholar.org/678b/9d3a688d2bd43c40693e5dfa55e25d8233a9.pdf.

a “forgetting curve” when it comes to nuclear power plant construction: Overnight costs have continually risen rather than declined (see illustration below[16]).



https://www.sciencedirect.com/science/article/abs/pii/S030142151300774X

This suggests nuclear power’s future depends on design breakthroughs that might reverse this trend. Small modular reactor designs for plants producing between 10 to 500 MWe generating capacity are now being developed with this in mind. The question is how much cheaper these smaller units will be compared to current large reactors. A key reason nuclear vendors made their plants larger and larger over the last half century was to exploit the economies of scale. The economy of scale small reactors aim to exploit are reductions in the capital costs per plant that might come if there are commercial orders for hundreds of the machines. But if the cost of the electricity these small reactors produce is not lower than that associated with larger reactors, small reactors backers could easily suffer the same economic disappointment as owners of large plants are currently experiencing.[17]

To determine what these costs might be, one would want to add up all of the costs of designing, building, operating, and retiring an electrical power plant. This would include its

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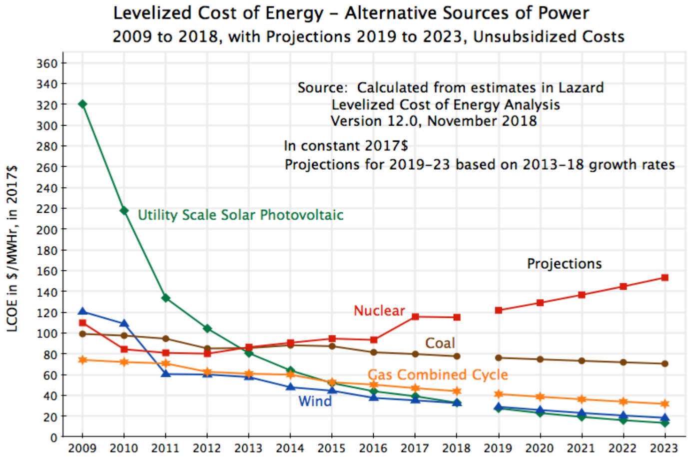
16, Grant Harris, et. al.,“Cost estimates for nuclear power in the UK,” Energy Policy, November 2013, pp. 431-42, available at https://www.sciencedirect.com/science/article/pii/S030142151300774X.

17. See Michael Schellenberger, “If Radical Innovation Makes Nuclear Power Expensive, Why Do We Think It Will Make Nuclear Cheap?” *Forbes*, July 18, 2018, available at https://www.forbes.com/sites/michaelshellenberger/; M.V. Ramana and Zia Mian, “Small Modular Reactors and the Challenges of Nuclear Power,” *Forum on Physics and Society,* January 2017, available at https://www.aps.org/units/fps/newsletters/201701/reactors.cfm; World Nuclear Association, “Small Nuclear Power Reactors,” October 2019, available at https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx, and A Abdulla, M J Ford, M G Morgan, and D G Victor, “A retrospective analysis of funding and focus in US advanced fission innovation,” Environmental Research Letters 12, 2017, available at http://iopscience.iop.org/article/10.1088/1748-9326/aa7f10/pdf.

construction costs, the costs to finance this construction, the plant's operation and maintenance costs (including any and all fuel-related costs), and the plant's decommissioning costs. If you divide this total figure by the total number of kilowatts the plant produces over its lifetime, you get the "levelized" cost of plant. This final number can be measured in cents per kilowatt hour or dollars per megawatt hour. The figure below is a levelized cost chart comparing some of the most popular electrical sources, including nuclear power plants.[18] As you can see, the levelized cost for new nuclear power plants in Europe and the U.S. is substantially higher in dollars per megawatt hour than for most nonnuclear alternatives.



https://aneconomicsense.org/2019/06/20/the-increasingly-attractive-economics-of-solar-power-solar-prices-have-plunged/

What it might cost to construct a modern reactor in other countries is a challenging question to answer. Comparing costs in North America with costs in Europe is relatively easy as many of the nuclear projects these regions use common vendors and similar cost accounting systems. In both continents, nuclear construction costs are quite high. Comparing these costs with those in Asia, however, it is more difficult. Clearly, they are lower given lower labor costs. But how much lower is a matter of controversy, as command and corporatist economies make it difficult to

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[18] See *An Economic Sense*, "The Increasingly Attractive Economics of Solar Power: Solar Prices Have Plunged," June 20, 2019 available at https://aneconomicsense.org/2019/06/20/the-increasingly-attractive-economics-of-solar-power-solar-prices-have-plunged/; US Energy Information Administration, "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2019," February 2018, available at https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf; and Lazard's Levelized Cost of Energy Analysis—Version 13.0, November 2019, available at https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf.

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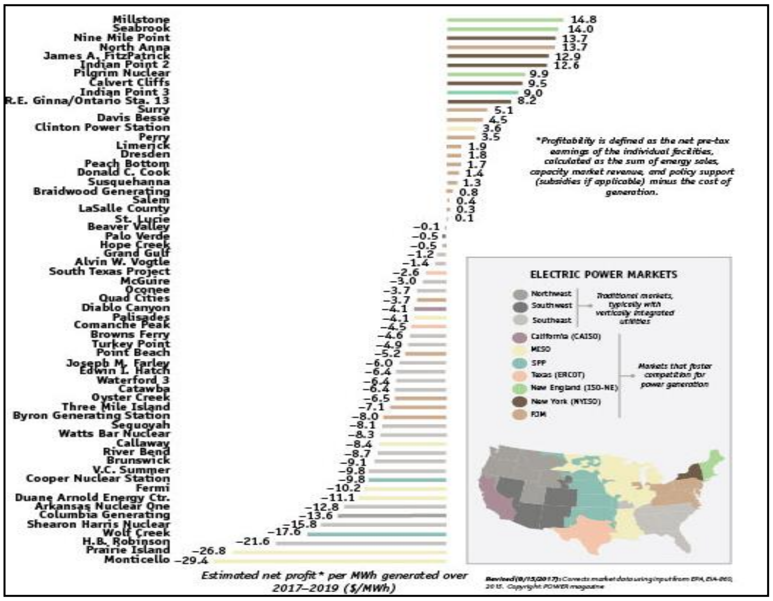
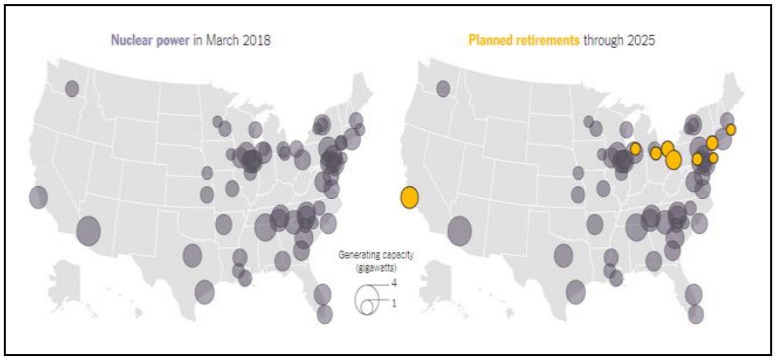
compare financing costs. There also can be major differences in nuclear safety and construction standards.

One trend that is occurring consistently abroad, however, is the retirement of existing plants and the slowdown of construction of planned nuclear capacity. In the United States, natural gas and renewables have become so cheap that it is challenging for nuclear utility companies to maintain their share of the market without additional, new subsidies. For many utility companies, the cost to operate and maintain existing reactors is more expensive than replacing them with new gas-powered plants.[19]



https://www.powermag.com/the-big-picture-nuclear-financial-meltdown/

This is causing an increased number of planned U.S. reactor retirements.



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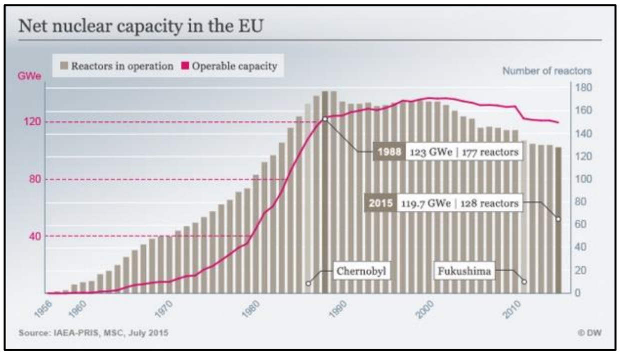
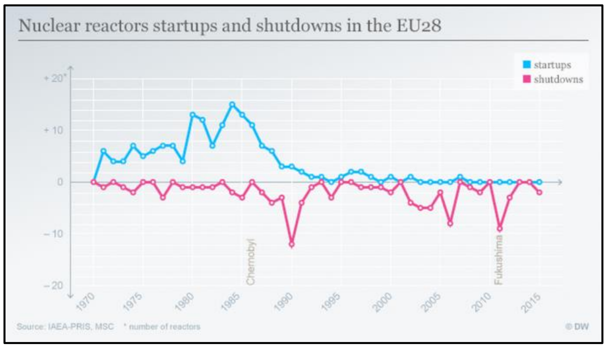
[19] See Sonal Patel, "THE BIG PICTURE: Nuclear Financial Meltdown," *Power Magazine,* August 1, 2017, available at https://www.powermag.com/the-big-picture-nuclear-financial-meltdown/.

For similar reasons, and because of public safety concerns, this trend toward reactor retirements is occurring in Europe as well (see charts below) [20]:


Net nuclear capacity in the EU

Source: IAEA-PRIS, MSC, July 2015

© DW

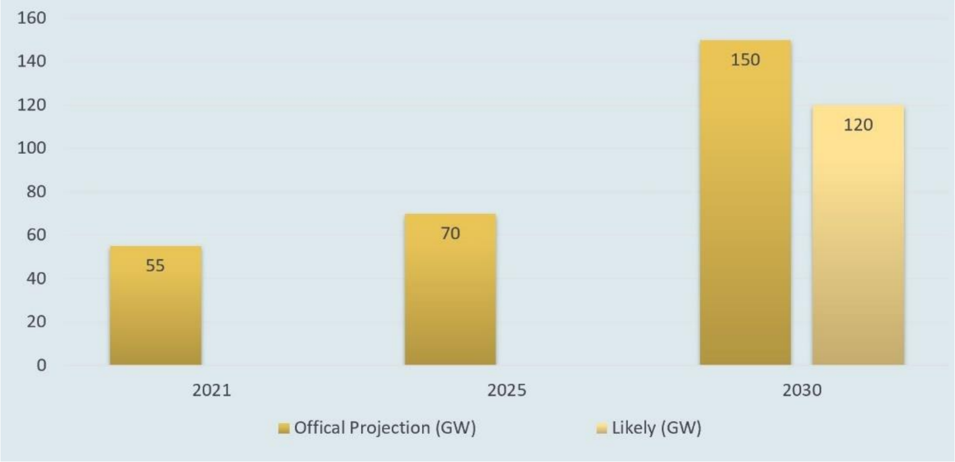

Nuclear reactors startups and shutdowns in the EU28

Source: IAEA-PRIS, MSC * number of reactors

© DW

Reactor retirements also are happening in Asia. Before Fukushima, Japan had over 50 reactors operating. Today Japan only has nine reactors on line, with a handful more to be restarted. The South Korean government meanwhile says it wants to reduce its current fleet of 24 plants to roughly 14 by the mid-30s, and Taiwan intends to unplug all 5 gigawatts of its current reactor capacity by 2025.

Even in China, the rate of nuclear expansion is coming down. Beijing has safety concerns and lacks the trained manpower to meet its ambitious construction goals. Below are adjusted projections made recently in *Nuclear Engineering International*.[21] It remains to be seen just how far and how fast China's nuclear fleet will grow.



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[20] These graphs contained Irene Banos Ruiz ,"Nuclear power faces uncertain future in Europe," DW, April 26, 2016, available at https://www.dw.com/en/nuclear-power-faces-uncertain-future-in-europe/a-19215273.
[21] See Steve Kidd, "Nuclear in China – why the slowdown?," Nuclear Engineering International, August 10, 2017, available at http://www.neimagazine.com/opinion/opinionnuclear-in-china-why-the-slowdown-5896525/.

Energy Subsidies: Yet Another Costing Complication

Every energy type—renewables, fossil fuels, and nuclear—are the beneficiaries of government energy subsidies. These include production tax credits and accelerated depreciation schedules, loan guarantees, feed-in tariffs, clean air credits, partial recovery of the costs of government regulation, and federal commercialization development cost sharing arrangements. Rarely are all these subsidies figured in to the price and cost comparisons for different kinds of electricity resources. What further complicates these comparisons is that each energy type is subsidized differently and for different durations.

In the case of nuclear power, there are several significant subsidies. Among the most important of these are federal loan guarantees, federal production tax credits, federal caps placed on the amount liability nuclear utilities assume for offsite damage in the case of an accident, and federal assumption of responsibility for nuclear waste management. Subsidized loans allow nuclear power plant builders to borrow at discounted interest rates (sometimes near or at zero percent), thus reducing reactor capital construction costs by billions of dollars. Similarly, energy production tax credits can increase the profitability of nuclear electrical production by at least as much.[22]

Federal liability caps for off-site damage caused by a nuclear accident are also a significant indirect subsidy. Remediation of the nuclear accident at Fukushima is projected to cost between $200 billion and more than $700 billion. Under U.S. law (the Price-Anderson Act), U.S. nuclear utilities, though, need to collectively maintain only roughly $450 million dollars of liability insurance. In the case of an accident, the Secretary of Energy may waive the requirement for the utilities to pay any more than this amount. If he does not, the utilities must pay roughly $13 billion over seven years to help remediate the offsite damages. Their maximum liability per accident, however, is capped at this amount. If the remediation costs run over the amount the utilities must pay, the Federal government pays the difference directly out of the U.S. Treasury. By one recent evaluation, this indirect subsidy could be worth between 22 to 57.8 cents/per kilowatt hour (KWh). These figures are significant, as the Department of Energy

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[22] 22. See Henry Sokolski, ed., Pure Risk: Federal Clean Energy Loan Guarantees (Arlington, VA: Nonproliferation Policy Education Center, 2012), available at http://www.npolicy.org/thebook.php?bid=24 and Doug Koplow, "A Case Study of Subsidies to Calvert Cliffs," in Nuclear Power's Global Expansion, ed. Henry Sokolski (Carlisle, PA: Strategic Studies Institute, 2010), 335-382, available at http://www.npolicy.org/userfiles/image/A%20Case%20Study%20of%20Subsidies%20to%20Calvert%20Cliffs_pdf.pdf.

has estimated that the future levelized cost of nuclear power is roughly 10 cents or more per KWh.[23]

Finally, the federal government has assumed all of the costs associated with the final, off-site disposal of nuclear waste. The utilities do not pay out of pocket for these expenses but instead collected a federal waste management fee from their ratepayers. This fund currently is roughly valued at $43 billion.

Fresh and Enriched Uranium: Nuclear Power's Economic Bright Spots

Partly because of reduced demand, increased supply, and technical advances in uranium extraction and uranium enrichment, the price of uranium ore (yellow cake or U3 O8) and enrichment (measured by separate work units or SWUs) are relatively low (see charts below):

https://world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/uranium-markets.aspx

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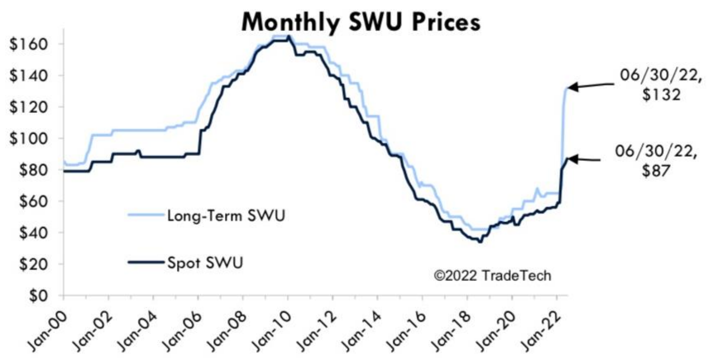
[23] See Nuclear Liability Insurance (Price-Anderson Act)," National Association of Insurance Commissioners, updated August 10, 2018, available at https://www.naic.org/cipr_topics/topic_nuclear_liability_insurance.htm; and U.S. Nuclear Regulatory Commission, "Fact Sheet on Nuclear Insurance and Disaster Relief Funds," March 29, 2012, available at https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/nuclear-insurance.html and John J. Laureto & Joshua M. Pearce, "Nuclear Insurance Subsidies Cost from Post-Fukushima Accounting Based on Media Sources," Sustainability, December 12, 2016, available at https://res.mdpi.com/sustainability/sustainability-08-01301/article_deploy/sustainability-08-01301.pdf?filename=&attachment=1.



$130/SWU

April 2023

https://www.uxc.com/account/PasswordRequest.aspx

While these two trends have not increased the levelized life cycle (lifetime) costs associated with nuclear power, they have not reduced it by much either: Nuclear fuel cycle costs make up no more than ten percent of nuclear power's total life cycle costs. The more immediate impact of low uranium and uranium enrichment service prices is to make the recycling of plutonium (i.e., the chemical separation of plutonium from spent fuel, fabricating it into mixed oxide fuel (MoX), and then recycling it in light water or fast reactors) uneconomical. Recent studies indicate that uranium yellow cake prices would have to increase roughly 10 to 20-fold from current prices to for reprocessing to make economic sense. This takes into consideration whatever spent fuel management value recycling has been claimed to have.[24] Finally, because of the current oversupply of uranium enrichment capacity worldwide, near and mid-term investments to expand existing enrichment capacity are economically unattractive.[25] Both of these market-driven conclusions align with nonproliferation efforts to reduce or ban further enrichment and reprocessing, especially in states that currently do not engage in such proliferation-prone activities.

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24. Matthew Bunn, Hui Zhang, and Li Kang, *The Cost of Reprocessing in China,* (Managing the Atom Project, Belfer Center, January 2016), available at https://www.belfercenter.org/sites/default/files/legacy/files/The%20Cost%20of%20Reprocessing.pdf and Matthew Bunn, Steve Fetter, John P. Holdren, & Bob van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel,* Belfer Center for Science and International Affairs, December 2003, available at https://ocw.mit.edu/courses/nuclear-engineering/22-812j-managing-nuclear-technology-spring-2004/readings/repro_report.pdf.

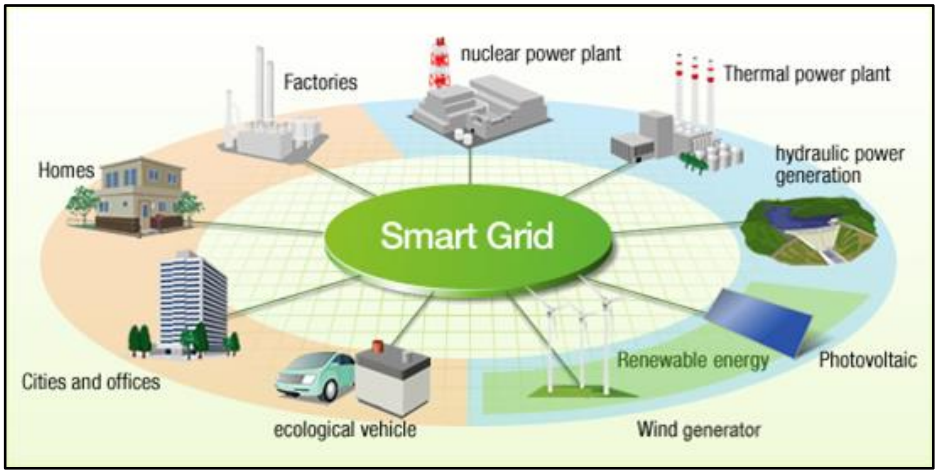
25.Steve Kidd, "Uranium Enrichment – Why are Prices Now Much Lower and What is the Impact?" *Nuclear Engineering International,* December 2016, available at http://www.neimagazine.com/opinion/opinionuranium-enrichment-why-are-prices-now-much-lower-and-what-is-the-impact-5692128/ ; and Thomas Meade and Eileen Supko, "Enrichment excess is here to stay," Nuclear Engineering International, October 13, 2015, available at http://www.neimagazine.com/features/featureenrichment-excess-is-here-to-stay-4691321/.

Emerging Energy Technologies and the Future of Electrical Generation and Grid Distribution

Natural gas, coal, hydro and nuclear have long dominated the fuel types used to generate electricity. New technologies, however, have made the use of wind and solar more popular. In this regard, one of the most important group of technologies to emerge are those supporting the development of smart grids.

What are smart grids? Essentially, improved versions of the electrical distribution systems we currently have. Smart grids measure electrical consumption more accurately and quickly by using upgraded meters and are capable of moving large amounts of electricity from base and peak-load generators using high voltage direct current line (HVDC), along with intermittent renewable electrical sources, with greater agility using advanced switching technologies.

Smart grids also are able to manage various forms of electrical storage (grid battery storage, integrated electric vehicle batteries, pumped hydro storage, super-capacitors, etc.) much more efficiently than existing grids. The aim of smart (or smarter) grids is to be able to juggle many new sources of electricity with a variety of consumers while keeping the grid balanced. For example, the smarter a grid is, the more it is able to monitor demand and shift loads, making it possible to "store" intermittent renewable generated electricity on the grid for a time.[26] Below is a basic schematic of such a grid.



https://www.nextbigfuture.com/2016/08/nextbigfuture-interview-with-ieee.html

One of the greatest challenges facing the development of smart grids is their use of intermittent electricity sources, such as wind and solar. Solar, of course, comes on strong during the day and is strongest midday. As portrayed in the peak and base load charts

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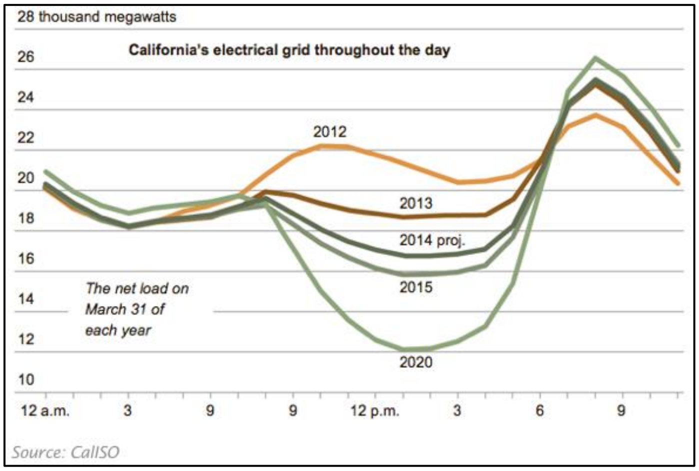
[26] See Brian Wang, "Next big interview with IEEE Fellow Massoud Amin on Smart cities and smart grids," *IEEE Spectrum,* August 9, 2016, available at https://www.nextbigfuture.com/2016/08/nextbigfuture-interview-with-ieee.html.

previously, in the middle of a typical summer day, when it is hot, you are using the most electricity. Now, if you are generating solar power in the mid-day, you may be supplying not just what peak demand requires, but also what base load generators would otherwise supply. As a result, the base load generators, which produce electricity midday at a much higher cost than solar, may have to be taken off line, otherwise the surplus solar will have to be wasted or exported to an outside electricity market. What complicates the supply picture even more is that once the sun goes down, demand may still be high enough to require ramping up the large base and peak load generators. This is not possible with nuclear power plants, which cannot be safely ramped up or down quickly. Nor is it cheap or easy to ramp up large fossil fueled base-load generators. All of these demand and supply swings increase the risk of destabilizing the grid.

The severity of these supply and demand swings can be projected as a function of how much solar power (and other intermittent electricity sources such as wind power) one supplies to the grid. One way to portray this is to graph 'net load' i.e., how much electrical demand remains after you subtract the amount of intermittent renewable electricity that is being supplied to the grid. California's grid operator (Independent System Operator) was one of the first to graph current and projected net load for a typical spring day in California from 2012 through 2020. These projections produced what has now come to be known as the "duck curve":



Source: CalISO

The top yellow-brownish curve shows mid-day net demand (electricity demand after renewable generated electricity has been subtracted from the total being provided) peaking at roughly 22 thousand megawatts electrical (MWe). By 2020, when much more solar power was installed on the grid, however, the net load midday was 10 thousand MWe less. That means that by 2020, base load generators provided far less electricity midday. Yet, in 2020, peak demand spiked from 6 p.m. to 9 p.m. such that both peak and base load generators had to be resorted to produce roughly 10 thousand MWe.

This set of complications are worth avoiding. To reduce the 6 to 9 p.m. ramp up in demand, you want to flatten the curve by having stored electricity on the ready so you don't use your base or peak load generation so much to fill the 10 thousand MWe gap. You use solar and wind power when it is most efficacious to do so during the day, store surplus amounts of it so that when the sun goes down or the wind is not blowing, and draw on those surpluses to meet the demand that remains (in this case, late afternoon and evening demand).[27]

Technically, there are several ways to do this. One way is to use lithium batteries. These storage systems, however, are still expensive to use for anything but relatively short periods (at most a few hours or less).[28] There are a number of new electric grid storage battery concepts, though, that promise to bring prices much lower, including flow batteries.[29] In the meantime, attempts are being made to exploit the battery storage potential the growing number of electric vehicles might afford. The idea here is to tap the electricity stored in these vehicles' batteries when they are parked and have them be topped off at residential and public parking locations.[30] Yet another scheme being developed is to produce hydrogen with surplus electrical power (from renewables or excess base load capacity) and use fuel cells to store electricity.[31]

Other kinds of nonelectric batteries are also being explored. An electricity storage concept that is being commercially employed in the Middle East, Australia, South Africa, and China is concentrated solar power (CSP). Mirrors are focused to reflect solar energy to super heat liquid sodium. This hot sodium is then used to produce steam and electricity after the sun goes down. States in the world's sunny regions are currently building CSP systems to produce electricity from 4 p.m. to 10 a.m. The cheapest of these projects will produce electricity in the Middle East, Australia and Chile for less (7.3 cents or less per kilowatt hour) than the cost of new

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[27] Becca Jones-Albertus, "Confronting the Duck Curve: How to Address Over-Generation of Solar Energy," US Department of Energy, Office of Energy Efficiency & Renewable Energy, October 12, 2017, available at https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy.

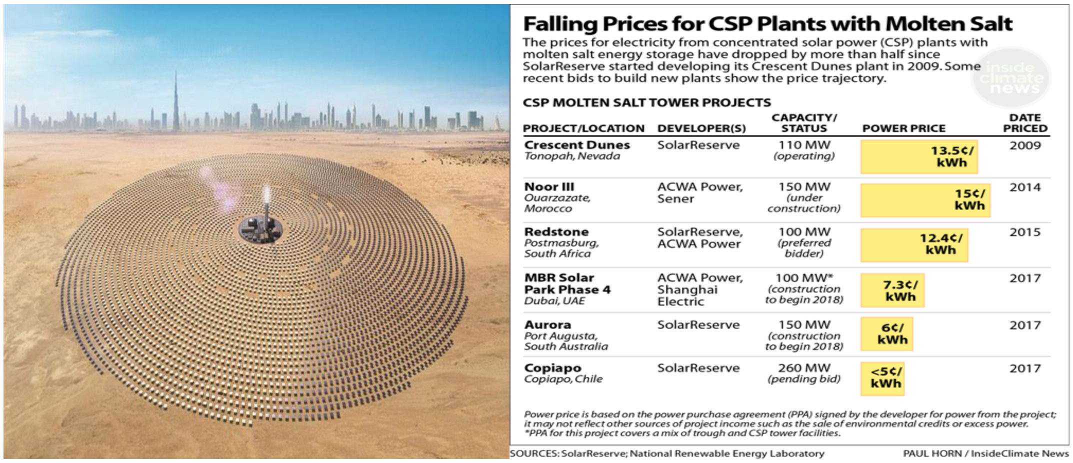
[28] Peter Maloney, "IHS: Grid-scale Lithium Battery Storage Prices Will Decline by Half by 2019," Utility Drive, November 25, 2015, available at https://www.utilitydive.com/news/ihs-grid-scale-lithium-ion-battery-storage-prices-will-decline-by-half-by/409822/.

[29] See "New Iron-Based Batteries Offer an Alternative to Lithium," *Yale Environment 360 Digest,* October 1, 2021, available at https://e360.yale.edu/digest/new-iron-based-battery-promises-to-be-a-cheap-alternative-to-lithium.

[30] See Todd Woody, "Car Companies Take Expertise in Battery Beyond the Garage," New York Times, March 25, 2014, available at https://www.nytimes.com/2014/03/25/business/car-companies-take-expertise-in-battery-power-beyond-the-garage.html.

[31] See Julian Ryall, Power Choice: The Future: Hydrogen-powered Cars in Japan, Japan Today, May 6, 2018, available at https://japantoday.com/category/tech/power-of-choice-the-future-of-hydrogen-powered-cars-in-japan.

nuclear power (at 11 cents per kilowatt hour). When used in tandem with solar photovoltaics, these CSP systems can provide solar electricity 24/7—see below[32]).



Falling Prices for CSP Plants with Molten Salt

The prices for electricity from concentrated solar power (CSP) plants with molten salt energy storage have dropped by more than half since SolarReserve started developing its Crescent Dunes plant in 2009. Some recent bids to build new plants show the price trajectory.

CSP MOLTEN SALT TOWER PROJECTS

PROJECT/LOCATION	DEVELOPER(S)	CAPACITY/ STATUS	POWER PRICE	DATE PRICED
Crescent Dunes *Tonopah, Nevada*	SolarReserve	110 MW *(operating)*	13.5¢/ kWh	2009
Noor III *Ouarzazate, Morocco*	ACWA Power, Sener	150 MW *(under construction)*	15¢/ kWh	2014
Redstone *Postmasburg, South Africa*	SolarReserve, ACWA Power	100 MW *(preferred bidder)*	12.4¢/ kWh	2015
MBR Solar Park Phase 4 *Dubai, UAE*	ACWA Power, Shanghai Electric	100 MW* *(construction to begin 2018)*	7.3¢/ kWh	2017
Aurora *Port Augusta, South Australia*	SolarReserve	150 MW *(construction to begin 2018)*	6¢/ kWh	2017
Copiapo *Copiapo, Chile*	SolarReserve	260 MW *(pending bid)*	<5¢/ kWh	2017

Power price is based on the power purchase agreement (PPA) signed by the developer for power from the project; it may not reflect other sources of project income such as the sale of environmental credits or excess power.
**PPA for this project covers a mix of trough and CSP tower facilities.*

SOURCES: SolarReserve; National Renewable Energy Laboratory

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Finally, there are mechanical batteries. The most popular of these are pumped hydro systems. They use surplus wind and solar power to pump water up to a level that can be tapped to produce hydro power later. Here, again, the challenge is finding a place to store enough pumped hydro to provide for a substantial amount of stored power. Also, cost is a major limitation. One recent European mechanical battery concept now under development is to use an electric crane to stack concrete blocks using surplus electricity during the day and then using the gravity this stacking has stored to produce electricity mechanically later.[33]

All of these attempts at electric grid battery storage could alter electrical systems significantly. If any become truly economical, they would make not just renewables far more attractive, but eliminate most, if not all, of the need to build or operate base load generators of any sort. In this case, they could render the current electrical grid more of a backup system rather than a primary provider of electricity.[34]

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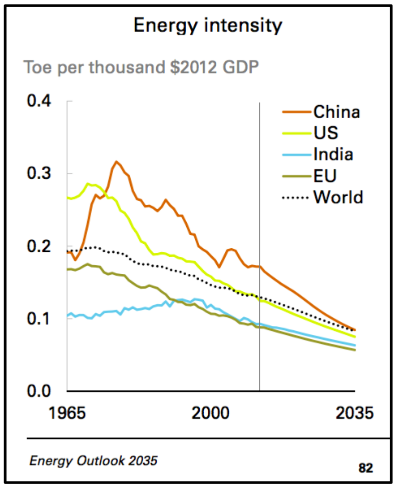
[32] Peter Fairley, "The United Arab Emirates' Nuclear Power Gambit," *IEEE Spectrum*, January 4, 2018, available at https://spectrum.ieee.org/energy/nuclear/the-united-arab-emirates-nuclear-power-gambit.

[33] Akshatqz Rathi, "Stacking concrete blocks is a surprisingly efficient way to store energy," *Quartz,* August 18, 2018, available at https://qz.com/1355672/stacking-concrete-blocks-is-a-surprisingly-efficient-way-to-store-energy/.

[34] See Matt Slowikowski, "How Storage Could Transform the U.S. Power Grid," *Oilprice.com,* August, 17, 2016, available at https://oilprice.com/Energy/Energy-General/How-Storage-Could-Transform-The-US-Power-Grid.html; "Distributed generation: Devolving power," *The Economist,* March 8, 2014, available at https://www.economist.com/business/2014/03/08/devolving-power; and Rocky Mountain Institute et. al, "The Economics of Grid Defection", 2014, available at https://www.homerenergy.com/pdf/RMI_Grid_Defection_Report.pdf.

Electricity: Future Demand

Besides making electricity clean an affordable, there is the challenge to make enough of it. It is established that economies that move up from poverty consume more electricity. Yet recently, experts have also determined that economies have been growing while reducing per the amount of energy need per dollar of gross domestic product.[35]



Meanwhile, many experts believe the world's population will continue to grow. This assumption, however, is rebuttable: As the educational levels of women increase, statistically their fertility declines. The UN understands this and has projected that with changes in fertility, world population might peak by 2050 and, then, decline.[36]

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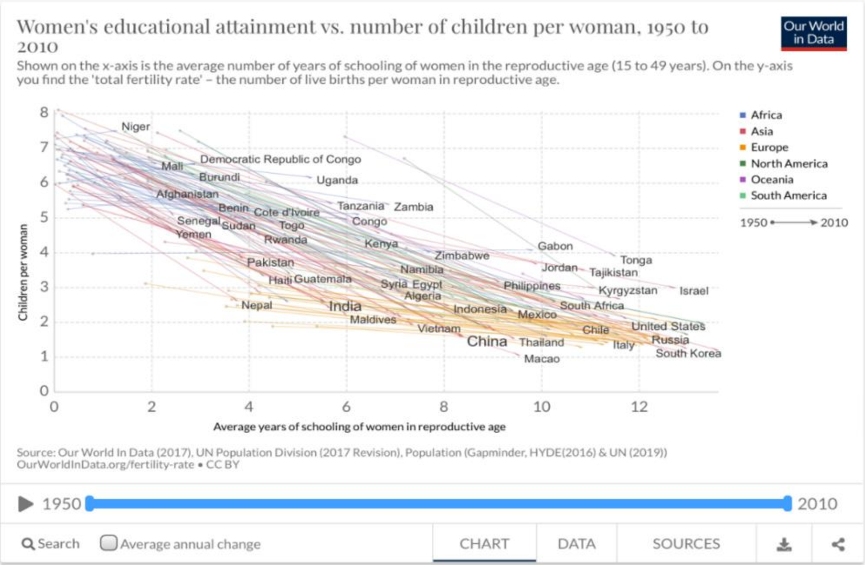
[35] See US Energy Information Administration, "Global Energy Intensity Continues to Decline," July 12, 2016, available at https://www.eia.gov/todayinenergy/detail.php?id=27032.

[36] See "Question: The United Nations Population Division Projects Future Population Growth. The Four Projections," available at https://www.chegg.com/homework-help/questions-and-answers/united-nations-population-division-projects-future-population-growth-four-projections-grap-q23707509.

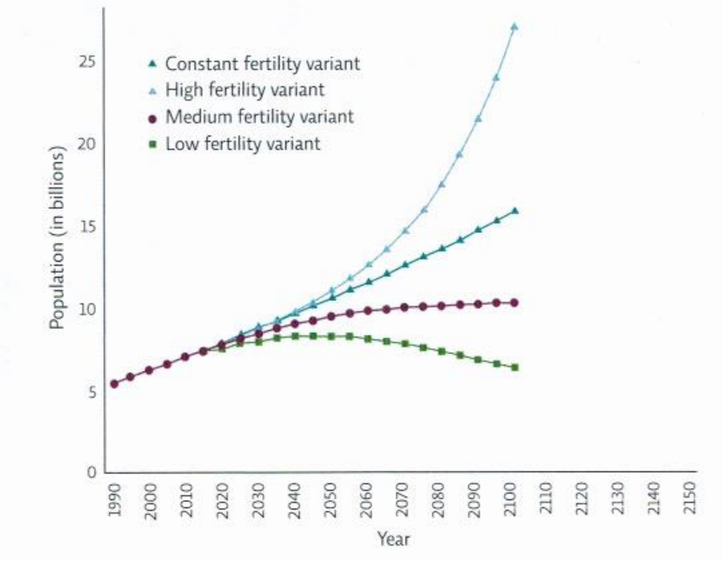


Women's educational attainment vs. number of children per woman, 1950 to 2010

Shown on the x-axis is the average number of years of schooling of women in the reproductive age (15 to 49 years). On the y-axis you find the 'total fertility rate' – the number of live births per woman in reproductive age.

Source: Our World In Data (2017), UN Population Division (2017 Revision), Population (Gapminder, HYDE(2016) & UN (2019)) OurWorldInData.org/fertility-rate • CC BY

GRAPH A Estimated and Projected World Population According to Different Variants



As greenhouse gas emissions have roughly tracked population (see graph below),[37] the implications of a possible population decline could be significant environmentally.

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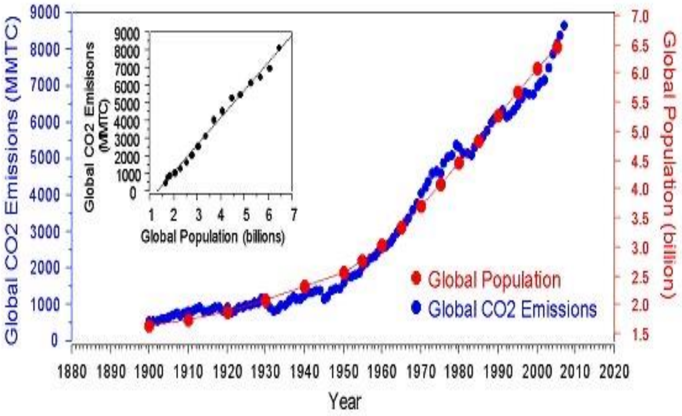
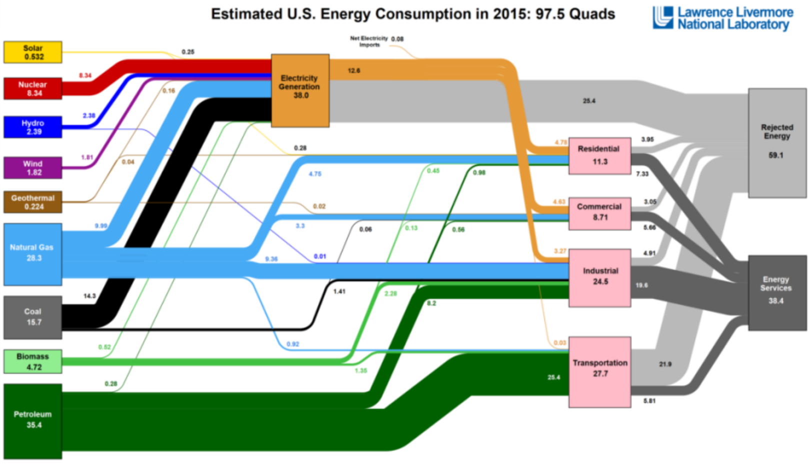
[37] See "Twenty-first Century Tech, Climate Skeptics Point to World Population as the Real Problem," September 22, 2014, available at https://www.21stcentech.com/climate-skeptics-point-world-population-real-problem/.



Yet another unknown is how much efficiencies associated with energy and electricity consumption and production could improve. Certainly, the current amount of energy that literally goes up in smoke while producing electricity, heating and locomotion even in the most advanced economy — the United States — is roughly twice that of the energy put to practical use. In the case of electrical production, the proportion of energy that is wasted is even higher (see graphic below):


Estimated U.S. Energy Consumption in 2015: 97.5 Quads

Source: LLNL March, 2016. Data is based on DOE/EIA MER (2015). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 0.65% for the residential sector, 0.65% for the commercial sector, 0.8% for the industrial sector, and 0.21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

Will population growth abate? Will the portion of transport driven by electricity continue to grow over that driven by fossil fuels? Will lifestyles change regarding consumption generally? How clean must electrical generation be? These are additional unknowns that together with the others already mention will determine future electricity demand and how it will be met.