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13.5 Summary

13 Deep Decarbonization

In the first unit of this course ("Simple"), we saw that burning carbon permanently adds CO_2 to the air, and that CO_2 absorbs outgoing heat to warm Earth's climate. In the second unit ("Serious"), we saw that the consequences of continued warming due to increases in CO_2 can quickly and permanently become devastating for society, the economy, and nature.

This third unit of the course ("Solvable") considers how global catastrophe can be averted. We learned in Module 10 that ***sustainable development requires simultaneously dealing with carbon emissions and socioeconomic inequity***. In Module 11 we learned that economists are nearly unanimous in recommending strong action through ***pricing carbon***, though they can't yet agree on a price. In Module 12 we learned that the countries of the world have spent three decades negotiating ***pledges to achieve net zero carbon emissions***, and that much stronger policies are being implemented at regional, state, and local levels.

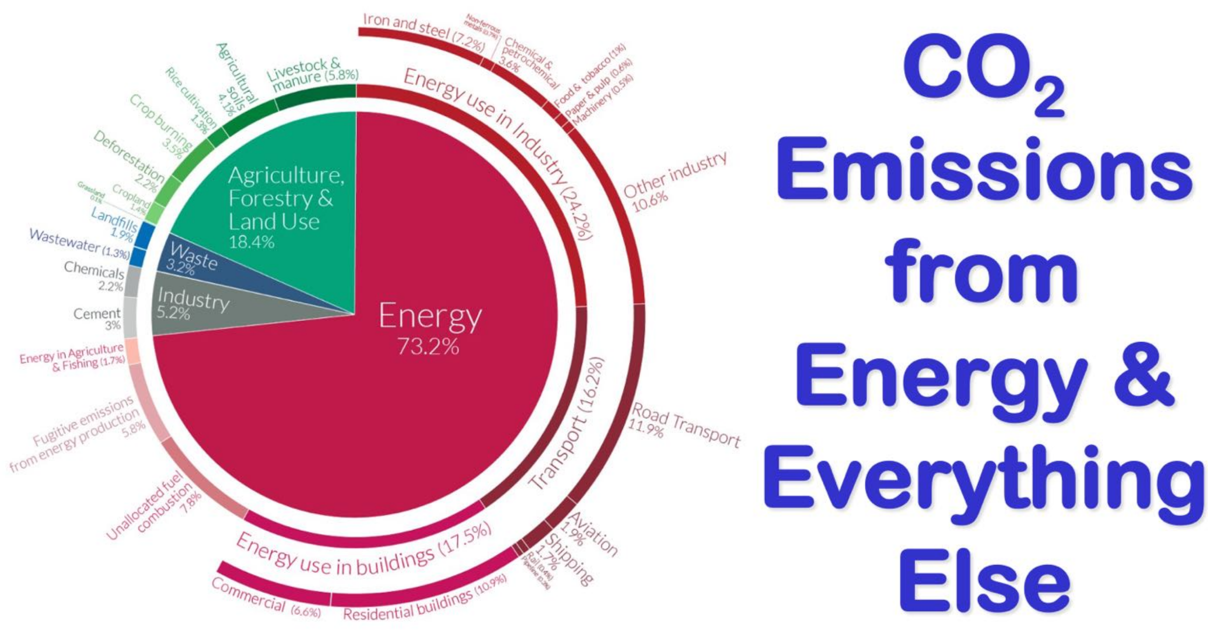
All these preliminaries emphasize that it's imperative for the world to:

Of course, the challenge is to very rapidly replace the goods and services which have historically been enabled through burning carbon (energy, transportation, manufacturing) with non-carbon alternatives.

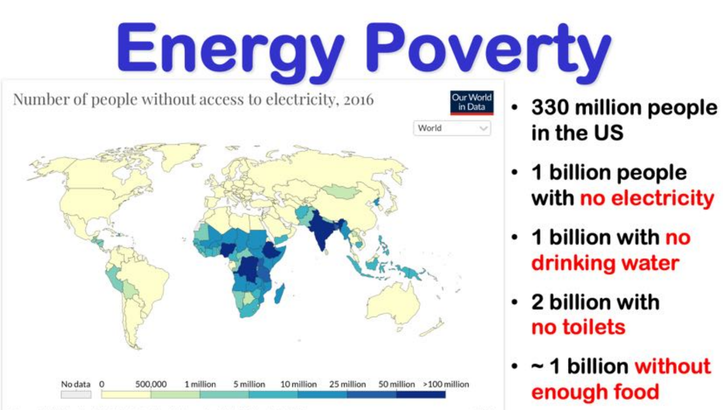
In this module we consider the practical steps required to quickly stop setting carbon on fire.

13.1 Decarbonizing Energy and Everything Else

By far, ***most CO_2 emissions arise from producing energy***. According to Our World in Data, energy accounts for about three fourths of emissions, with Agriculture, Forestry, and Other Land Use (AFOLU) accounting for most of the rest. Therefore, we will focus on ***decarbonizing energy*** for most of the rest of this module. Other sectors are important and will become more so as low-carbon energy displaces fossil fuels in the coming decades, but there can be no avoiding climate catastrophe without decarbonizing the global energy system.



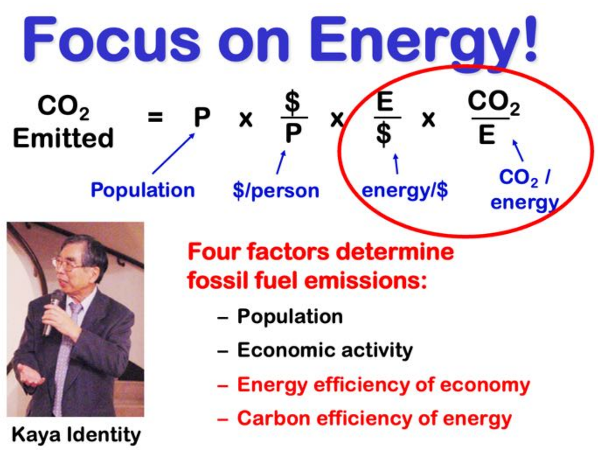
Source: Our World in Data, 2020. Data from Climate Watch, 2020.



As we emphasized in Module 10, rapid development and deployment of noncarbon energy must be happen at the same time as we address severe inequality of opportunity around the world. Huge numbers of people experience energy poverty, and the delivery of inexpensive and reliable carbon-free power to billions of energy-poor people is a top priority for solving the climate problem.

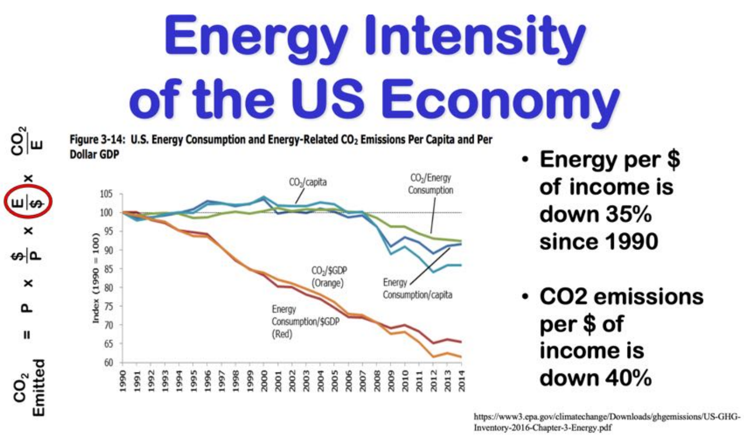
Using the Kaya Identity, we learned that population growth is no longer the driver of rising CO_2, and in fact the only remaining regions of the world with rapid population growth are the same regions that suffer from extreme energy poverty. Addressing energy poverty and extreme deprivation in these regions will be absolutely critical in achieving a demographic transition and stabilizing global population. This means that decarbonizing energy and ***alleviating extreme poverty are complementary, not conflicting goals*** in the coming decades.

The [Kaya Identity](#) shows that decarbonizing the world while addressing severe poverty requires a focus on the energy intensity of income and the carbon intensity of energy – that is, on the third and fourth Kaya factors.



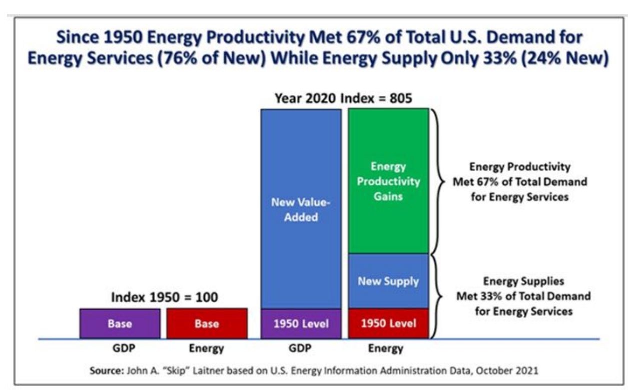
13.1.1 Energy Intensity of GDP

Historically, the ***energy intensity of income has fallen quite fast*** in the developed world. In the United States, this factor has fallen nearly 40% in a generation as services overtook manufacturing and industry became more efficient. European counttes have moved even more rapidly in this direction.



Since 1950, about two-thirds of economic growth in the United States has been "fueled" by improvements in energy productivity (that is, income per unit of energy), rather than by new energy supply. Middle income countries that have more recently experienced a demographic transition are now experiencing this shift toward higher energy productivity.

There are some really exciting developments in energy efficiency that will continue to drive improvements in energy intensity in coming decades. Chief among these are huge improvements in the energy efficiency of buildings and transportation. In both these sectors, the ***energy savings are expected to come at negative financial cost***: that means it's cheaper to use energy wisely than it is to waste it. Huge and almost immediate financial savings can be achieved by plucking low-hanging fruit in how we design, construct, and operate buildings with better heating, lighting, and insulation. More livable cities with better transit and mixed employment/residential neighborhoods can dramaticaly reduce the energy required for transportation. Vehicle electrification is just getting started, and electric vehicles are dramaticlaly more energy efficient than carrying a combustion power plant around and converting heat into motion.



13.1.2 Carbon Intensity of Energy

Even the rapid historical improvements in energy intensity have been outstripped by the pace of economic growth in developing countries. Per-capita income grew 3000% in China from 1990 to 2020 even as energy intensity plummeted. So the relative improvements in energy intensity have not been rapid enough to produce absolute decreases in CO_2 emissions, much less put the world on track to meet the targets of the UN FCCC negotiations.

To avert a global catastrophe, rapid gains in energy productivoty must be paired with very rapid ***decarbonization of the energy supply***. This is the fourth Kaya factor: CO_2 emissions per unit energy, measured in grams of CO_2 per kW-hr of energy.

In the past 15 years, there's been a revolution in electricity production from noncarbon sources. Solar, wind, and hydropower were among the most expensive sources of electricity in 2008 but are now the ***cheapest sources of electricity almost everywhere***. Even better, electricity is typically produced centrally and used across a distributed grid. This means that it's possible to switch out generating technologies and achieve dramatic improvements in the carbon intensity of energy without disruption to end users who power their lves with centrally-produced electricity.

In the words of climate writer Dave Roberts, a simple plan for deep decarbonization is:

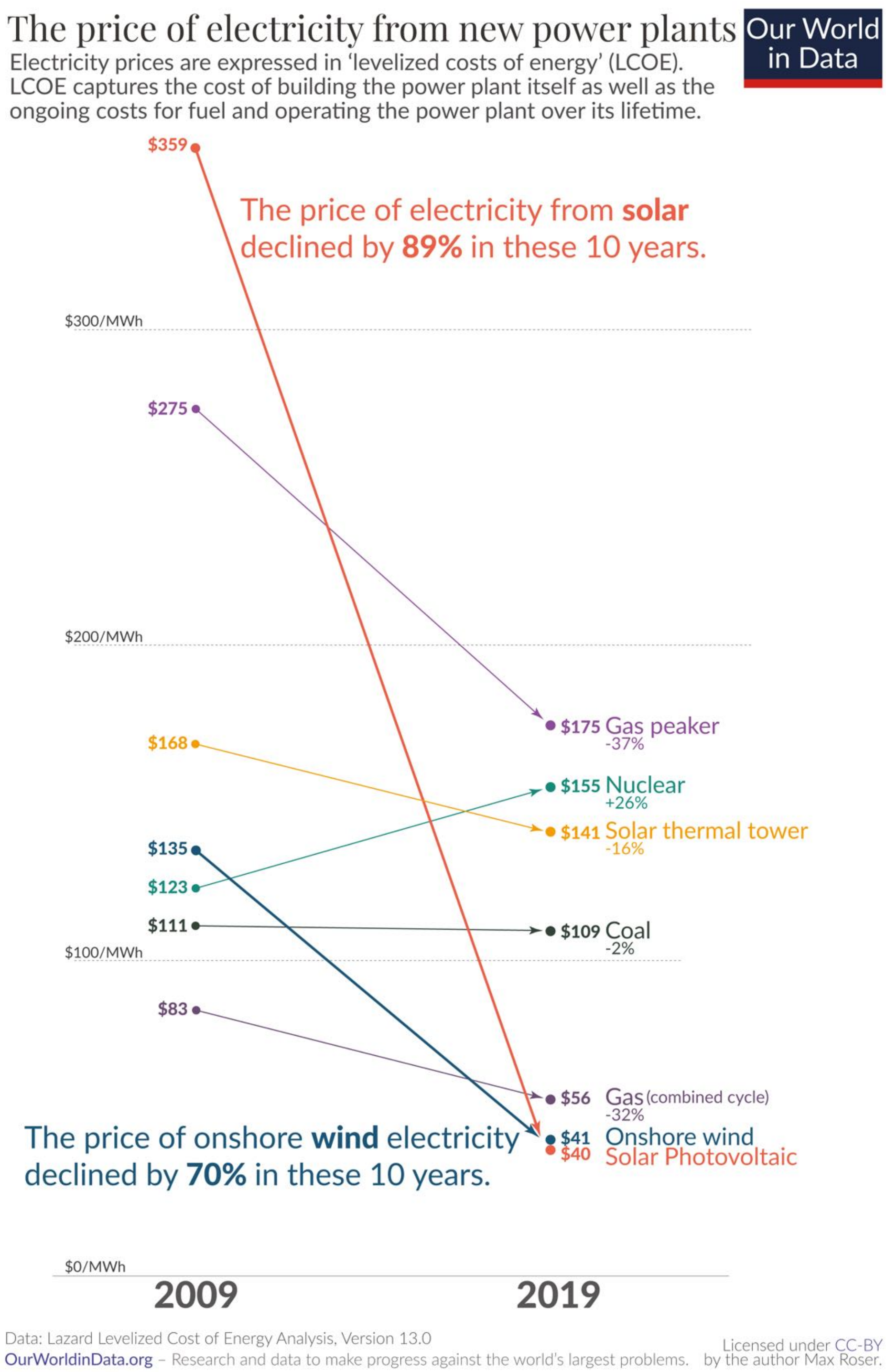
1) **Clean up the electricity supply and**
2) **Electrify everything**

The first step (decarbonizing electricity) is already well underway across the developed world. The second step (electrification) is still gaining traction.

13.2 Cleaning Up Electricity

13.2.1 Weighing Costs and Benefits

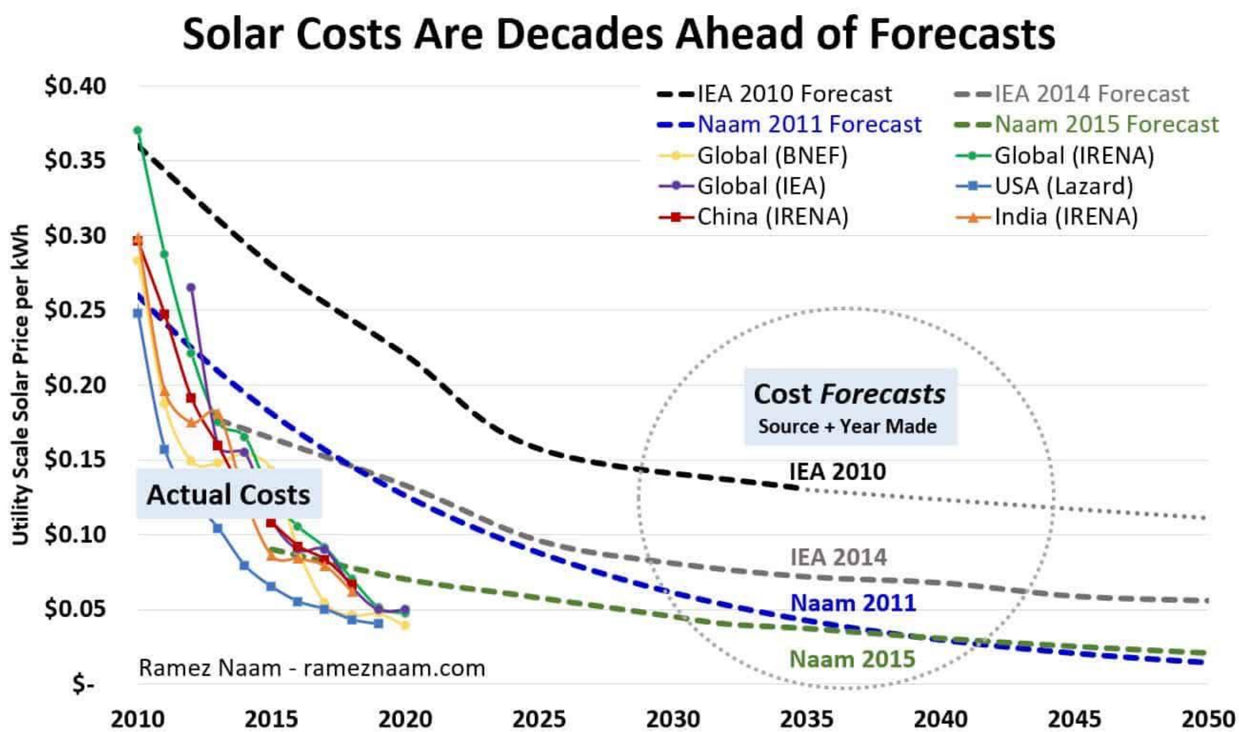
The ***past decade*** has seen a revolution in the market for centralized production of electricity, with ***solar and wind power falling by about a factor of 10***. During the same period, the price of electricity from coal has remained constant and the price of electricity from gas fell modestly. Since Russia invaded Ukraine, the price of electricity from gas has skyrocketed, highlighting the ***unreliability of fossil fuel supplies***.



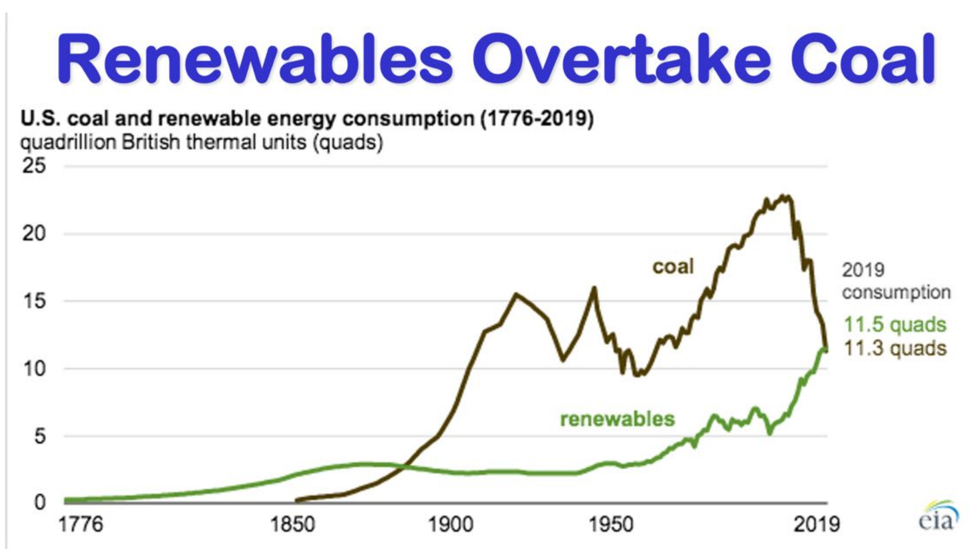
The data shown at left are "levelized cost of electricity," (LCOE) which integrates the total lifecycle costs of power. These include the cost of credit (finance), construction, mainteneance, operation, and delivery of the electricity, and eventual decomissioning of the power plant. It is LCOE which is passed on to consumers in the form of utility bills.

Retail prices for electricity are typpically quoted in dollars per kilowatt-hour ($/kW-hr) and average around $0.10 in the central United States. This translates to $100/MW-hr on the chart at left, so an electric utility selling electricity made from coal is unlikely to be profitable. By contrast, gas-fired electricity was profitable until the war in Ukraine, whereas ***wind and solar power can be made for less than half the retail cost of electricity***.

Nuclear power is more expensive even than power from coal, but it produces very little CO_2 emissions. Solar thermal power involves boiling water using sunlight and using the resultting steam to power turbines, just as combustion plants do. This is still pretty expensive (though cheaper than nuclear power), but like nuclear or coal it can produce electricity long after sundown because of residual heat stored in the system.



It is truly remarkble that the costs of wind and especially solar power have plunged so fast. A decade ago, virtually nobody was forcasting that solar power would be cost competitive with coal and gas until the middle of this century. In the real world, solar power is now much less expesnive than coal or gas. As a result, ***coal combustion has collapsed*** in most of the developeed world.



The table below compares 10 different sources of energy for electricity. Lifecycle CO_2 emissions (first column in table) from cleaner sources are not just lower than for combustion sources – they are 10 to 20 times lower. The levelized cost (LCOE) is quoted before the collapse of Russian gas exports in 2020 drove up the wholesale price of gas by 200%, but already it is clear than clean electricity is less expensive than combustion-based power.

Electricity Sources

Source	CO2 Emissions (gCO2/kW-hr)	Levelized Cost ($/MW-hr)	Capacity Factor	Advantages	Disadvantages
Coal	820	109	60	Dispatchable	Smoke, Dust
Gas	490	56	50	Dispatchable	CH4 leaks
Biomass	230	110	55	Dispatchable	Forest loss
Solar PV	41	40	29		Daylight only
Geothermal	38	75	70	Dispatchable	Rare
Solar thermal	27	143	33	Evening hours	Cost
Hydro	24	50	44	Dispatchable	Rare
Offshore Wind	12	83	50	High wind	Logistics
Nuclear	12	155	89	Dispatchable	Cost, politics
Onshore Wind	11	38	30		Intermittent

https://ourworldindata.org/cheap-renewables-growth
https://en.wikipedia.org/wiki/Capacity_factor
https://en.wikipedia.org/wiki/Life-cycle_greenhouse_gas_emissions_of_energy_sources
https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/

Capacity factor is the percentage of maximum power that can be delivered in the long term. For example the capacity factor for solar photovoltaic (PV) power (solar panels) is less than 30% because PV panels only make electricity during the day and they are less efficient during cloudy weather and when the sun is low in the sky. Onshore wind also has a relatively low capcacity factor because of the inherent variability of wind speeds. Coal-fired power plants average only 60% of their maximum generation rate because they have to be shut down for maintenance or curtailed for business reasons. Nuclear power produces almost 90% of its theoretical maximum output.

The ***biggest advantage of expensive electricity from combustion is that it's "dispatchable,"*** meaning it can be generated any time demand is favorable. Cleaner energy sources such as wind and solar are not dispatchable but are rather available only intermittently. This ***intermittency is a major engineering challenge*** because its imperative that power be available when and where its needed, not just when the wind blows or the sun shines.

In the first decade of this century the price of hydrocarbon "natural" gas fell dramatically due to advances in extraction tehcnology and led to wholesale replacement of coal-fired with gas-fired power plants. ***Burning gas emits only about half as much CO_2 as burning coal*** for the same amount of electricity, so switching fuels from coal to gas cut CO_2 emissions across much fo the developed world.

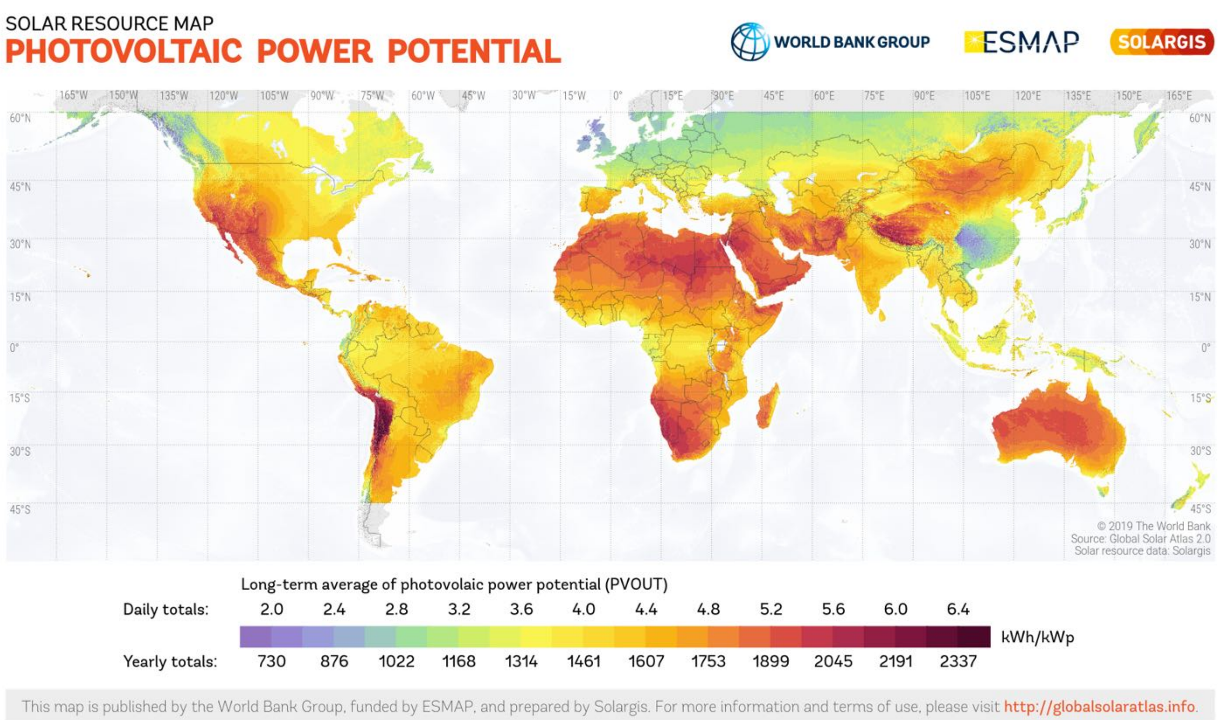
The ***Russian invasion of Ukraine in 2022*** led to a huge increase in the wholesale price of gas used to make elexctricity – more than 200% at this writing. The disruption of fossil fuel supplies caused a cascade of inflation and political crisis around the world and led many countries to question the reliability of energy produced by burning carbon.

Figure 13-1: Wholesale price of natural gas over the past decade. Source TradingEconomics.com

The skyrocketing price of previously cheap gas has done the work climate economists expected governments to do decades ago: it has dramatically increased the price of carbon relative to much cheaper and more reliable sources like wind, solar, hydro, and geothermal energy.

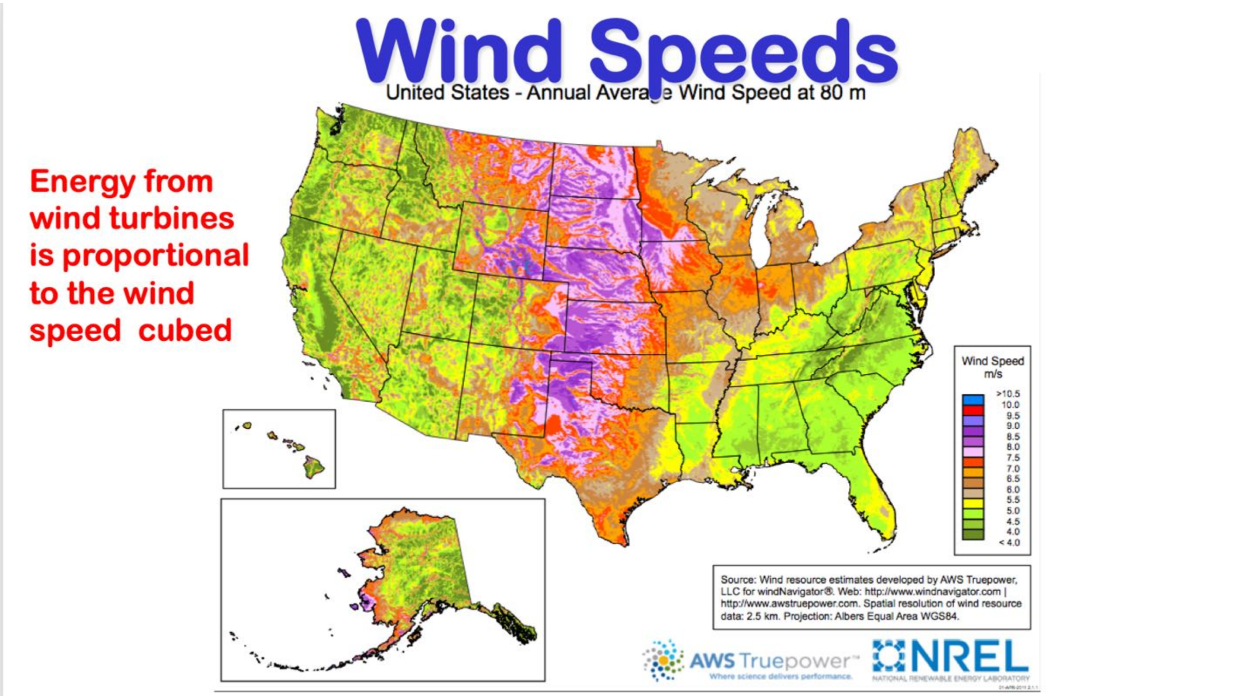
13.2.2 Solar Energy Resources

Solar energy is especially abundant in arid and semiarid regions across the subtropics including Africa, southwest and central Asia, Australia, and western portions of the Americas. Many of the places with the best resource are (not coincidentally) very sparsely populated so making the best use of solar energy resources requires long-distance transmission.

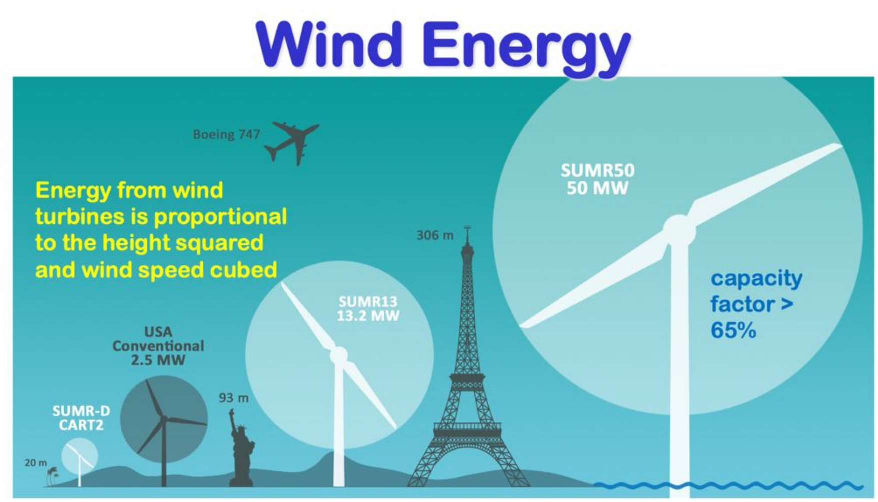


13.2.3 Wind Energy Resources

Like traditional combustion sources, wind energy is converted into electricity by the familiar mechanism of a rotating turbine generator. But the amount of energy produced by a spinning



wind turbine doesn't scale linearly with the wind speed: instead it ***increases with the cube of the wind speed***. This means that if the wind speed doubles, the power increases by a factor of $2^3 = 8$, so it is especially important to place wind turbines in high-wind areas. In the United States this typically means the relatively flat a low vegetation region of the Great Plains. Since wind speeds increase with height, the very strong dependence of wind power on wind speed also favors very tall towers so that turbines can extract wind power aloft. The ***power produced by a single turbine scales with the square of the size of the blades***, so besides being tall it is also most efficient to make them very large. The most efficient (and profitable) wind turbines are now more than 1000 feet tall and generate more than 50 million Watts of electricity.



Note that the biggest wind turbines are now designed for use offshore (in the oceans). It is much more expensive and difficult to build huge wind turbines offshore, but the increased efficiency and power generation is increasingly worth it.

The wind is typically much stronger and less variable over the oceans than on land, because of friction associated with vegetation, topography, and buildibngs. This means that the energy ***resource for offshore wind is tremendous***. It's worth the extra expense of building offshore to get more power, and there's also a financial incentive to build very tall offshore turbines.

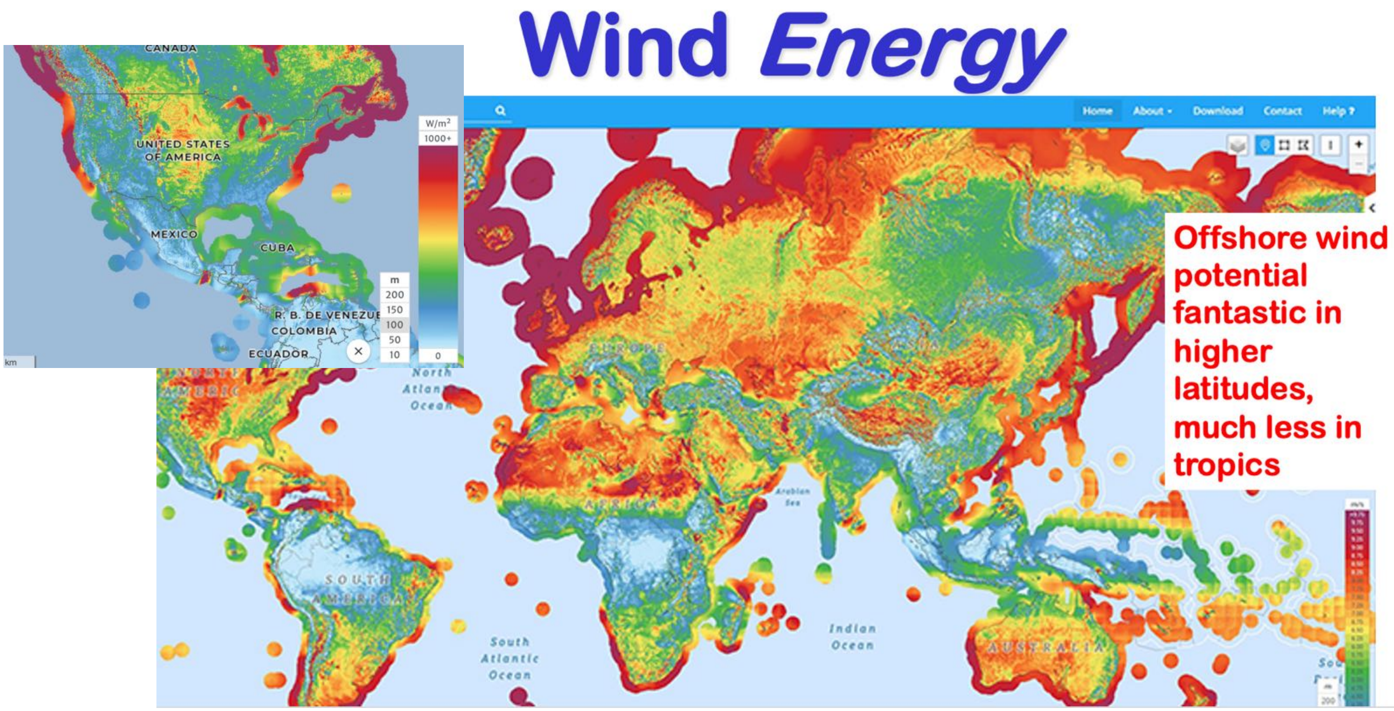
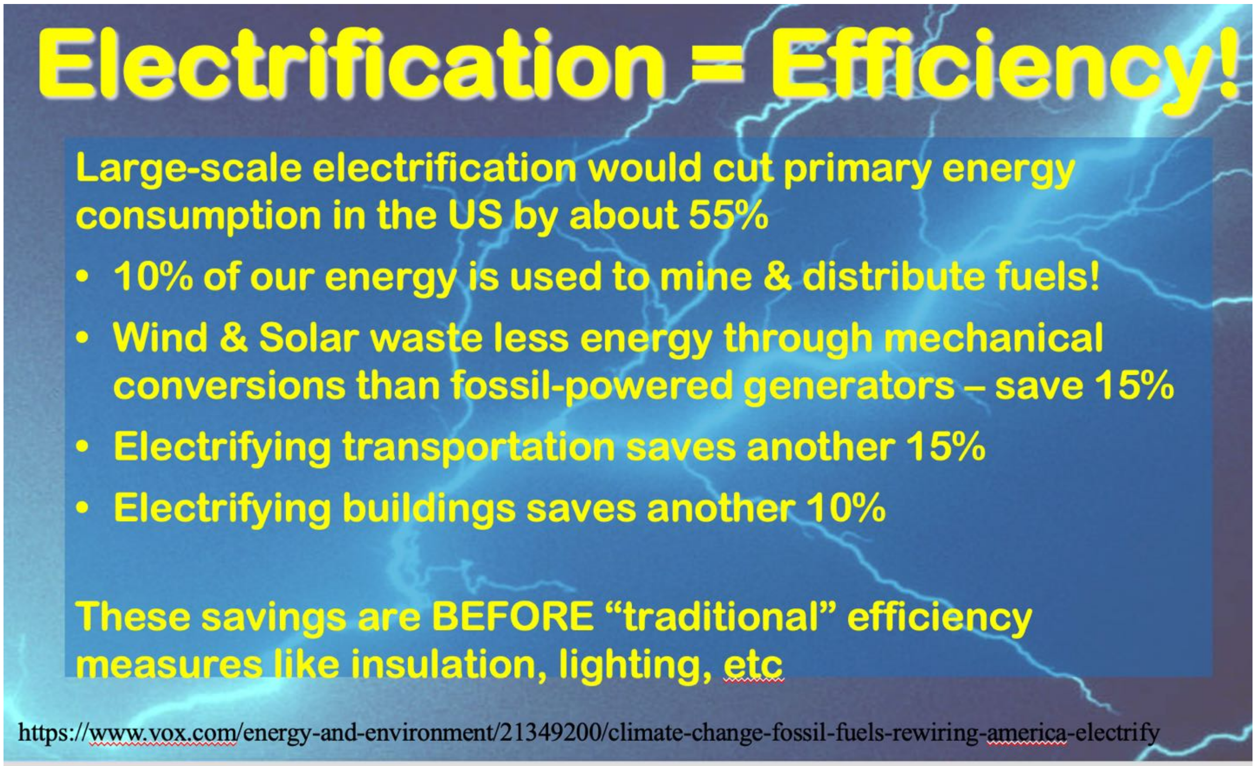


Figure 13-2: Global distribution of wind energy (not speed). Global Wind Atlas. Technical University of Denmark, CC-BY-4.0

Offshore wind energy is much more plentiful worldwide than onshore wind. The lower intermittency of offshore wind means that capcity factors in many regions are greater than 65% (***higher than for coal-fired power plants***). Furthermore, offshore wind resources are often much closer to highly populated regions with lots of energy demand, espcially near the east coast of North America, the west coast of Europe, and the east coast of Asia, though undersea transmission is complicated and expensive to build.

13.3 Electrify Everything

Economy-wide electrification is seen as key to deep decarbonization because it builds on existing centralized power distribution grids and can immediately leverage profitable investments in clean generation. Electrification also pays dividends in efficiency, because energy is lost at each conversion step: for example, heat energy in internal combustion engines is lost when it's converted to mechanical energy in pistons, then more is lost through gearboxes, trtansmissions, differentials, and rolling wheels. Perhaps the most economically important

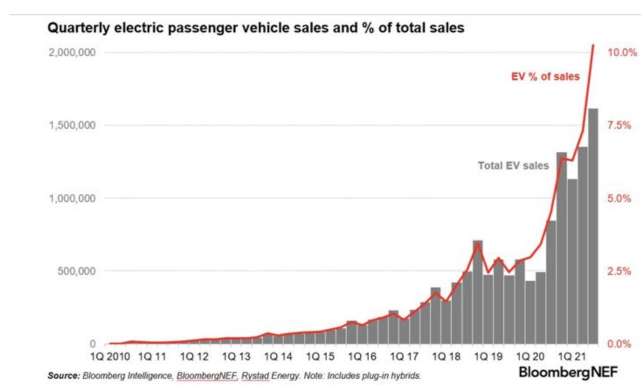


benefit of electrification is the reduction in health costs of combustion, especially for end uses such as vehicles, cooking, and heating.

Electrifying the entire US economy would ***reduce primary energy consumption by 55%,*** going more than halfway to zero emissions even without changing the way we make electricity! Thermodynamic efficiencies are the biggest parts of this savings, and more than 10% of energy is actually used to mine and distribute fuels which would be obsolete in an all-electric future. The 55% energy savings due to electrification come before the more traditional effcicncy measures such as improvements in insulation and lighhting.

Transportation is an especially rich target for energy savings through electrification. Europe has more than 9000 km of electric rail lines connecting city centers at speeds of over 250 km/hr (155 mph). China has nearly three times that much. Intercity transport can be faster, cleaner, cheaper, and more enjoyable than the ridiculous gridlock of our constantly-under-construction freeways.

Electric vehicles were prohibitively expensive a decade ago, but advances in battery technology and economies of scale have ***driven their prices steadily downward***. In many countries new electric vehicles still cost more than their gasoline-powered predecessors, but more than make up for this extra purchase price in lower operating and maintenance costs. [Worldwide, EVs now make up more than 10%]



of new vehicle sales. More than 30% of new vehicles in China and more than 80% of new vehicles in Norway are now EVs.

Figure 13-3: External heat exchanger of an air source heat pump for heating and cooling of a residential building. Wikimedia commons

Heating and cooling of residential and commercial buildings use a lot of energy, and are still major consumers of oil and gas. Newer contruction favors combining heating and cooling into a single system using heat pumps driven by electricity. Heat pumps use condensing and evaportaing fluids to literally ***move heat from cold places to hot places***. This is the technology behind refrigeration and air conditioning, and can also be applied to heating by transferring heat from outdoors to indoors. Heat pumps can use a "ground source" by extracting heat from relatively warm soil in winter or a simpler (and much cheaper) "air source." Air source heat pumps in cold climates use more electricity than ground source heat pumps, but far less than older resistance heating using baseboards. Air source heat pumps can efficiently heat well-insulated homes in Colorado. Electric heat pumps can completely eliminate the need for burning fossil fuels in buildings and is one of the cornerstones of economy-wide electrification.

Cooking with electricity used to mean inefficient and unpleasant stove-top burners with resistance elements that took a long time to heat up and cool down. Modern induction stovetops use less electricity and feature instant changes in cooking temperature, even more responsive than gas cooktops. They use magnets below the cook top to induce electric currents in the pan itself.

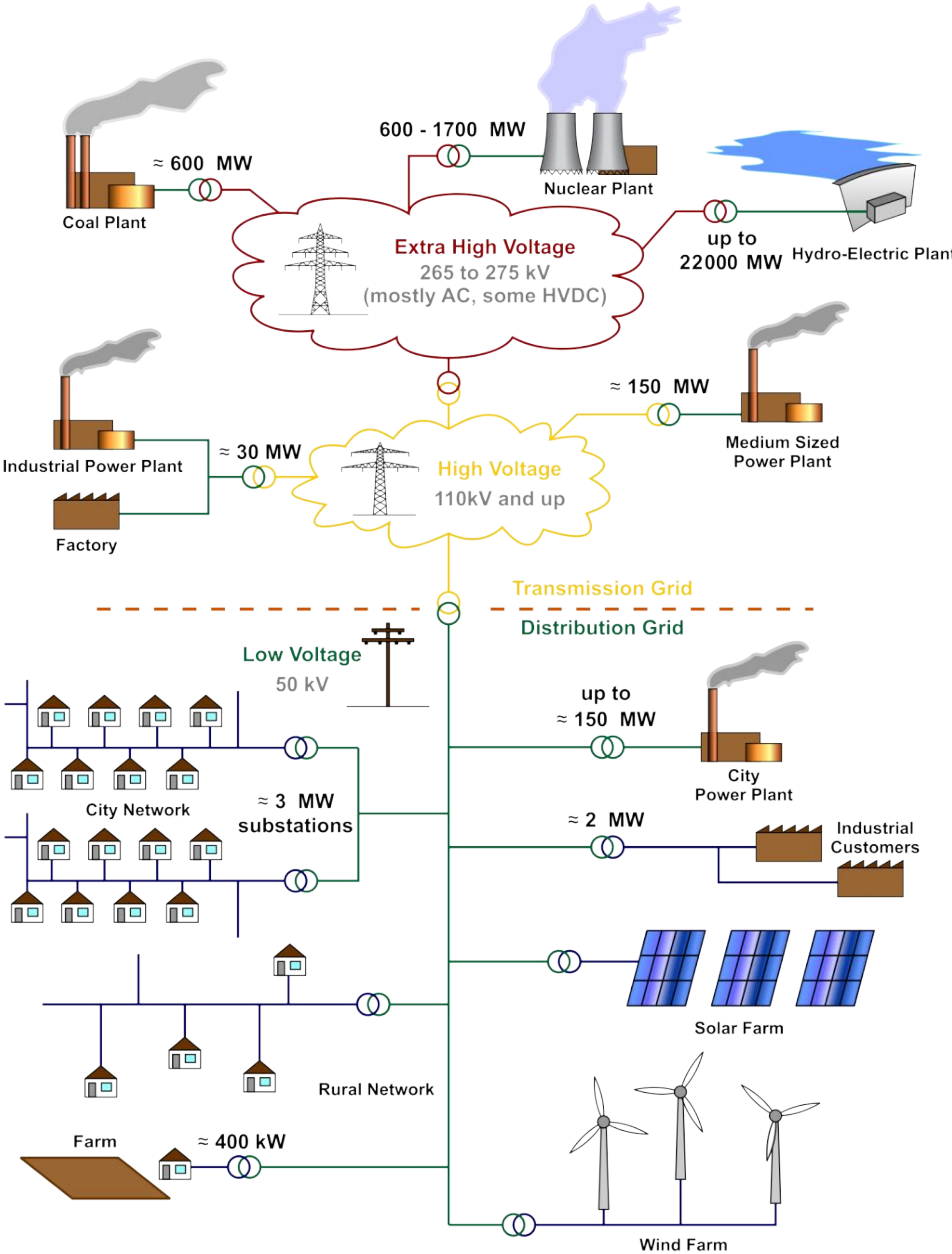
Some aspects of economy-wide electrification will be more difficult. Some of these "final frontiers" include airplane travel and heavy manufacturing such as steelmaking or cement production that require very high temperatures. Altogether, between 5% and 10% of industrial processes will require new technologies to be decarbonized. ***Nevertheless, more than 90% of today's fossil fuel emissions can be eliminated by economy-wide electrification***.

13.4 Grid Integration

As we've seen, generating clean electricity is already cheaper in 2022 than by burning carbon. The real challenge is ***matching electrical supply and demand*** everywhere all the time. This is known as grid integration. Electrical grids manage the transmission and distribution of electrical power from many generating sources to many users, regulating the voltage, current, and frequency (Fig 13-4).

13.4.1 The Problem of Variable Demand

Historically there was no way to store energy on commercial power grids so all supply and all demand (usually called "load" in the jargon of the electrical power industry) had to be matched everywhere at all times. This has always been a technical challenge.



13-4:General layout of electricity networks. MBizon, originally derived from de:Datei:Stromversorgung.png. Figure Reproduced from Wikipedia. CC-BY-3.0

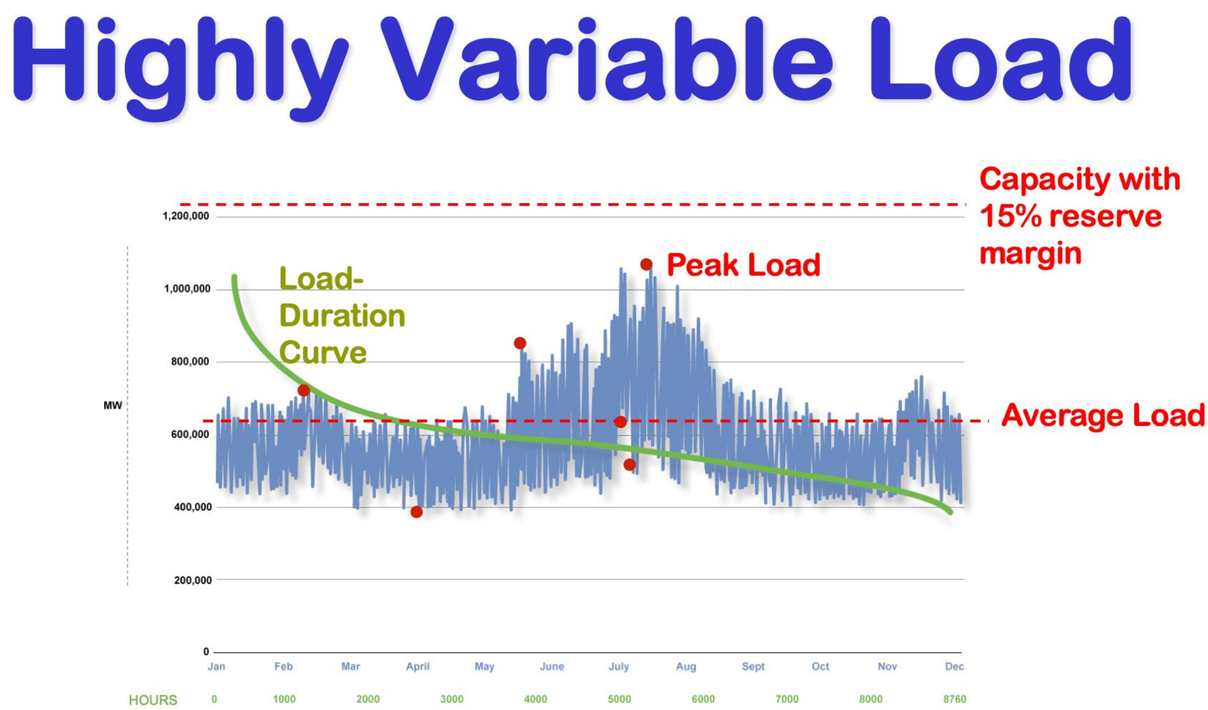


Figure 13-5: Hourly variations in electrical demand over the course of one year. Blue line shows each hour consecutively. Green line is the same hourly data, ordered from highest to lowest load. The green curve is called the Load-Duration Curve

Consider the variations in hourly electrical demand (load) over the course of a single year (Fig 13-5). There are ***major fluctuations each day*** because people generally use much less electicity while they sleep. These daily cycles appear as 365 vertical lines on the graph. There's also a ***seasonal cycle with higher demand in summer*** than winter because home heating in the United States is still primarily by burning carbon whereas summer cooling uses electrically-powered heat pumps (air conditioning).

The ***average load is only about half of the peak load***. The grid must be able to deliver peak power during a handful of hours on the hottest summer afternoons when millions of consumers arrive home at dinnertime to fire up their cooling systems, cook dinner, watch TV, and play video games. In practice, electrical utilities can't know in advance what the maximum demand for those few hours will be, so they must build capacity to deliver about 15% above the anticipated peak demand.

The green curve in Fig 13-5 is called the Load-Duration curve. It's precisely the same data as the blue line but instead of being plotted by time the load data have been re-ordered from highest to lowest. The x-axis for the green curve shows the number of hours during which demand exceeds the number on the y-axis. The load-duration curve shows that the grid operates well

below the average load most of the time, and exceeds the average load less than 20% of the time.

The huge mismatch between average and peak load poses both engineering and financial challenges to grid operators. ***Electrical grids must be "super-sized" to generate, transmit, and deliver power at a rate that customers only want to pay for during a tiny percentage of hours***. Gigantic power plants, high-voltage transmission lines, and other expensive infrastructure has to be built and maintained, yet much of the capacity is idle most of the time. Electric utilities must take on huge debts and continuously pay interest on that capital investment to maintain the grid infrastructure that is very rarely used.

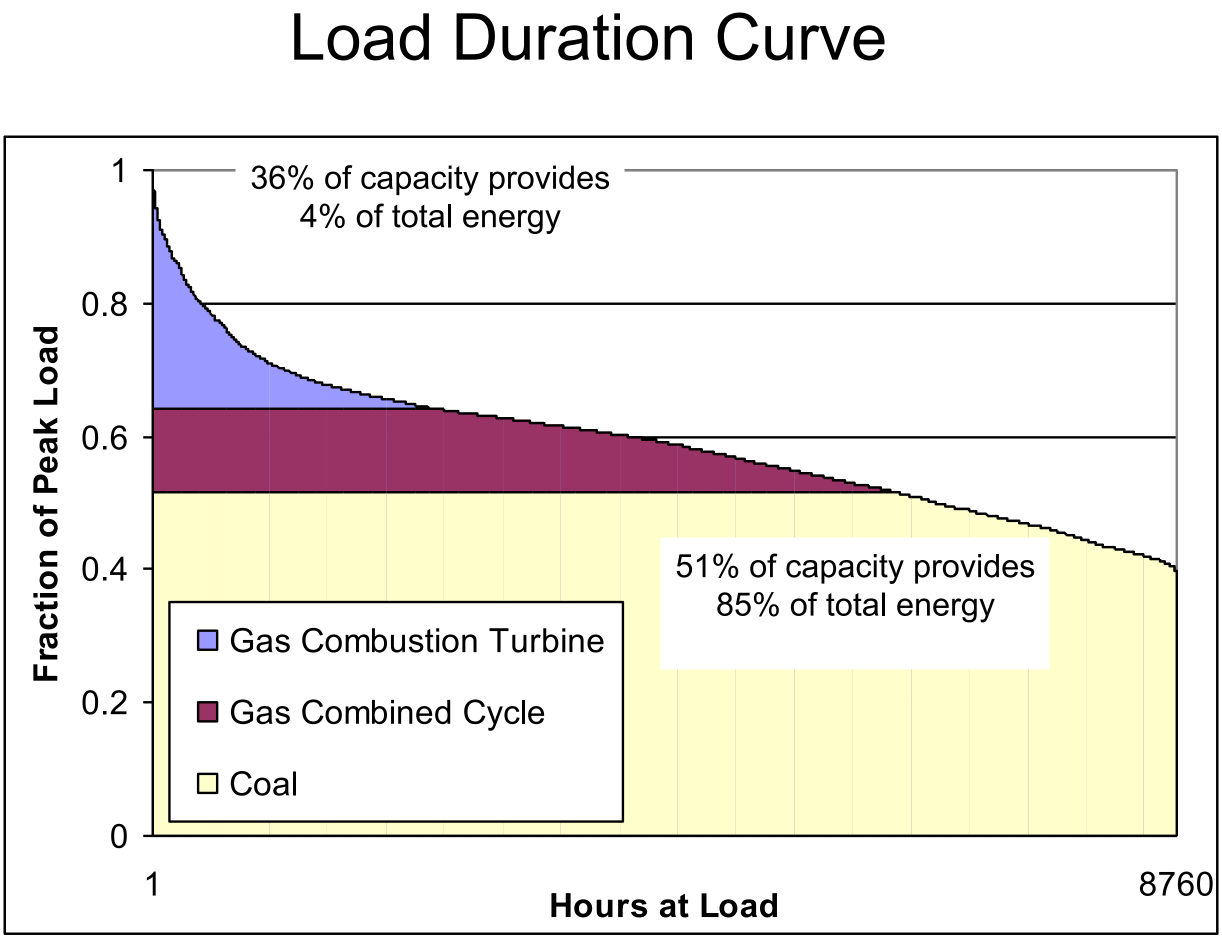


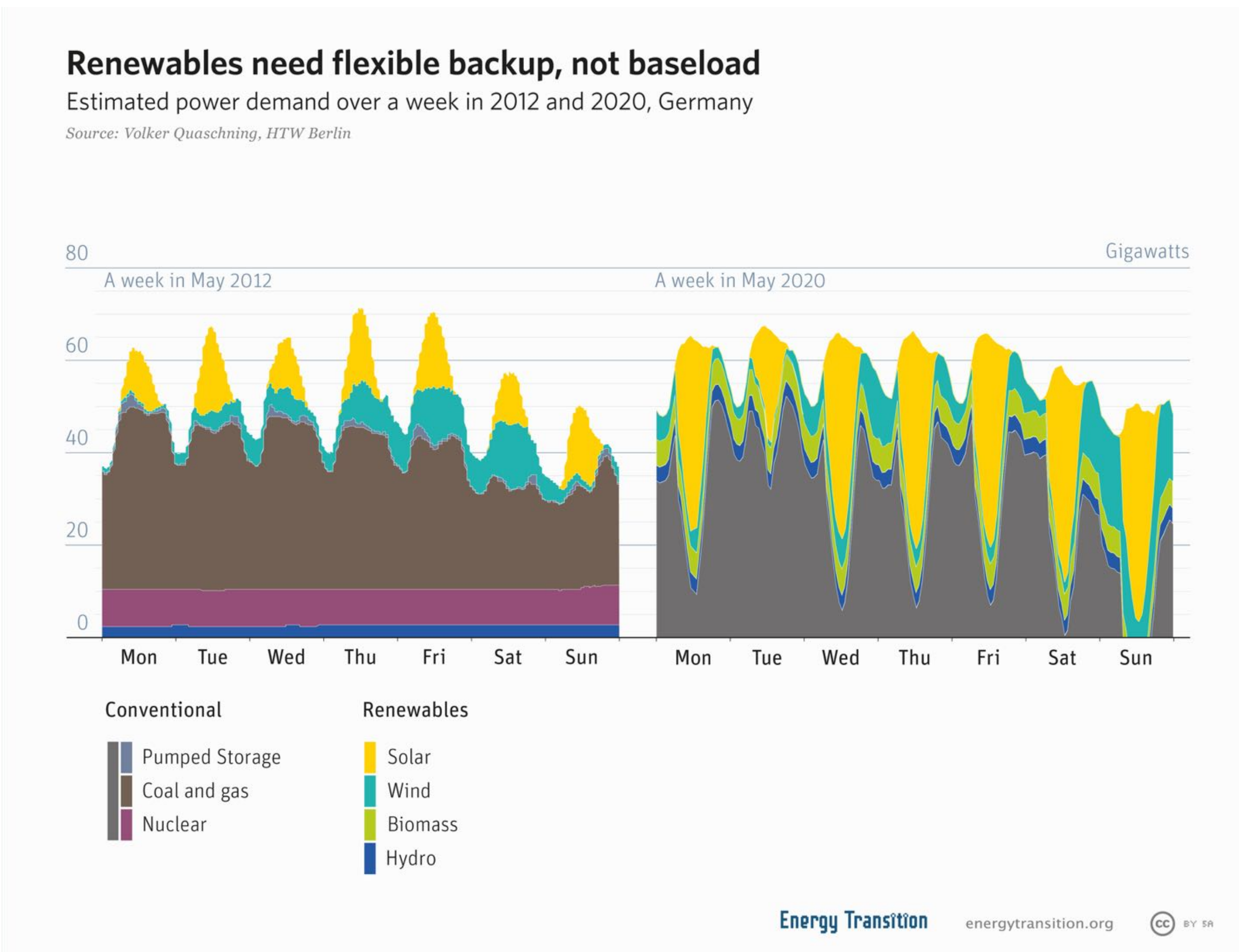
Figure 13-6: Example load-duration curve for a utility with three sources: coal providing baseload power, gas combined cycle providing load-following power, and gas turbines providing peak power

Changing the power output of coal and nuclear plants is very slow, so gas-fired power plants are typically used to adjust generation to fluctuating loads. Short duration bursts of peak generation is often supplied by gas turbines. These are very much like jet engines on airplanes, but powered by methane. They are very expensive to build and operate but can be cranked up and down very quickly to match rapidly fluctuating demand. In the example shown in Fig 13-6, gas turbines provide just 4% of the total energy but 36% of the grid capacity. Because these expensive machines sit idle almost all the time their capcity factors are extremely low, so the levelized cost of electricity (LCOE) from these facilities is extremely high.

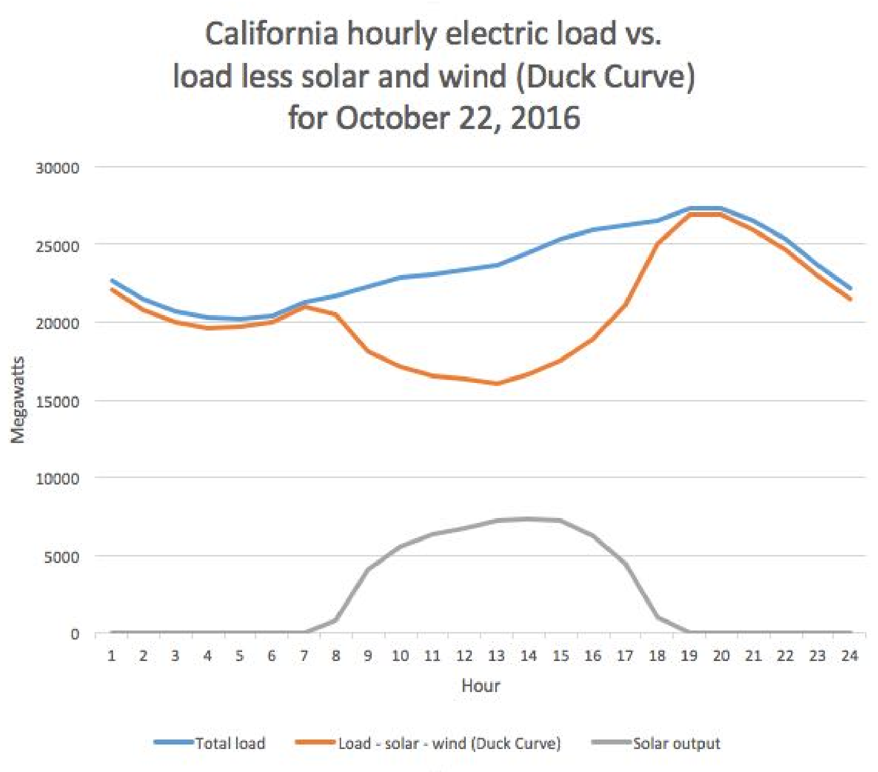
13.4.2 The Problem of Intermittent Supply

As more and more intermittent sources like solar PV and wind are added to the grid, it becomes more challenging to match supply and demand (load) under all conditions.

It's easy to imagine a worst case for a power grid supplied entirely by wind and solar generation during an ***extended period of very cold and cloudy weather in winter with no wind***. In fact Germany has pioneered the development of flexible grids in which "conventional" energy sources like fossil fuels and nuclear power are used as backup for solar and wind.



In the near term the more presing problem of grid integration involves a much more common interaction between sunshine and power demand that happens almost every day during the summer months.



The daily cycle of load typically peaks in early evening, but of course the daily cycle of PV power peaks at noon. This ***mismatch between sunlight and power demand means that expensive fossil fuel generation is little used at mid-day but must suddenly be ramped up to meet rising evening demand just as the sun sets***.

As the amount of solar PV on the grid rises, it may in fact supply more energy at mid-day than can be used. In this case demand for other sources drops below zero and the wholesale price of power can become negative. Without a way to either store energy on the grid or sell excess power to neighboring utilities, this situation results in "curtailment:" essentially discarding excess power that is generated but not needed during very sunny mid-day periods.

13.4.3 Balancing Supply and Demand

There are at least five major engineering strategies to achieve grid integration that include highly variable sources and loads:

1) Demand management or "peak shaving"
2) Mixing complementary sources
3) Source or load shifting over time (storage) and
4) Source shifting over space (long-distance transmission)
5) Incorporating a Small Fraction of Clean Firm Power on Grids

Demand Management

Demand management can be straightforward and low-tech. For example, the City of Fort Collins, Colorado charges more than three times as much for retail electricity during peak demand periods each day (2 PM to 7 PM in summer and 5 PM to 9 PM in winter). Consumers can reduce their costs by postponing major uses of electricity (laundry, dishwashing, EV charging) until off-peak hours.

More sophisticated demand management can be controlled with software. Consider a home at 6 PM in July during a heat wave, when load peaks across the grid and the very most expensive gas turbines spin up to meet soaring demand. Every watt that can be saved in this situation is very advantageous to both the consumer and the utility. In the moment, ***even a tiny reduction in demand can avoid a rolling blackout***. In the long term, shaving a tiny bit off the peak avoids costly borrowing to finance building new power plants and transmission lines that may cost many billions of dollars.

In this situation, "smart grid" or "smart metering" software sends pricing signals from the utility that the next kW-hr of power purchased will be very expensive. Software in the home might then allow the hot water heater to switch off (typically with a large amount of previously heated water still in the tank). Fans might spin a little slower, and the thermostat might creep up a few degrees to reduce the power load for cooling.

Complementary Sources

Another key to 24/365 reliability of clean electrical grids is that ***different sources are available at different times***. Power from solar PV peaks at mid-day and is completely unavailable at night. Similarly, PV power is greatest during the summer months when days are long and the mid-day sun climbs high in the sky. Wind power has the opposite pattern: it tends to be greatest duriung the night and winter.

Concentrating solar (thermal) power uses the heat from the sun to melt salt, which is then piped through boilers to create steam and run tubines. Concentrating solar power (CSP) accujmulates heat for many hours, typically reaching a maximum near sundown when demand is greatest. CSP is currently more expensive than PV but can complement PV by providing power just as PV declines in late afternoon.

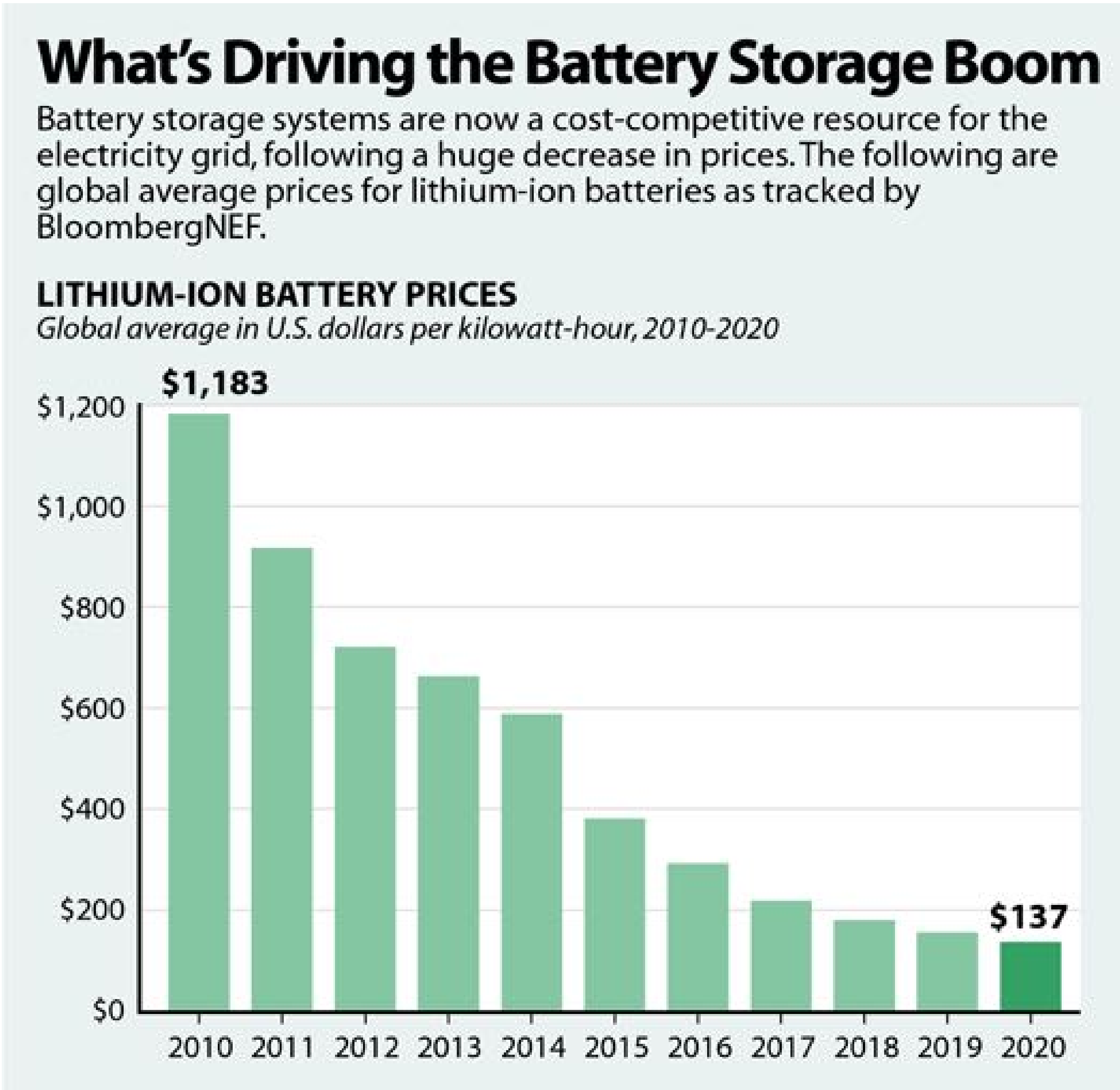
Hydropower tends to be very steady as long as sufficient water is stored behind dams. In the mountain west of the USA hydropower production is somewhat seasonal with most power available during spring snowmelt before solar PV and CSP reach their peaks in summer.

Grid-Scale Storage

Grid-scale energy storage is still in its infancy. Large-scale energy storage by "pumped hydro" involves using electricity to pump water uphill into reservoirs during the day and then letting it run back down through turbines in the evening. Flow batteries use large tanks of liquid electrolytes which can be replenished like a fuel cell and may have lower costs than lithium-ion batteries.

One of the most important services provided by grid-scale storage is to ***smooth out peak loads***. In this case, battery ***storage competes against the most expensive gas peakers***. The cost of lithium-ion batteries has declined almost 10-fold in the past decade due to the huge increase in battery manufacturing for electric vehicles.

In addition to peak shaving, grid-scale battery storage is also useful for ***regulating voltage and frequency on the grid***. As electric cars and trucks replace internal combustion vehicles,

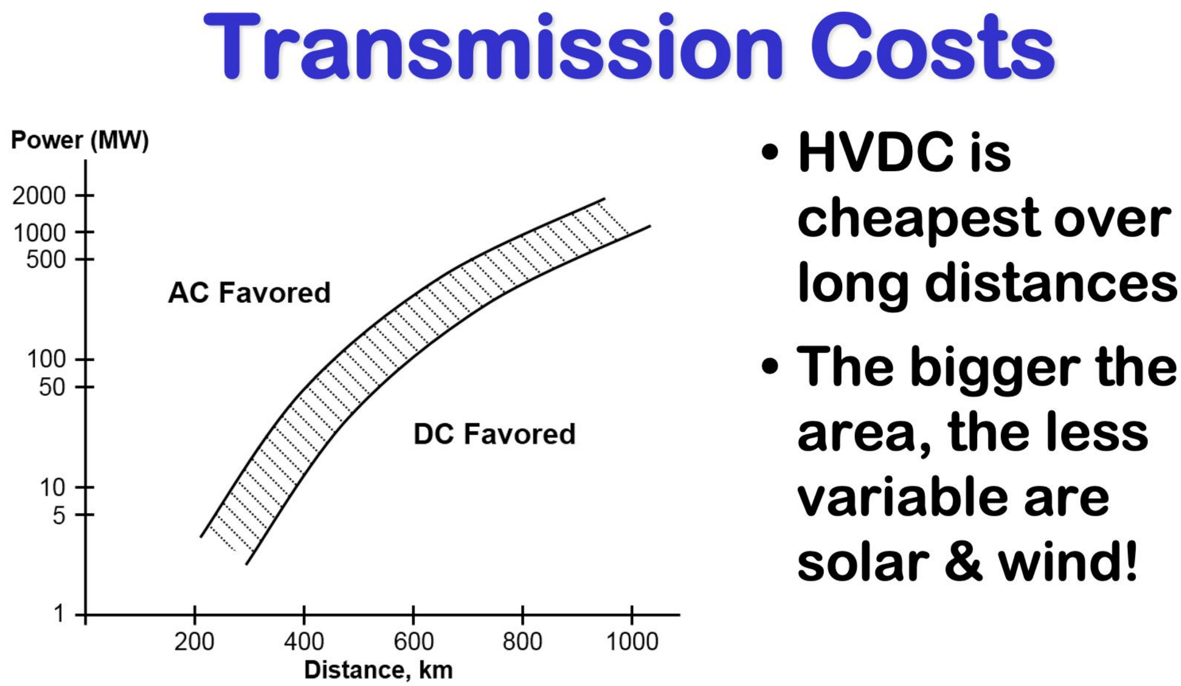


SOURCE: BloombergNEF PAUL HORN / Inside Climate News

distributed storage becomes a viable way to smooth variable loads. Vehicle-to-grid (V2G) integration technology is intended to leverage the enormous battery capacity of privately-owned EVs to time-shift demand for electricity. The idea is that ***EVs can charge during the day when cheap solar PV is abundant and then return energy to the grid in the evening*** to offset peak loads.

Long-Distance Transmission of Electricity via HVDC Lines

The greater the distance over which electrical supply and demand can be integrated on the grid, the less intermittent it is. The ***sun always shines, and the wind always blows somewhere!*** Regions of cloudy skies and calm winds are not random but are rather associated with traveling weather disturbances which have a characteristic length scale. When the grid covers an area larger than the scale of weather (500 to 1000 miles), it is much less vulnerable to intermittency than a grid covering a small area. The trouble is that it’s very hard to move power over sufficient distances to match good generating weather to high demand.

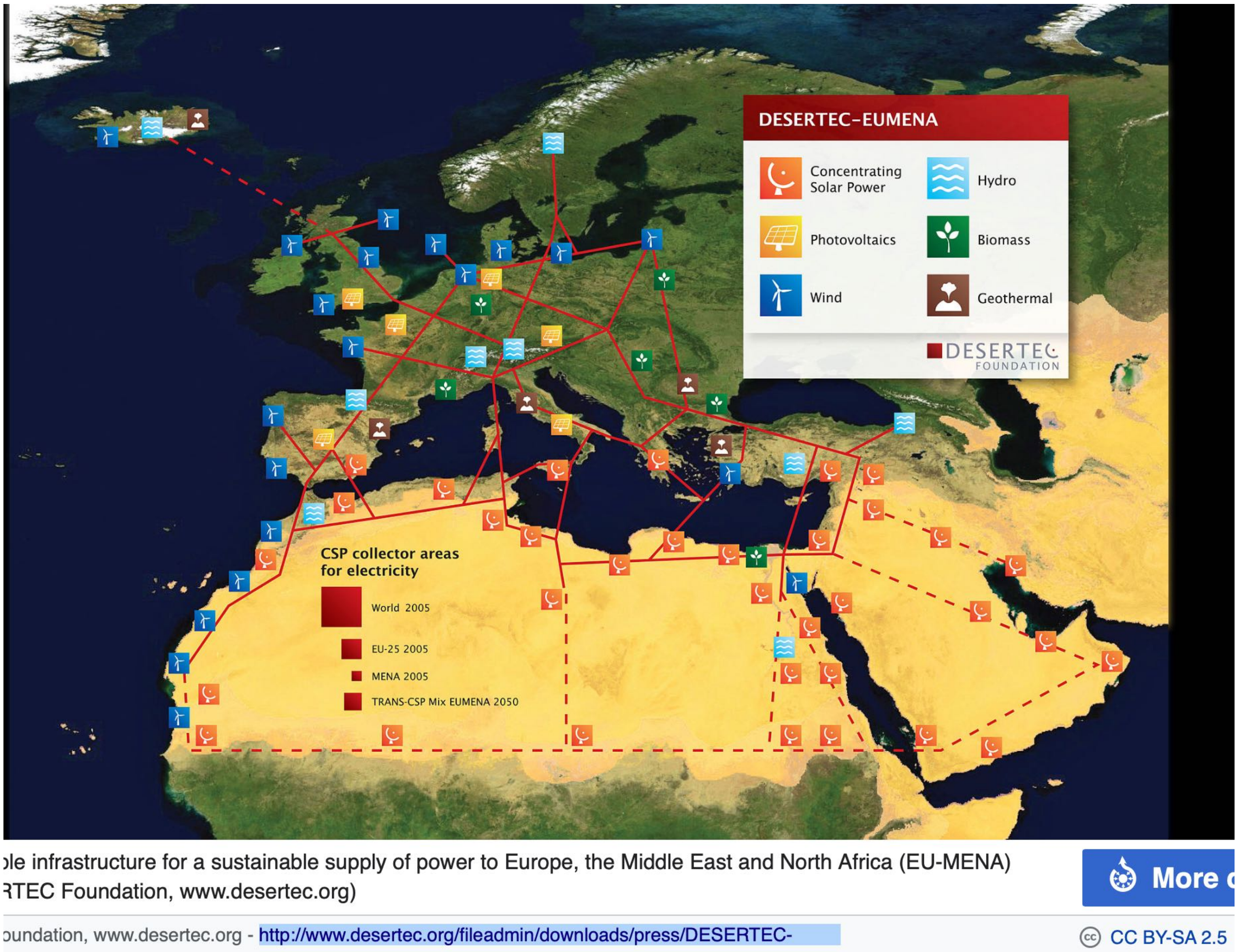


Conventional power grids using alternating current suffer from ***excessive line losses*** for distances of more than a few hundred km, even at very high voltage. Effectively this means that electrical power must be manufactured “just in time” within about 500 km (300 miles) of where it’s used. Ultimately, this is the main reason for the problem of intermittency of clean electricity.

Fortunately, it’s possible to transmit huge amounts of power over very long distances using high-voltage direct current (HVDC) lines. These systems require expensive conversion from AC to DC and back again, and dedicated power lines. Think of them as ***“interstate highways” for electrical power***. The idea is NOT to replace the AC distribution and wiring we use now. Rather specialized HVDC transmission lines can move power from remote places where it’s generated (think deserts for solar and oceans for wind) to where it’s needed (think big cities).

In the US, building HVDC transmission lines would allow expensive fossil fuel plants close to population centers to be replaced with much cheaper wind and solar while minimizing the problems of intermittency. Cost savings from inexpensive generation would offset construction costs for a nationwide HDVC transmission network in less than a decade [MacDonald et al (2016)].

China and Brazil are already building HVDC transmission at millions of volts over thousands of miles. A consortium of European and African countries is currently working with DESERTEC to develop a huge HVDC transmission network that can efficiently share long-distance solar and wind power from the Sahara to the Arctic.



Clean Firm Power

It has become clear in the past few years that electrical grids reliably serving 100s of millions of customers can cut emissions 80% or more using the technologies outlined above. Wringing that last 20% of emissions out of the electricity grid is very expensive though, requiring expensive battery storage and surplus generating capacity to deal with longer periods of calm winds and low sun. These ***costs can be mitigated by supplying a small but significant fraction of energy supply with sources that are called "clean firm power."***

Clean firm power is dispatchable like fossil fuels but doesn't produce CO_2 emissions. Examples include nuclear fission, large-scale geothermal generation, hydropower, and fossil fuel with carbon capture and sequestration (CCS). Detailed engineering studies show that US power grids can be retrofitted to achieve net zero emissions in a generation for no extra cost with just 20% clean firm power.

13.5 Summary

The world must ***stop emitting CO_2*** to avoid ecological and economic catastrophe. The vast majority of CO_2 emissions arise from ***burning carbon to generate energy***. These emissions can be eliminated quickly and cost-effectively by (1) ***cleaning up the electricity*** supply and (2) ***electrifying*** energy use as much as possible.

The past decade has seen incredible progress in generating, storing, and transmitting low-carbon electricity that is now substantially ***cheaper than historical high-CO_2 energy*** systems. ***Economy-wide electrification*** requires replacing traditional transportation, heating, and industrial energy supply with low-carbon electrical power.

Balancing supply and demand of electricity on a 21st Century power grid requires a ***combination of demand management, mixing complementary sources, grid-scale storage, long-distance transmission, and clean firm power***.

This is already happening in many parts of the world. It's most expensive and difficult in the rich world where incumbent technology is already in place and must be retrofitted. It's far cheaper and easier to build modern low-CO_2 energy systems from scratch, so it's especially important to ***develop and deploy these systems in the developing world*** where nearly all new energy demand is now emerging.