THE DISADVANTAGES DILEMMA:
MEETING THE CHALLENGES OF DECARBONIZING ELECTRIC POWER

Joan Hoffman May2022
Professor Emerita of Economics
John Jay College of Criminal Justice, CUNY

WHY DO WE NEED TO KNOW ABOUT ELECTRIC POWER ?

Is Electric Power Creation Important?

Yes! Even with continued exciting advances in energy efficiency and successes by thoughtful advocates of reduced consumption (1), we shall need more electric power facilities for three reasons: deprivation, growth, and substitution. Globally, 1 billion people, including 60,000 US Native Americans, are without any electric power and 4 billion are underserved (2,3) Population growth and increasing electrification of transportation, heating and cooling require more electricity production. (2) Thirdly, replacing carbon spewing fossil fuels necessitates building more non-carbon electric power sources.

How big is the fossil fuels replacement challenge?

Can we do the job? Not easily. Fossil fuels dominate electricity production at over 60% of production in the US in 2020 and at 63.2% globally in 2019. (See Table 1 and Figure 1 Sanke Diagram).(4,5). Only 17.1% of US electric power comes from renewable energy and 22.9% from nuclear fuel. Figures 1,5 Replacement of fossil fuels requires rapid expansion of renewable sources. However, some renewable sources, such as hydropower, are already close to their maximum potential, and characteristics of renewable sources like wind and solar, create other obstacles that require discussion

Table 1: RELIANCE ON FOSSIL FUELS
US Energy mix 2020

gas 39%

coal 22%

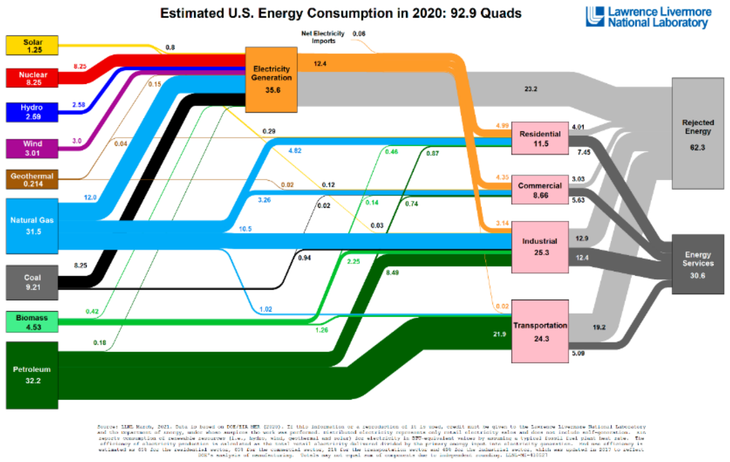
nuclear 20%

renewable 18%

https://www.iea.org/data-and-statistics/charts/electricity-mix-in-the-united-states-january-december-2020

global electricity mix from fossil fuels 2019: 63.2%
https://ourworldindata.org/electricity-mix

Figure 1 **US ENERGY CONSUMPTION 2020** (https://flowcharts.llnl.gov/)



Why Do Reliability and Dispatchability Make Fossil Fuel Use Seductive?

We can reliably access fossil fuels around the clock and in all seasons, allowing us to use them as a base, bulk power for our average daily power needs. Their additional lure is that fossil fuel is dispatchable because its plants can alter output quickly, such as ramping up to fuel peak summer air conditioning demand or down to prevent harm from some unplanned power surge on the system. A power grid must provide both reliability and dispatchability: these needs are especially difficult for wind and solar to fulfill.

Why Is Resilience Important?

The ability of the electric power to recover from damage has become increasingly important as climate change increases the occurrence of extreme weather, inherently threatening to a system which transmits its product long distances and delivers much of it over power lines held up in the air and exposed to weather. (Underground lines are not only more expensive, they make problems harder to locate and repair and are vulnerable to harm from underground animals.)

Why has there been a spotlight on wind and solar as a replacement for fossil fuels?

Environmentalists have long championed wind and solar power. (See 6,7,8 for extensive reports.) Their initial attraction was very low life cycle carbon footprints, which are only 2% to 10% of that of gas and coal. (See Table 2) (9) Also, wind and sunshine are free, but the infrastructure to access them and power storage, such as batteries, are not. These costs, long a significant obstacle to their widespread use, have recently declined sharply, especially for utility scale power plants and have made them competitive, even with natural gas plants (10) Wind and solar are now the fastest growing type of electric power in the US. In 2019 wind was only 7% of US power generation, but it's capacity grew 8% and solar, providing under 2% of generation, expanded a hefty 13%. (11.12)

Table 2.:CARBON FOOTPRINT (g CO2 eq./kWh) **2021**

Table 2. Ranges of Lifetime carbon footprint for electricity fuel sources

(Range depends on technology used; for details see source)

Coal Power 751-1095
Natural Gas 49-220
Nuclear 5.1-6.4
Hydro 6-147
Solar 8-122
Wind 7.8-23
https://unece.org/sites/default/files/2021-10/LCA-2.pdf

Enthusiasts applaud this trend, but there is debate about future reliance on wind and solar. Critics warn that argue that disadvantages such as lack of reliability and dispatchability create significant problems, and that a full cost assessment for wind and solar must include their especially high needs for storage and transmission, costs often omitted from comparative studies. (6,7, 10) . They predict that reliance on wind and solar will produce future regret. (13)

How to proceed? By identifying obstacles to reliance on wind and solar and their proposed solutions, the following discussion should help the reader frame useful questions.

WHAT ARE THE CHALLENGES TO RELIANCE ON SOLAR AND WIND FOR ELECTRIC POWER?

Disadvantages most particular to wind and solar number three: their uneven availability over time (intermittency) and space, durability, and weather vulnerability. They share with all other power sources problems of fragmentation, toxicity of their material footprint, and local safety concerns (LSN) disputes.

UNEVEN AVAILABILITY

WHEN ? The Intermittency Problems

Sun and wind are both fickle. They vary in both the short and long term. The ability of wind and solar to complement one another since the sun shines during the day and wind tends to blow at night is limited. Sun power not only disappears at night. it alters with changes in cloud cover and snow. Wind is inconsistent in speed. If winds blow too hard, over 55 mph, the wind turbines themselves must be shut down for safety. (14,15) Sun and wind can also absent themselves over long periods, of days, weeks and months. Sunshine is scarce in winter, and periods of wind drought are normal. New York regularly has 3 weeks of no effective wind in the off shore area in which it is building wind turbines. (16) In 2019 a 9-day wind drought was reported in the UK. (17) Predictive models can plan for changes in access to sun and wind power, but the models cannot change the capricious personalities of weather itself. (18)

Maintenance differences also cause power variation over time. Solar panels produce more power if kept clean of dust and snow. For the many scattered, independent owners of rooftop solar panels and others, there is some financial incentive to clean, maintain and upgrade their systems, but no monitoring or responsibility to do so.

Power variation has always threatened grid reliability. Power loss can cause blackouts; power excess can harm equipment. Sun and wind intermittency has greatly increased power fluctuations, increasing the need for dispatchable energy. Ensuring that the demand and supply of power is balanced requires checks every 4 seconds. Insufficient power entails a quick switch to an alternative energy source. Surplus power necessitates speedy curtailment of some power source, sometimes wind and solar themselves (reducing their efficiency). 19, 20 In practice, natural gas power plants, which can rapidly ramp their output up and down, have been meeting most of the increased need for dispatchability due to use of wind and solar energy. Critics have labeled wind and solar plants as sources of demand for natural gas. A non-fossil fuel remedy for variable energy is external storage such as batteries, which can store and release power instantly, but there are limitations to this solution, as will be discussed. (21).

WHERE? Why can't wind and solar work everywhere?

Sun and wind have quite diverse geographic personalities. The sun shines and the wind blows very weakly or unreliably in many locations. Some areas in the US are quite cloudy; one city has over 300 cloudy days per year. (22) The best location for large solar farms, which are much more efficient than rooftop solar, are out west, far from eastern population centers, and requiring long transmission lines. (23) Wind, is not effective for electricity production at all unless it is at least 6-9 miles per hours and wind turbines do not operate at full capacity until 30 miles per hour. (24) Some places in the US have average windspeed of about 1 mile per hour and most US cities are well under 20 mph average windspeed; the best places for wind turbines are on mountain tops, across the western .US plains, and off shore in the ocean, all requiring transmission lines to reach population centers. (25,26)

CAPACITY AND SPACE

HOW MUCH MORE CAPACITY?

Lack of wind and sunlight results in wind and solar power plants producing only 25% to 35% of their nameplate capacity (size of generator), much less than other energy sources. For instance, wind and solar must have 3 to 4 times the nameplate capacity of a nuclear plant to produce the same amount of electricity, because nuclear power plants need to be shut down only occasionally for maintenance. (27-9)

HOW MUCH MORE SPACE ?

Because of their low capacity, wind and solar require and dominate a lot of space, from 45 to hundreds as much area as an equivalent amount of nuclear power. (23,8) Their visual impacts create local resistance. Wind turbines spread out over much more space than an equivalent amount of solar, but are more compatible with agricultural and other pursuits, which can be located in the land under the tall turbines. Solar plants can usurp 90 % of the area needed for electricity production and their shade inhibits plant growth. This leads to concerns about losing prime agricultural land to solar panels. (30) However, agrivoltaics has improved prospects for compatibility between agriculture and solar power. For some crops in some places it has been found that solar panels can provide desirable shade and moisture retention and plants, thus grown, can improve panel performance by cooling them. (256,257,258)

One estimate of land area required for wind and solar for a completely renewable grid by 2050 would be the area taken up by the 7 states of AK, IA, KS, MO, NE, OK, and WV (one million square kilometers (km2) and not counting 64000 km2 for offshore wind.) The amount of area that would be completely consumed by power production would be the size West Virginia. (30)

DURABILITY

HOW LONG? What is the Durability Consideration?

Speedy construction of wind and solar plants is one of their attractions, but fast up is accompanied by fast down. Wind and solar take less than half the construction and project time of a nuclear plant for instance, but they wear out relatively fast at 25 to 30 years, about a third of the time for a nuclear plant. (31-37)

Table 3: Construction and Project Time For Electric Power Plants

Construction Time

Time to build plants: Construction and total project time

Construction time for nuclear is much greater than for wind and solar.

Nuclear 7.5 year average (historical range 3 to over 30 years)
3 years for 18 recently built reactors
http://euanmearns.com/how-long-does-it-take-to-build-a-nuclear-power-plant/

Wind
10 MW 2 months
50 MW 6 months https://www.ewea.org/wind-energy-basics/faq/
3000 MW 3-4 years https://en.wikipedia.org/wiki/Chokecherry_and_Sierra_Madre_Wind_Energy_Project

Solar
250 MW 1.5 years https://www.seia.org/research-resources/development-timeline-utility-scale-solar-power-plant

Project time from planning to linking to grid is much longer than construction and greatest for nuclear.

Wind 2-7 years
https://amperem17.imanengineer.org.uk/question/how-long-does-it-take-to-build-one-wind-turbine/ or 7 years
https://www.energycentral.com/c/ec/how-long-does-it-take-build-wind-farm
Solar 250 MW 6 years https://www.seia.org/research-resources/development-timeline-utility-scale-solar-power-plant
Nuclear 10-15 years (recent plants taking longer due to increased concerns
https://www-pub.iaea.org/MTCD/Publications/PDF/te_1555_web.pdf

WEATHER

WHAT ARE THE WEATHER VULNERABILITIES?

Direct exposure to weather, and, therefore, extreme weather, is inherent in the very design of wind and solar installations. The power outages of all forms of electric power in the February 2021 deep freeze in Texas demonstrates an important aspect of weather vulnerabilities for all energy sources. Because extreme weather happens in short bursts, and protections against severe problems such as high winds, plunging or soaring temperatures, and earthquakes raise costs, often protective investments in protection and resilience are not made. (38,39,40)

Weather vulnerabilities of wind and solar are plentiful. Tall turbines more apt to gather the best winds, but also attract and even create their own lightening. (41) Standard wind turbines pull in their blades to huddle against the base for protections against winds up to category 3 hurricanes. (35) Some blade designs fan out for wind protection, and both solar panels and wind turbines can be built to withstand stronger winds characteristic of category 4 and 5 hurricanes. However, even category 6 hurricanes are anticipated due to climate change. (42) One positive note is that very tall cylindrical designs which can both survive and operate in typhoon prone areas in Asia have demonstrated some success. (43) Freezing cold can cause turbines to stop unless investment in heating has been made. (44,45) Snow can cover solar panels. Although more sunlight increases solar panel production, extreme heat can reduce their performance. (46) Earthquake damage would vary with the type of both earthquake and infrastructure and can be reduced with design alternations, a topic now being researched. (47) While the dangers and solutions will vary with geography, the vulnerability of wind and solar to extreme weather necessitates overcoming the profit goals and budgetary concerns which have been limiting investment to protection against average conditions. System resiliency requires accounting for severe weather.

*SHARED DISADVANTAGES FOR ALL POWER PLANTS (**Fragmentation, Toxicity, Local Safety Concerns**)*

FRAGMENTATION: What are the potential problems?

How to coordinate all the decisions in the very complex electric power system? With difficulty and not always successfully. The many divisions of ownership and control in the both public and private traditional power system already created inconsistencies which have hampered operations. Even greater fragmentation of decision making about both maintenance and replacement of power infrastructure is inherent in the smaller capacity of individual wind and solar units with diverse ownership spread out over the country. Current research on how to create interoperability among the grid's increasingly varied systems is critical and will be an ongoing need. (48).

WHAT ARE THE TOXICITY DANGERS AND MATERIALS PROBLEMS?

Wind and sun are carbon free, but the infrastructure and steps needed to capture their energy produce not only greenhouse gases, but also other toxic substances. The high carbon footprint materials of cement, concrete and steel are the major ingredients of wind and solar plants. Wind and solar plants require 20 to 30 times as much material as a natural gas plant (tons per Terawatt hour) Attention to emerging possibilities for reducing the carbon footprint of their infrastructure is warranted. (49-51) Also their ingredients, such as rare earths, and those of their back up storage batteries, such as lithium, are mined around the world, generating toxicities along their supply chains and resulting in end-of-life waste disposal problems. Innovation in sustainable nontoxic materials, and other improvements is ongoing, but for the present, the wide dispersal of wind and solar facilities raises the challenge level of safe waste disposal. (52,53)

The rare earth ingredients of wind and solar power and their batteries present criticality concerns. While not more rare than gold, their presence is often widely dispersed both in area and among countries. These ingredients, with impossibly spelled names such as dysprosium, neodymium, and yttrium, provide properties essential to the performance of wind turbines and solar panels such as magnetism, luminescence or catalysis. Their availability is affected by such factors as country policies, regulation of their quite toxic extraction processes, and competition. Substitutes are often not available. (52,53)

LOCAL SAFETY CONCERNS (LSN)

All forms of electric power encounter local safety concerns (LSN) protests, and they can arise in any phase of the system, including construction, production, waste treatment, and delivery. Local safety concerns protests can affect siting of transmission lines, which are critical to the expansion of wind and solar. Studies of the issues advise that overhaul of regulations and negotiation systems is necessary to enable siting. (6,7,8) Understandably, local safety concerns delays add to project time.

HOW TO COPE WITH UNAVAILABLITY, ESPECIALLY INTERMITTENCY?

Can the power system manage the vast expansion in intermittency that would accompany extensive reliance on wind and solar power? Utilities have always confronted availability problems due to maintenance needs or equipment failure, and have, already for years, been devising new strategies to cope with the acceleration in intermittency as wind and solar sources have come on line. The current tool chest includes flexibility, storage and power sharing through distributed power and wide area transmission. *Storage is integral to all solutions*. All have limitations, and whether or not these tools will be sufficient is a question yet to be answered.

Flexibility, Storage, Distributed Power And Wide Area Transmission

Flexibility

Flexibility tools seek to reduce demand for electricity when there is no sun or wind, and shift it to periods when they are available. Utility customers already voluntarily lower air conditioning temperatures on very hot days to help avoid black outs and use delay starts on washing machines to schedule the washing during a low-price time period. (54) Advocates of a wind and solar powered anticipate significant expansion of financial incentives for power shifting and massive investment in smart appliances and vehicles that would expand the capacity for shifting by providing means of power storage. (6,7,8)

Storage: Short Term and Long Term

Short term storage

How can the storage so critical to reliance on wind and solar for electric power be provided? Storing excess energy when wind and sun are strong and drawing on stored energy when they are absent are capacities necessitated by wind and solar intermittency. Short term storage providing hours of backup power does exist in batteries and hydropower. Hydropower and pumped hydro can provide hours of backup power, but they are not accessible everywhere and depend on precipitation levels, likely to decline in some places as a result of climate change. Also pumped hydro is a net negative producer of electricity because it uses more energy to pump than it provides when the water is released. (55) Individual batteries which can dispatch electric power instantly, are designed for only about 4 to 6 hours of backup power. Battery packs can provide more, prices have declined, and they are now in use throughout the grid to absorb power surges and bolster lags in supply, but their weight, bulk and cost constrain their use. Intense research is underway to improve performance, and advocates foresee a gradual replacement of older cars and appliances with smart versions which provide both short term storage and flexible energy use for the electric power system. (6,7,8,56). While some of these changes can be built into new designs, people would have to make or be able to afford the required individual purchases.

long term storage

While there have been definite gains in providing affordable storage for the short term or daily intermittency problems, how are long term power gaps to be filled? Answers inspiring confidence are still missing. Giant packs of 4 or even 6-hour batteries are not a practical or affordable solution. Potential solutions generally espouse faith in human creativity and include some combination of bioenergy, synthesized fuels such as hydrogen, hydropower, carbon capture and sequestration, and nuclear generation (e.g. 16,6,7,8) These topics, to be discussed later, require either future investment, innovation or development.

Storage and Distributed power

Another solution to variable availability is distributed power, which places generation close to its use, reducing power loss from transmission and providing resilience. Fossil fuel provides a form of distributed power, since it can be transported to and stored at power plants. The vision for wind and solar entails a vast expansion of distributed wind and solar generators with back up storage, including smart vehicles and appliances. Micro-grids in which generators had time differentiated power needs would be designed for power sharing, enabling reduction of imbalances. Islanding or disconnecting the microgrid from the main grid when power outages threaten can create islands of resilience. (57,58,59,60) However, the intermittencies of wind and solar can create instability within the microgrids themselves and the systems call for the expense of smart intelligent hybrid inverters on the solar systems to monitor and store and release electricity to handle the unstable flows. (57)

Wide area transmission

Despite the absence of a system of national grid connections in the US, Wide Area Transmission is recommended as a means of coping with power variability. Although the US has independent regional systems, the proposal is for transmission lines covering wide enough areas to connect areas temporarily short of power to those that can generate power. One argument is that expanding the number of renewables in the system reduces the chance of any one source being out. (61) While this generality is true, clustering of viable locations for wind and solar might alter those chances. In any event, the system depends on transmission with its attendant local safety concerns problems (56), highlighting the need to examine transmission and the power grid which enables it.

THE GRID AND TRANSMISSION CHALLENGES

Electric power, once created, must be transmitted, a task more complicated than most people realize. The US lacks a national grid, but across the regional grids there is a call for upgrading the aging grid and transmission system, which already presents safety and delivery problems. Upgrading would include massive investment in technical *tools like switches, monitoring and communication devices, extensive storage, software, and control centers.* To create a transmission grid that would be viable for wind and solar requires meeting five challenges: rapid expansion, power loss due to resistance, balancing tools, cybersecurity, compatible laws and regulations.

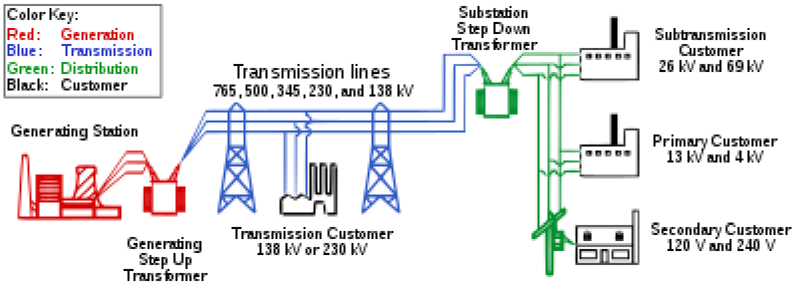
Rapid Expansion

Both the distance between good wind and solar sites and population centers and the strategy of using wide area transmission increase the need to replace aging lines and expand the system. One study estimates that 4 to 5 many transmission lines as existed in 2010 would be needed for a fully renewable grid. Making these investments speedily is a prerequisite for a wind and solar reliant grid by 2050. (8) Ownership fragmentation and profit-based decision making hinder the rapidity of making needed investments.

Preventing Resistance Loss

Resistance loss on power lines increases with distance. This is why grids have transformers (red in figure 2), Just as increasing the force of water as it leaves a hose allows the water to overcome the resistance of air to spurt further and more strongly, step up transformers send electricity from generators through spirals which increase the electricity's force or voltage, and happily, reduce its resistance to its passage along the transmission lines (blue in figure 2).. But just as we water tulips with slow moving water from a watering can, so must we temper the force of electricity before sending it to customer distribution lines (green in figure 2), to avoid burning out customer equipment, by passing it through spirals in step down transformers. A wind and solar powered grid requires complementary investments in transformers. Using distributed power with back up storage and microgrids decreases transmission distances, but requires transformers and other equipment for links with the broader system. (62,63)

Figure 2: Electricity Generation and Transmission System https://en.wikipedia.org/wiki/Electric_power_transmission



The Balancing Tools for Instabilities (__Balancing, Switching, Communication, Monitoring And Control)__

All grids must manage instabilities. The system must be properly equipped to balance the supply and demand of power, switch alternating (AC) and direct current (DC) flows, manage the two-way flows of renewable energy to and from the grid and contend with system incompatibilities due to differences in ownership.

Wind and solar increase the number and complexity of needed devices. Their tasks include: detection and diversion of unneeded power surges to avoid equipment damage, spotting conflicting signals in equipment which can occur due to their two-way flows, switching between AC and DC current. Solar is DC while homes use AC; inverters make the switch. Wind turbines make AC, but back up battery storage uses DC; rectifiers make this switch. Long distance transmission for wide area transmission goals uses high voltage direct current (HVDC) which must be both stepped down and converted to AC for use in homes. Also, wear and tear on traditional equipment, such as tap loaders, increases due to the two-way flows. (64, 65,66,67,68,69)

The system requires control centers in which decisions are made every five minutes or even every 6 seconds. The jobs in these NASA like control centers are even more complicated than flight control jobs. The rising complexity created by renewables leads some critics to predict an unmanageable system. There is an already existing demand to further augment the system of computer assisted decision making with smart technology to automate routine decisions. Unfortunately, that solution expands the threat of cybersecurity. (67,68)

Cybersecurity

The steadily increasing intricacy of the web of monitoring, analysis and communication required for two-way wind and solar makes understandable the desire to automate routine decisions. However, the escalating number of such devices increases the systemic cybersecurity risk, and smart devices are not only on the lines, but also in customer sites. Smart devices will complement all power sources, but more would accompany reliance on wind and solar. Efforts are underway to diminish this vulnerability, but it exists and must be considered. (70) Cyber attacks against US utilities have increased markedly in recent years and over half of utilities experienced an attack in 2019. (236,7) Increasing attention to protection against cyber attacks is being given at the national and international levels. (239)

The Ownership Fragmentation And Economic Incentives Complications

Although the costs of upgrading the electricity system will be high, one comprehensive study, which included both transmission and storage expenses, estimated that final costs should not exceed what is spent today. An entirely renewable system had the highest unit costs. (8) As extreme weather increases, increasing resilience investment is likely to raise costs.

A multitude of decision makers, both private and public are making these investment decisions, which could interfere with the needed system of compatible laws and regulations. (238) To overcome the fragmentation and the profit incentive to avoid incurring costs, there is a push to expand the role of public power and regulation of power. (71) However, public ownership brings the pressures of bureaucratic budgets and can entail corruption. Effective public management requires transparency, monitoring, and accountability.

SUMMARIZING THE ADVANTAGES AND DISADVANTAGES OF RELYING ON WIND AND SOLAR

Advantages

The four major attractions of wind and solar are their low carbon footprint, cost free fuel, speed of construction, and ability to use them to form microgrids for resilience.

Disadvantages

Their disadvantages include their daily and seasonal intermittencies, which diminish their generating capacity and reliability, their contribution to grid instabilities due to 2 way flows, the requirement for both short and long term storage , their considerable transmission costs both in extent and quality of equipment, their variation in location availability and quality, their short replacement life of 25-30 years, toxicities along the supply chain, and vulnerability to weather, their need for smart technology which increases systemic cybersecurity vulnerability, fragmented decision making and greater exposure to local safety concerns conflicts due to extensive spatial requirements as a result of their low power density.

Needs For A Wind And Solar System That Will Affect Climate Change:
Effectiveness requires rapid expansion of wind and solar generation and both short and long term back up storage as well as a swift expansion and upgrading of the transmission system.

Obstacles To Meeting the Needs
Hindrances to meeting decarbonization needs with wind and solar included uncertainties characteristic of fragmented decision making, short term storage, lack of long term storage technology, conflicts with other high priority spatial needs such as high quality farmland, local safety concerns, fragmented and profit based decision making affecting quality of maintenance and upgrading investment, lack of laws and regulation suited to emerging system, expectation of more extreme weather and poor incentives for resilience based investment

INTERMEDIATE CONCLUSION

Not yet. There is not yet a case for being able to rely on wind and solar for all or the bulk of our electric power needs. Future research and development may solve filling the many short term and especially long-term power gaps, produce extreme weather protections and the required transmission system. Over time needed laws, regulations and local safety concerns negotiation might evolve. However, the climate problem is urgent, making exploring the potential of alternative sources of non-carbon energy sources to provide electric power of keen interest.

DO OTHER RENEWABLE ENERGY OPTIONS SOLVE THE PROBLEMS?

Hydropower

The marvels of hydropower's are several. It is reliable and dispatchable because it is always available and the flow can be dialed up and down quickly. However, it cannot be a general power solution for several reasons. First, it is not plentiful. Not every river can support hydro power, and it was only about 7% of our power in 2020. (72) Even one optimistic estimate that it could be increased by 50%, would take it to only about 12% of our current electricity capacity. (73) Second, its location on water bodies requires transmission line investment to reach population centers. Third, the dams and reservoirs that service hydro power also serve local communities need for flood control, drinking water, irrigation, navigation, local habitat needs and recreation. Fourth, drought and atmospheric warming have already reduced the capacity of exiting hydropower plants and portend continued evaporation problems. (73) In sum, hydropower is wonderful if you can get it, and investment in extended transmission and technological improvements are underway to allow more people to access it, but its specific location requirements, competition for its use and global warming will keep it as a niche solution, and one that requires attention to the impact of climate change on its continued availability.

Geothermal

Yes, geothermal heat is steadily reliable and exists everywhere inside the earth, but it cannot be a general electric power energy source. Currently, it provides less than 1% of US electricity consumption.

Even an optimistic prediction that by 2050, 26 times as much power could be generated by geothermal, would bring it to less than 9% of US electric power generation. (73,74)

Why? One reason is access limitations. In the US geothermal heat is close to the surface out west, where tectonic plates pushed hot rocks so high that they heat hot springs bubbling out of the earth, but moving eastward, the needed level of geothermal heat for electric power occurs deeper and deeper inside the earth, where the rock is less porous and harder to drill. The best suited surface locations tend to be out west, distant from population centers, requiring extensive transmission line investment. The deeper locations require not only drilling investment, but for access to the really valuable, very deep heat of above 150 degrees centigrade, the invention of materials and metals that will not melt at those temperature must occur. (76,77)

Another reason is hazards. Hot springs geothermal can release toxic and greenhouse gases (although much less than fossil fuel plants). So can geothermal systems that inject cold water into the ground to be heated to create steam. If water is taken from the ground, subsidence is a danger. Drilling for deeper heat can stimulate earthquakes in some locations. A current development envisioning a double loop system in which cold water is injected in tubes to be heated by hot rock and then rise into the plant to heat steams has inspired optimism. Earthquake potential would limit locations. (78,79)

A successfully located geothermal power plant might help offset the gaps in wind and solar coverage, But, due to its limitations and hazards, it would be a niche and not a common solution. However, geothermal driven heat pumps, which do not require such deep drilling, can be used for both heating and cooling and can help reduce the demand for electric power. (80)

Biomass and biofuels

Why do doubters argue against using biomass to make biofuels to fight global warming? Its attractions are notable. It can be accessed at all times and in all seasons. Biomass can make electricity directly and is a candidate to fill in during long term wind and solar power gaps. Its use for heating and transportation can reduce the demand for electricity. There is no need for exploration and pipeline expenses. It can use otherwise unusable waste in landfills and from manufacturers. (81,82)

Globally, people use biofuels in many forms such as wood, ethanol, and biodiesel to cook, heat, make electricity and fuel transportation. In the US it is only about 5% of energy use and only 9% of that is for electricity (the rest being for industry transport). (81) Is expanding biofuel use wise? Where does the constituent biomass come from and what are the carbon footprints and drawbacks of these fuels.?

Biomass sources are plant or animal materials ranging from trees and crops like corn to sewage sludge and manure. Energy extraction is achieved in three ways: direct burning, transformation into gas or liquid biofuels, and biological decomposition into a gas. Besides direct use for heating and transport, biofuels create steam to turn electricity generating turbines. (83,84)

The original optimism about biofuels has declined for five reasons: efficiency, carbon footprint, time frame, ecological side effects, and escape of gases. First, while making methane from food waste can reduce make use of an undesirable carbon leak, biomass fuels are, per se, less efficient than gasoline and emit more carbon dioxide per unit of energy than a coal plant. (82,86) Second, consideration of the entire life cycle of using forests and crops to provide fuel has led to the conclusion that they are not, after all, carbon neutral because their use just uses the carbon they had removed from the atmosphere, but rather have a negative carbon footprint. (88) Third, burning wood of any kind (“waste wood” or whole tree) puts carbon into the air, and replacing trees with young saplings does not offset the carbon emissions for decades or even longer. The time frame for reducing atmospheric carbon is much more urgent than that. A certificate of forest sustainability does not mean that these disadvantages have been overcome, for sustainability certificate criteria were developed before the keen interest in carbon accounting and did not include carbon impacts. (85,86)

Fourth, biomass crops require a lot of land and can have, without proper land management, numerous detrimental ecological effects. Displacement of crops with better carbon storage, reduction of forested terrain and its capacity for carbon capture, harm to wild plants, habitat and biodiversity, and negative impacts on soil and water have all been observed and caused concern. (81,82,85,88)

Fifth, while creating biogas from sewage sludge and manure offers the possibility of creating, from waste, a transportable, storable fuel with a zero to negative carbon footprint, consideration of the entire process of production, storage, transport and consumption, reveals opportunities for escape of the warming gases of carbon dioxide, methane and nitrous oxide and also other pollutants such as carbon monoxide, sulfur dioxide and hydrogen sulfide. Controlling storage and the "digestion" process can significantly reduce escape of gases. Also, spreading a fertilizer manure that has been through the digestion process, releases less methane into the air than untreated manure. (87) However, the scalability virtue of biogas creation which allows small scale decentralized production implies decentralized monitoring of quality control procedures.

Recommending massive reliance on biofuels, given their net impacts, does not seem wise, but because they can be transported and stored, and we do not yet have good solutions for the long-term power gaps of wind and solar, some will probably urge their use.

Carbon Capture ***Utilization, And Storage (CCUS)***

Can we extract carbon dioxide from the air and stow it where it cannot leak back? (1,2.3) It is sobering to learn that most estimates of requirements to keep the earth's temperature rise below 1.5 degrees Celsius by 2050 assume not only reduction of greenhouse gas emissions, but also some methods of negative emissions to achieve that goal (.89,90) Are carbon capture utilization and storage systems (CUSS) effective? We can only afford honest assessments which avoid the temptation to focus too narrowly on some positive results. We must consider the entire life cycle impact of any CUSS system on greenhouse gases including fuel sources for the entire life cycle and the duration of the sequestration as well as viable financial support (public, private or NGO) for the processes. (91) Another concern is that capture efforts will divert resources from desperately needed emission prevention investment. (90,92) The three current approaches to capture include: engaging nature's systems, capturing carbon emissions from point sources and the air itself and storing them, capturing carbon emissions and storing them by utilizing them in useful products, sometimes long term.

The first method uses nature's systems of carbon capture, utilization and storage (CCUS) such as plants. Results of efforts to expand and emulate those systems have eroded the original optimism. This method includes massive reforestation (afforestation) and grass planting projects, but plants return carbon dioxide to the atmosphere at the end of their lives, too late to meet the human emergency. (91) Critics also question the net effects of massive reforestation projects including less nourishing habitat for plants, reduced soil capacity for carbon absorption and plant nourishment, reduction in local needs being serviced by so called marginal lands, and the often-higher demand for water. (89)

Carbon capture and storage, the second method, must overcome 4 barriers to be a useful approach to reducing atmospheric carbon: energy source, energy requirements, transport and storage. First, while human CCUS technologies have been in use for almost half a century, 50 large operations exist around the earth and there is growing investment in carbon capture technologies, they have often been fueled by fossil fuels and to achieve negative emissions, the energy to extract the carbon, should be carbon free itself (93,90). The second impediment is due to scarcity. Carbon dioxide is only 4% of natural gas and 15% of coal power plants emissions and a minute .04% of the atmosphere. Also, the hydrogen and nitrogen clinging to the carbon dioxide must be separated. An extremely energy intensive process is needed as a result. This would create yet more demand for our critically needed renewable energy supply. The third set of difficulties involve transportation, including the necessary condensation of carbon dioxide to 1% of its former volume for its transport (by pipeline or ship) and the deficiency in the quantity and quality of existing pipelines. The pipelines can and do leak. (93,94,95) There is a bill in Congress (the Scale Act) to provide funding for pipelines and storage of captured pipelines. (90) Environmental critics might be concerned that the proposed bill is a way to extend the life of the fossil fuel industry by capturing its carbon emissions. These three combined barriers to "green" carbon capture are daunting, and while work to overcome them is underway, not yet, if ever, can we expect large scale impact on carbon dioxide in the sky.

The fourth hurdle to carbon capture and storage is reliable storage. Underground storage requires injecting the carbon dioxide into porous rock like sandstone at a depth of around 3000 feet so that the pressure will shrink the gas to 1% of its former volume. A non-porous cap prevents leaks to some extent, but not entirely. (91) A recent alluring possibility of permanently storing extracted carbon dioxide as carbonate rock inside the fractures of volcanic basalt rock, which is widely available around the earth, has been discovered. The caveats include the need for rock with appropriate absorption, a non-carbon source of energy, and adequate water supplies because of its intense water requirements (25 tons of water per ton of carbon dioxide). The possibility of substituting sea for fresh water is still unproven. Also, there would have to be financial support for extracting and storing the carbon such as a tax on carbon emissions or payment for carbon storage. (96) Additionally, while the ability of microbes to turn methane into calcium carbonate is easily found, there also has been a report that some microbes can ingest calcium carbonate into methane. (97,98) Such a result would worsen warming since methane has stronger warming effects and carbon dioxide itself. The project was small scale in comparison to the need, but the need for permanent storage is so great, that exploration of the potential will certainly continue. Effective storage is a puzzles yet to be effectively solved.

The third approach to removing carbon from the atmosphere is to capture and utilize the carbon, at least temporarily. There are four ways carbon can be utilized: uptake to promote algae growth, conversions into fuels and chemicals, providing services as working fluids, and mineralization into useful inorganic materials. (99) Few provide long term, permanent storage like calcium carbonate rock does; most are considered helpful either because they postpone the rise of carbon dioxide into the atmosphere such as planting trees does, or diminish its use because the carbon dioxide is reused and substituted for "fresh" fossil fuels.

The first process of utilizing captured carbon is to stimulate algae growth for uses such as fuel, food, and soil nutrients, thus, reducing the demand for fossil fuel to make similar products. The second process employs captured carbon dioxide, often with the help of catalysts, to create synthetic fuels, chemicals, and plastic. Plastic is one such use that could become long term storage. Some companies have been able to integrate captured carbon and carbon efficiency into their production process sufficiently to label their products as carbon negative and some of their redesigned products provide long term storage. (90) The third process combines captured carbon dioxide with an alkaline reactant, to mineralize it into carbonates, which can be used in construction and has potential for long term storage. Its estimated market is, however, small market. (100,90) The fourth system of utilization entails piping captured carbon dioxide underground to recover residual oil and then leaving it on site for storage. Drawbacks include the use of fossil fuel energy for extraction, the production of even more fossil fuel, and the possibility of leakage from storage. (99) The four processes, while considered helpful if successful, are not considered a major contributor to solving the climate emergency. (90) Also, even if technical problems are solved, the price of the captured and utilized carbon would have to be low enough to create viable markets, an uncertain result, especially given the energy intensity of the process.

A separate happy note on cement and concrete is warranted. On the one hand, the manufacture of cement, a necessary binding agent for concrete, is made by combining limestone with other ingredients, and emits carbon dioxide. The world uses so much concrete that it produces 7-8% of carbon emissions. On the other hand, because of the limestone in the cement, over years, the concrete actually absorbs from the surrounding air as much as 30% of the amount of carbon dioxide emitted during cement manufacture. Three possibilities for reducing cement's carbon footprint include: first, insuring that a renewable energy is used in production, second, reducing through substitutes, the amount of limestone used to make concrete, and third, capturing the carbon dioxide in the manufacturing process and embedding it in the concrete for permanent storage, which would also increasing its strength. These processes are underdevelopment, but optimists hope that enough successful developments combined with the newly discovered carbon dioxide sponge effect of concrete will allow it to become a carbon sink by the end of the century. (101,102,103)

The considerable investment required to develop and expand the capture, transport and storage of CUSS calls for a price on carbon if done in the private sector (104). Because so many of the benefits are external to the operations producing emissions, some analysts see public power investment as vital and necessary. (105) Capturing emissions from improperly capped and leaking fossil fuel wells seems desirable, but whether using private or public resources, it is vital to not use carbon capture to perpetuate new fossil fuel emissions.

Evaluation of carbon capture should consider its high energy intensity, which would increase demand for non-carbon energy. Utilization development should be directed at non-leaking, long term storage such as use in products like plastic or concrete. The criticality for the human race of preventing and reducing carbon dioxide build up will lead to continued development of carbon capture, necessitating scrutiny of the entire life cycle of proposed technologies to ensure a viable contribution to reducing atmospheric carbon and fighting climate change.

Hydrogen

Hydrogen offers hope for wind and solar electric power's long term storage problems, but the path forward is neither well-worn, nor certain, and has potential diversions. Hydrogen's allure includes its reliability, dispatchability and transportability as well as its carbon dioxide free fuel emissions of only oxygen and water. However, it should be noted that not only does some oxygen combine with nitrogen in the air to produce pollutants, but water itself causes 60% of the earth's greenhouse effect but, if it condenses out of atmosphere to make clouds, it can contribute to cooling. The impact of a significant increase in water vapor from a source like hydrogen production is uncertain and being studied. (106,107) Also, hydrogen has a low and even negative energy return on investment (EROI); 1 units of energy per 4 or 5 dollars invested, while fossil fuels are running at 10 units per dollar EROI and wind, solar and nuclear are also positive at around 9 to 20 units per dollar, and none are as high as hydropower at 84 to 1. (108) However, hydrogen has proved useful and is already in widespread use. As a result, considerable experience with making, transporting and storing hydrogen that is made with fossil fuels exists. Almost all (98%) of current hydrogen production is brown (sometimes called grey) or made with fossil fuels and only 1% is labeled blue because the carbon is captured and stored. (109, 110) However, green hydrogen, made without carbon emissions, is needed to fight climate change. Therein lie the difficulties.

The challenges exist in green hydrogen's production, transport and storage requirements. Hydrogen, although ubiquitous on earth, always exists in some chemical combination, never alone, and must be produced. (111) Doubt exists about fulfilling the soaring demand for hydrogen anticipated for use in aviation, shipping, industry and electric power even if, as many expect, due to its low efficiency (only a fourth of energy per unit than that of natural gas), it will lose to batteries for powering cars and heat pumps for heating and cooling buildings. The impediments to meeting a projected ninefold increase in global demand from 8.4 to 74 exajoules between 2021 and 2050 are even greater for green hydrogen, much less efficiently produced than brown hydrogen. (112,113,114, 115)

Can green hydrogen production meet the projected need for global expansion of hydrogen capacity from .3GW at present to 5000 GW in 2050, which is what the International Renewable Energy Agency (IRENA) estimate is needed to support needed uses such as electric power, transportation, and heating to keep the global temperature rises below 1.5 degrees centigrade? There are three areas of difficulty: electrolysis, water, renewable energy. (113,116) First, a limit to the rate of expansion in the production of electrolyzers required for the electrolysis used to manufacture green hydrogen is one barrier. Hydrogen produced with green electrolysis is 5 times more expensive than by other methods, creating a disincentive for investment. Insufficient capacity and supply also currently exist for some critical ingredients of green electrolysis, iridium and platinum. (117,118,119,120) The second potential difficulty is that water requirements present constraints in some areas. Total or average water use measures for electrolyzed hydrogen can mask problems of particular places. Electrolysis converts water to hydrogen and oxygen, diminishing the local water supply. Water will reappear when hydrogen fuel combines with oxygen to create water in the emissions but if the hydrogen is shipped elsewhere, local water is, in effect, exported. Localities supporting electrolysis must be able to afford water export, and climate change promises increasing water shortages. Also, insufficiently pure or sea water will require the expenses of desalination and of disposal of the brine. (112 ,121) A third potential hindrance is that the supply of renewable energy itself may not be sufficient. Plans to use excess periods of wind and solar to make green hydrogen present not only practical problems of storage and delivery, but the very production of wind and solar themselves is not considered adequate to meet global needs for electric power alone. Also, every expansion in wind and solar carries a demand for more green hydrogen to meet long term power gaps, which implies a demand for wind and solar to create that green hydrogen, an expanding circle of demand. Despite a rapid rise in wind and solar production, the current investment policy and regulatory climate would require such changes as improved financial incentives and support for siting to meet the estimated need for a 4-fold increase in renewable energy global between 2020 and 2030. (113) Creativity has given rise to improved ways of meeting short term power gaps such as combined wind, solar and storage systems (e.g

122,123), but long-term storage is an enduring challenge. Unfortunately, alternative power sources do not offer a ready cure. Why?

Hydro, geothermal and nuclear power are reliable low carbon electric power sources that could, if they were available, reduce the demand for hydrogen per se and could also, provide steady production of hydrogen. The US government has a grant competition for integrating the use of nuclear power to produce green hydrogen. (124) Supply challenges to expanding these energy sources are significant, and while they would overcome the expanding circle of demand for wind and solar, they all use electrolysis and would also face the electrolyzer capacity and local water supply issues. In sum, the current capacities to produce the projected needs for green hydrogen do not yet exist, and all methods face storage and transport challenges. (106)

The daunting storage requirements for liquid hydrogen include compression to 700 times atmospheric pressure, refrigeration at minus 253 centigrade and preventing escape of its very tiny molecules. Experience with brown hydrogen storage exists, but it is a significant expense. (111) All scales of hydrogen production entail storage. Wind and solar farms using free intermittent excess power supply to create hydrogen, must pay for storage. (125, 126) Steady green hydrogen production exists in some areas where the desert meets the sea, because cool winds of the night can complement the sunlight of the day, providing reliable electric power without transmission costs. However, these sites are in Australia and Africa, far from areas of demand, requiring storage and then transportation of the hydrogen. (127)

Transportation of the compressed, refrigerated liquid hydrogen implies many costs. Colorless and odorless, hydrogen is not easily detected but is flammable and explosive, as well as capable of embrittling metal, which eases the leaking of the very small molecules. (111,128) Pipelines at about a fourth the cost of trucking or shipping are the most economic mode of transport. Few hydrogen pipelines exist in the US. Natural gas lines can and have been used to lower the carbon footprint of natural gas by including up to 25% of hydrogen in the mix. However, a large buildup of hydrogen delivery by pipeline would require both new lines and replacement of existing ones to provide lines that can withstand the embrittlement and provide pumping to overcome loss of compression over distance. (106) These problems and widespread local safety concerns resistance to gas pipelines adds to the deterrence and is one reason alternative transport methods are being developed. (111,128)

Solid methods of storing hydrogen as metal hydrides (metals which are bonded to hydrogen as oxygen is in water) reduce the stringency of storage and transport demands, but the metals are relatively heavy and expected to be used for particular needs. However, development of metal hydride storage is ongoing for some uses has been shown to be feasible. (127, 129, 130,131) A stronger interest is being shown for a storage and development path through ammonia.

Chemistry helps explain the development of a hydrogen to ammonia path. Ammonia (NH_3) actually contains more hydrogen per unit volume than hydrogen (H_2) itself. It is easier to store and transport and, as one of the most widely used chemicals in the world (providing 80% of global fertilizer), already has a well-developed global infrastructure to store and transport it, including a network of underground pipelines in the US. There is also development underway to use it as a fuel directly. There is long familiarity and experience with handling ammonia's disadvantages such as the potential for steel corrosion and potential for explosion. (132, 133)

However, traditional ammonia production, which requires high temperature and pressure, has a high carbon footprint, and accounts for almost 2% of both global carbon emissions and energy use. (134, 135, 136, 137) Current ammonia comes from fossil fuels (brown ammonia), but green ammonia can be made from green hydrogen by adding nitrogen, extracted from the air. The green ammonia could then be stored and transported significantly more cheaply than hydrogen, using the already developed infrastructure for ammonia. Green ammonia would reduce ammonia's considerable carbon footprint, but that use would divert hydrogen use from the electric power industry. If green ammonia is used as a feedstock for industrial and agricultural needs, it would lower ammonia's carbon footprint but reduce availability to create green hydrogen for long term renewable electric power storage needs. Further development of the use of ammonia as fuel could make it one of electric power's future long term storage solutions. Also, it is possible to extract hydrogen from ammonia for use in the electric power industry, and although this is a hydrogen to ammonia to hydrogen process, it can be more economical than shipping hydrogen directly. (132, 118,138) In all cases, green ammonia requires green hydrogen, and the problems that could emerge with scaling up production such as electrolyzer capacity, criticality of electrolysis ingredients, local water availability, and the expanded renewable power needs for creating green hydrogen remain. Enthusiasm for the expanded potential of green ammonia for meeting the challenges of climate change is fueling further research and development. (137)

The urgency of the recent International Panel on Climate Change (**ipcc) report** will intensify the current rush to increase green hydrogen production. The industry is in early stages of development and the ingenuity of the varied development projects and steady expansion of its production will contribute to fighting climate change, but it is not likely to be a major and timely solution to wind and solar's long term storage needs. Also, note that many regions with high electricity demand, such as Europe, do not have the capacity to produce sufficient renewable power or hydrogen for their projected needs and plan on importing both from other areas, presenting the question of whether those local environments can support the export demand without damage. (139) Scaling up the use of green hydrogen and ammonia must be based on using renewable energy sources, but critical and careful eyes should be watching the entire global supply chain for the implications of such expansion on material limitations, potential environmental disturbances, labor and living conditions, and unfair environmental justice effects. Watchers should also strive to be sensitive to indications of unintended consequences of increasing the scale of operations around the earth. The many caveats raise the question for some about turning to nuclear power for electricity production, an exploration also inherently complex.

Nuclear

Introduction

More? Less? Should we increase or decrease our dependence on nuclear power from its current 20% proportion of our electricity supply? In the long run would it be more reliable than a wind and solar powered society? Is it too dangerous to use? The issues are complex. The following discussion uses the characteristics of the current most common nuclear power technology in the US (Light water reactors LWR) to clarify the nature of advantages and disadvantages of using nuclear power and then considers whether proposed alternative technologies can solve identified problems.

Advantages

Advocates claim 6 advantages for nuclear powered electricity*:* a low life cycle carbon foot print fuel that could not only make electricity but also to make green hydrogen and provide power for carbon capture, reliability, compactness, durability and weather resilience. They also consider it relatively safe and reason that that while it, like other energy sources and industrial materials, bears toxicities, that prudent methods can provide adequate protection against those toxicities, which they argue are misunderstood. Examination of these merits also reveals some of the criticisms made by opponents.

Carbon Footprint reliability and compactness

Nuclear power does not emit polluting carbon products like fossil fuel plants and its life cycle carbon footprint (which includes mining) is slightly better than that of solar power. (See Table 2). It can serve as a reliable base source of electricity because it operates around the clock and in all seasons. (140,141) Nuclear power's compactness advantage is considerable. Solar takes about 75 times the single use space and wind over 300 times as much mixed-used space as nuclear for an equivalent amount of electric power. (142) Nuclear power does not, however, have solar power's ability to provide so much distributed power.

Table 2.:CARBON FOOTPRINT (g CO2 eq./kWh) **2021**
Ranges of Lifetime carbon footprint for electricity fuel sources

(Range depends on technology used; for details see source)

Coal Power 751-1095

Natural Gas 49-220

Nuclear 5.1-6.4

Hydro 6-147

Solar 8-122

Wind 7.8-23

https://unece.org/sites/default/files/2021-10/LCA-2.pdf

Durability

Most nuclear power plants have **relatively longer lives** than wind and solar, but how much longer is in dispute. The world has 440 commercial reactors (96 in the US) which have been running around the clock, subjected to the intense heat, pressure and radiation for 30-50 years which makes the reactors vulnerable to corrosion stress cracks, especially at weld joints between dissimilar materials. Experience and anti-corrosion research have produced more resistant materials that are enabling the replacement of some vulnerable reactor parts with more corrosion resistant materials such as for cladding for fuel rods which were one source of the problem at Fukushima (246, 247).

In the US the initial licenses are for 40 years, longer than the 25 to 30 year expected life of wind and solar installations. Because so few plants have been built in the US since the 1970's, the plants are old and most 60-year licenses will expire in 2030. The oldest nuclear plant (Swiss) has lasted 51 years. Shutting down existing reactors would cause large losses of non-carbon electric power, and the impact of aging on plant components was given explicit attention in 2010 when the NRC established a study on how plants components aged to help devise guidance for plants on repair and replacement needs. More recently, the US government has set up a competition for funding to allow older reactors to make repairs to keep their systems running and allow them to qualify for license extension. (248)

However, it is the extension of operating permits that has cause considerable controversy. Critics of license extensions doubt the ability of maintenance to guarantee plant safety. More recently, in response to lawsuits by critics, the NRC stopped consideration of applications by 60-year-old plants for an extra 40 years or to 100 years, although providing a possible path forward by committing to openness to changes due to research. Another nod to the heightened need for safety was in a recent decision that 60-year plants applying for extensions to 80 years must update their applications to consider safety factors relevant to their plants such as climate change issues and the expected impact of aging on their facilities. (143, 145, 249)

Opponents question the feasibility of safe repairs not only because of accidents that have occurred but also because of inadequate maintenance models and problems such as leaking of underground pipes and fraying underground electrical lines located in inaccessible locations. (143,144,145,146,147,240, 241,244,245) Embrittlement or weakening of reactor vessel walls to radiation from within the reactor has raised particularly vociferous protests about extending reactor licenses. Cracks could release toxic gases which would endanger local populations. Besides replacing the reactor vessel, the only process for addressing the embrittlement, called annealment, is achieved by removing the fuel and heating up the reactor sufficiently to restore the flexibility of its walls. The annealed surface is itself subject to eventual embrittlement. No US reactors have been annealed; they have been shut down before they were declared too embrittled to be safe. (148,149 150,151,152,231)

One reason that interest in extending the life of old plants, despite the safety concerns, continues is because to do so is obviously cheaper and faster than shutting one down and building a new one. As discussed, it takes a lot of wind and solar power to replace nuclear plants, which have a record of offering reliable power. For those who wish to maintain rather than cut energy levels while reducing carbon emissions, the topic is of keen interest. Germany and France offer interesting contrasts. In Germany at the end of 2021 the decision was made to shut down their last 3 existing nuclear plants, but they have coal contracts that run until 2038. In contrast, France is going to build 3 more nuclear plants. (242,243) While, as a result of the Ukraine war, Germany is reconsidering, the decision is not easy to reverse. For instance, they lack uranium contracts. (250) Finland has decided to proceed with more nuclear power and has produced a report detailing their reasoning which includes the value of decarbonization and nuclear power's relative safety, in use and with modern waste storage methods. (259)

Weather

Historically, nuclear electric power plants' invulnerability to most weather problems has allowed them to serve as a welcomed back up for other more vulnerable power sources during national disasters and bad weather. However, when unscheduled outages do occur at nuclear plants due to equipment malfunction or weather, it is a large systemic loss, and outages have been increasing, in part due to extreme weather. (153,154) Nuclear plants might be protected from wildfires by clear cutting around them, but nuclear plant operations were halted by the recent unexpected deep freeze in Texas. (40) Expectation of more extreme weather and earthquakes and the experience of the Fukushima nuclear power plant accidents have led to calls for more research and development into improving nuclear power plant safety and protections. (155,156,157,158,159)

Relative safety

The low number of deaths caused directly by accidents from nuclear power constitute one part of advocates claims for its safety, assuming precautions necessary to the handling of any toxic industrial materials. 251,253 They further point out the toxicity of nuclear materials declines over time, while other industrial materials such as cadmium and mercury remain toxic indefinitely.

They also argue that radiation and specifically radiation dangers from the operation of nuclear power plants are misunderstood. Because uranium was on the earth before humans and leached into water and then was absorbed by plants, humans have always been surrounded by some radiation, are slightly radioactive themselves, and have some capacity to recover from low level radiation, such as x-rays and cancer treatment. (160,161,162,163) (See Appendix) Uranium in its natural state is only slightly radioactive and can safely be held in the hand, with hand washing afterwards. (164,165) It is exposure to high levels of radiation, which ionizes or alters the structure of molecules, that can sicken and kill humans. Nuclear power plants have very strong barriers to protect humans from such exposure during normal operations. While barriers can prevent penetration of nuclear radiation through the skin, some radiation, like alpha radiation, if breathed in, can be lethal. (166). Advocates point out that accidents that have caused the release of such gases have been rare, and that the normal operations of a nuclear electrical power plants do not present a risk to the public. (251) Safety issues for uranium as a fuel derive primarily from its mining and waste, which contain very high and long-lasting levels of ionizing radioactivity resulting from its transformations inside nuclear reactors. Thus, mining and waste disposal also require investment in strong protective barriers.

Disadvantages

Opponents of nuclear power raise five issues: the radioactivity of its fuel (uranium), the long term radioactivity of its waste, dependence on electricity and water, its long construction time and high unit costs and its proliferation dangers.

Radioactivity

Nuclear power plants do produce very high and long-lasting levels of ionizing radioactivity from which humans must be protected. (164,165) While very few accidents have caused release of such radioactivity, critiques argue that the area and long terms effects have been extensive. Short term deaths, if few, have occurred, and the long term impact of such exposures are still being studied and debated. (252,253) Uranium's dangers as a fuel are not from normal power plant operations but rather from its mining and the waste, due to the transformation of uranium inside the . (166)

Mining

One uranium mining hazard is radon, a radioactive gas which can sicken and kill miners. When uranium, due to its instability, loses neutrons, it decays to become first, radium, and then, radon gas. (167) (As uranium exists all around the earth, local testing for radon gas is encouraged. (168) Other hazards include uranium dust and water contamination. (225) Protections against radon gas and other hazards from mining exist, but vary in quality and implementation. *(*166, 169,225) Even though US uranium mining regulations have improved, severely toxic effects on the environment of all living things from past mining endure and US regulations do not cover countries where most uranium exists. (170). One concern of nuclear detractors is the need for more uranium mining. Nuclear supporters seek ways to not only increase mining safety, but to reduce the need to mine uranium, which will be discussed later.

Fuel Transformation

Inside the reactor vessel, the transformation of uranium fuel to potentially more dangerous forms is required to produce heat for the steam needed to turn turbines for electricity generation. In the Light Water Reactors (LWR) power plants used in the US today, the heat is created by the sustained release of radioactive neutrons from the fissile part of the uranium fuel, the part called U235, which is only 1% of the uranium atom. U235 is called fissile because it can support a sustained chain reaction of neutron releases. The rest of the atom, U238, is called fertile because, while not fissile itself, when hit with neutrons, it can produce other fissile elements called actinides, which cannot be burned in LWRs and, therefore, become part of the waste. Actinides, created inside the reactor, have even higher and longer lasting radioactivity than uranium itself. (171,172,173, 174) (Actinides, which include plutonium, are rare in nature, are referred to as transuranic elements, and are recorded in the periodic tables as elements 89-103.) (175) Any accidents which allowed overheating of the reactor could cause meltdown, and exposure of the public to dangerous levels of radiation from the transformed fuel. Thus, the neutrons from U235 are not only a danger to human molecules, themselves, but also when they create actinides.

Nuclear Waste

Opponents criticize the current nuclear technology's production of waste that contains components which remain radioactive for longer than human lifetimes, some even hundreds of thousands or a million years. (176,177) There are three factors to consider: the origin, the amount and the shielding and storage of the waste.

Origin and Amount of Waste

The origin of the long lived waste is the actinides created when neutrons released from the U235 strike Uranium (U238 (175) In most current reactors, only about 5% of the uranium fuel that is U235 is burned, and the rest, the U238, containing the long lived actinides, becomes waste. (160,166,178) While the reactor waste is a high percentage of the fuel, it requires little space for storage. Its volume since 1950 is surpassed in size by coal plants every hour and would fit in a 36-foot-high building spread out over a football field. Military waste is about 75% more, but the total volume still has a relatively small footprint. Tools, equipment and clothing used in nuclear processes must also be put in separate waste sites. These have lower radiation levels. (179,180,181,182,183,184). Advocates point to the steady loss of toxicity as the radioactive elements decay and the small space needed for the storage. Critics point to its long-lived toxicity.

Shielding and Storage of Waste

Advocates focus on, not only the relatively small volume of the waste, but also the effectiveness of protective shields. For example, radiation's use for medical purposes, albeit with concerns about risks, stimulated the development of protective shields, such used for x-rays. Advocates recognize that the highly toxic radiation of nuclear waste requires extremely strong protection. The containers used undergo intense tests such as being subjected to jet fuel fires and being dropped on strong, sharp spikes from on high. (185) Distance around waste is another required barrier. It is effective because radiation, like the beam of a flash light, becomes more diffuse, diminishing with the square of the distance from the source. (186)

Because nuclear waste is lethal for so long, even hundreds of thousands of years, the goal of long-term storage plans is generally specialized protective containers buried in deep geological sites. Unusual natural evidence supports this approach. Two billion years ago when the earth's uranium was 35% instead of 1% fissile and the level of oxygen was especially high, in certain locations and conditions, some uranium became sufficiently concentrated to create natural nuclear reactors that operated for up to a million years and have not moved more than 10 meters over the time period. (261,262) This record is offered to support the argument that deep bore hole storage in the appropriate land type can provide long term safety. (259 ,263)

Progress in developing long term storage that is acceptable to the public has been halting. Only one country, Finland, is actually constructing such a site. Another, Sweden, has submitted a licensing application, two more have identified sites, and 11 others are engaged in sites selection. The US does not have active site selection underway. (187) After abandoning a yucca mount site, the US is currently seeking communities willing to house nuclear waste. *(188)* It is also supporting development of deep bore hole storage with grants. Bore holes employ horizontal drilling so that the waste could be stored horizontally at a depth that would neither be too close to the surface nor too deep, where high heat could present problems. It is possible that the waste could be stored at the location of appropriately sited nuclear power plants. (264) More public education on nuclear waste storage would be needed to reduce current levels of resistance, but the increasing problems of climate change may open more minds to gathering more information.

Dependence on Electricity and Water

Nuclear power plants' critical dependence on water and electricity is likely to be a growing concern. Nuclear power plants are obliged to be near multiple water sources because of their reliance on water for cooling. (228) Operators are required to work with stewards of the local environment on water needs and other environmental impacts. (189) In some locations, with increasing drought, there may be less water and more competition with other users. Some plants, near the coasts, are vulnerable to flooding from sea level rise or Tsunamis such as happened at the Fukushima plant in Japan. (190) In other locations with increasing rain, flooding is also a concern. (191). If spent fuel cooling pools in seismically vulnerable areas, despite seismic construction standards, are cracked by an earthquake, then overheating and cracking of containers due to water loss, could create leaks of radioactive materials damaging to the local area. (224,226) Climate change will aggravate the water issues

A loss of electric power leads to automatic shutdown of power generation by insertion of control rods into the reactor, and reserve systems of batteries and diesel generators are used to keep pumps working. It takes three days to cool the reactor contents to a safe level. The short-term capacities of batteries and generators are augmented by reserves of diesel fuel (eg of over a month) and the ability to borrow generators from other plants. (192, 164, 193,194,195, 153,154) (This reliance on diesel fuel accounts for part of nuclear power's carbon footprint.) However, safety systems were not sufficient to prevent melt downs at Fukushima. (190)

A long-term loss of electric power is a bigger challenge. New waste must be stored in wet pools of water, cooled by pumps, for at least five years, after which it has lost enough heat to be contained in air cooled dry casks as it awaits long term storage solutions. The water protecting waste in pools must not only be sufficient in quantity, it requires steady and continuous cooling to prevent the waste from heating up enough to destroy protective barriers and cause local radioactive contamination. (192,196, 194,153) Industry concerns have inspired the research and development of passive cooling systems in which hot water automatically rises to a device allowing ventilation of heat to the atmosphere and the cooled water to sink back to do more cooling work. Results have been encouraging and further development and implementation is sought. (227)

Although nuclear accidents have been relatively few and fossil fuel toxicity has been tolerated for years, past nuclear practices, the seriousness of the accidents, the very extensive area affected by inadequate regulation and accidents such as around Chernobyl and on Native American reservations, and the durability of nuclear toxicities have created considerable resistance to using nuclear fuel to create electric power and to acceptance of nuclear waste sites. (197,198,199,170, 200,201) Advocates stress the small volume, the declining radioactivity and the effectiveness of the water barriers and dry casks.

Construction time and costs:

Disagreement exists about the implications of past very long nuclear power plant construction times for the future, the fourth issue for critics. Detractors argue that because of the precautions necessary for nuclear power plant construction, safe operation, secure waste disposal, that it has taken very long time to build them in the past and would also in the future. On average construction times have been over 7 years and total project time 10-15 years. Wind and solar were well below half of that and small projects can go up quickly. *(See Table 3)* While construction in some countries has been achieved in 3 to 5 years, US safety requirements could preclude such a fast time here. (202. Supporters reason that technological advances can enable faster construction of safer nuclear power. (203,204,205) They also point out that the shutdown of existing nuclear plants, given the slow rise of other renewable power sources, has meant substitution with fossil fuels and a rise in carbon emissions, as happened in New York. (206) The section on alternative technologies will provide further discussion of the future of nuclear power. With such long construction times, it is not surprising that nuclear power electricity costs have been uncompetitive, very few have been built in recent years, and some have been shut down. (197,207, 204)

Table 3: Construction And Project Time For Electric Power Plants

Construction Time
Time to build plants: Construction and total project time
Construction time for nuclear is much greater than for wind and solar.
Nuclear 7.5 year average (historical range 3 to over 30 years)
3 years for 18 recently built reactors
http://euanmearns.com/how-long-does-it-take-to-build-a-nuclear-power-plant/
Wind
10 MW 2 months
50 MW 6 months https://www.ewea.org/wind-energy-basics/faq/
3000 MW 3-4 years https://en.wikipedia.org/wiki/Chokecherry_and_Sierra_Madre_Wind_Energy_Project
Solar
250 MW 1.5 years https://www.seia.org/research-resources/development-timeline-utility-scale-solar-power-plant
Project time from planning to linking to grid is much longer than construction and greatest for nuclear.
Wind 2-7 years
https://amperem17.imanengineer.org.uk/question/how-long-does-it-take-to-build-one-wind-turbine/ or 7 years
https://www.energycentral.com/c/ec/how-long-does-it-take-build-wind-farm
Solar 250 MW 6 years https://www.seia.org/research-resources/development-timeline-utility-scale-solar-power-plant
Nuclear 10-15 years (recent plants taking longer due to increased concerns
https://www-pub.iaea.org/MTCD/Publications/PDF/te_1555_web.pdf

Some wish to point to nuclear power's low EROI (Energy Return on Investment),the energy output divided by the energy input. For comparison for oil around 1920 it was 1200/1 but has declined to around 11/1. Meta studies of estimates put hydropower relatively high at over 40, but hydropower is not easily available. Natural gas was given a 7, solar power a 6, nuclear power a 5 but, any comparisons should take into consideration that there is much debate on how to create this measure. (208) What is clear is that current incentives for investment in nuclear power are not strong. Advocates would argue that in light of the external benefits for fighting climate change, that incentives should be strengthened.

Proliferation

The fourth objection to nuclear electric power its potential for contributing to the proliferation of atomic weapons through either fuel preparation or waste transformation. Fuel preparation is necessitated because fissile U235 is only 1% of the uranium and a concentration of 5% is required to ignite and enable a sustained chain reaction of neutron releases to generate the needed heat. Therefore, mined uranium, usually in the form of uranium oxide called yellow cake, is heated to a become a gas which is then centrifuged to separate out a 5% fissile fuel. (The remainder of the fuel, called depleted uranium, has potential as a base for other fuels). (154,209) Because bomb ingredients require at least 20% fissile fuel, centrifuges set at 5% are not the worry, but the possibility of setting the centrifuges for higher concentrations is. This is why centrifuges are discussed and monitored in international nuclear agreements. (210,211,212)

Waste is a proliferation concern because in current US reactors the waste contains the highly fissile plutonium and other actinides. Much waste from current reactors comes in pellets with ingredients which impede making bomb fuel. However, some waste is being reprocessed to release the plutonium in order to combine it with the residual uranium (depleted uranium) from enrichment plants for use in creating a recycled fuel, called MOX. (210,211,212) The waste reprocessing does reduce the volume and average life time of the radioactivity of the waste, but does not remove the long-lived actinides from the waste and does liberate the fissile plutonium, a bomb ingredient. While some experts would not view materials in processing plants as efficient or likely sources of bomb materials, the plants were closed over 40 years ago in the US for both high costs and proliferation concerns including inadequate security. They do operate to produce fuel and reduce the volume and toxicity of waste in other countries. (211,212,229,230)

Will alternative technologies bring improvements?

“Slow” reactors.

Currently, the most common nuclear reactor in the US, light water nuclear reactors, today are called “slow” because water is used to cool and moderate the speed of neutrons emanating from the nuclear fuel. If the neutrons move too fast, they can fail to hit other U235 atoms to release more U235 neutrons and their heat in the needed sustained reaction. (172) Two advantages of the “slow” reactors are the low, 5%, level of need fuel enrichment, well below the 20% level of enrichment needed to make bombs and the pellet formed waste containing contaminants that interfere with making bombs. (210, 197)

Many of their disadvantages have already been discussed including their age, construction time, long term toxicity of waste, and dependence on water and electricity, the supply of which is not certainly reliable. Another issue is reliance on human assisted shut down. Most current shutdown systems currently involve human operators, who can and have made errors. (213,143)

Future slow reactors

Can future slow water reactors overcome these problems? The many years it took to build current fleet dampened investor enthusiasm. The US is striving to improve the economic prospects of such plants through such developments as vertical shafts and off-site production of steel bricks to reduce construction time and costs. Digital twins of reactors are being proposed to test and monitor for reduced costs and enhanced safety. Revenue enhancement has been sought through exploring co- production of hydrogen and other chemicals in the plants. (248, 254 255) Size, automated safety mechanisms and fuel alterations have also been suggested as improvements.

It is hoped the small, modular reactors can lower costs through standardization of parts and their offsite production in factories with economies of scale, lowering capital costs and shortening construction time. Expected safety improvements include not only automated safety mechanisms, but also, due to the smaller size and hence less fuel, shorter shut down times in emergencies and safety clearance of only 2/3 of a mile in contrast to 5-6 miles for large plants. (246, 254) It is hoped that that the lower startup costs and shorter construction times will create more investor interest in countries which, unlike China and Russia, do not have full state backing for construction. (213,143) However, some detractors consider the costs of managing dispersed waste a security problem. (232,233) Others question the realism of gains from standardization due to the wide variety of existing models and criticize the lower heat transfer efficiency because the pipes have to be so small. (234) Actual experience building and using small reactors for a number of years will determine whether small, modular reactors can provide "proof of concept" or will realize their promise. The Chinese are building them and the French, who have supply lines in place as a result of their prior use of nuclear plants, plan to build 3 small modular plants with an eye to a bump in world demand as many reactors reach retirement age in 2030. (254)

The proposed new fuel configurations thought to increase efficiency and safety involve thorium, a fertile fuel that, when bombarded with neutrons inside a reactor, can decay to produce fissile fuel that can sustain the needed neuron releases for heat. Thorium is a fuel best suited to slow reactors and has the advantage of not producing the long-lived actinides in its waste. Also, burning thorium produces elements that 'poison' bomb fuel production that are so radioactive and hot that they would melt the vessels used to create bombs. However, Thorium does produce Uranium 233 (U233) which has been used for bombs, and it is possible to extract the antecedent to U233 before the poisons are produced in the reactor and to then produce the bomb material. Combining thorium with fissile fuel to increase the burn efficiency and reduce the toxicity and volume of waste is another proposal that depends on the fuel chain producing the poisons. Also, one of the proposed enriched fuel ingredients is plutonium, which is bomb material and would have had to have been liberated from nuclear waste, a proliferation danger. (214,149,215) So, while the alternative fuels could possibly reduce waste toxicity and volume, and some proliferation dangers, they do not eliminate water dependency, waste toxicity and proliferation issues.

Another alternative slow technology being developed uses gas such as helium for cooling and graphite as a moderator to slow the neutron releases. Corrosion problems are minimized, gases are easily pressurized, and graphite, stabile at high temperatures, reduces radiation problems. However, the reactors are larger than light water reactors, and require more space and power for cooling and heat transmission and more loading of fuel. Furthermore, actinides still remain in the waste. (216) The cumulative problems of slow reactors explain the hope that fast reactors offer a more effective alternative.

Future Fast reactors:

How Fast reactors work

What are "Fast" reactors, and can they solve the problems of nuclear power such as long-lived radiation dangers, water and electricity dependency, construction time and proliferation potential? They are called fast because they do not use moderators, like water, to slow down neutrons enough to ensure that U235 would be hit to release more neutrons. Although often called advanced or generation IV reactors, they are based on an old technology, devised in the 1950's because slow reactors use only 1% of their uranium (the fissile U235 part), and there was a perceived (but non-existent) uranium shortage. Fast reactors can use the whole uranium atom, including the non-fissile U238 which is 99% of the atom. The unmoderated fast neutrons break the U238 into two plutonium isotopes (pu 239 & 241), which are powerful fuels. They produce 35% more neutrons than from uranium 235 alone. Fast reactors are 60 times more efficient in fuel use than slow reactors. (203) However, in contrast to the name, they are certainly not a quick fix because almost all are in the design, experimental and development stages. (Russia has one commercial fast reactor).

Advantages: Improvements offered by Fast Reactors

Fast reactors potentially offer 4 advantages: reduced reliance on water, reduction of volume and toxicity of waste, ability to create fuel. Unlike slow reactors, fast reactors use liquid metals rather than water for cooling and can operate at high temperatures and at atmospheric pressure. They can be designed to be breeders or burners. Breeders produce more plutonium fuel than they use. Burners can use up fuel, including the long-lived actinides, and reduce the volume of waste by a factor of five. Supporters argue that their advantages outweigh the disadvantages, but that is disputed by critics. (203,198)

The lure of fast reactors includes their smaller size, more efficient heat transfer, and lower dependence on water sources than slow light water reactors. The frequently used liquid sodium coolant is not corrosive. Designs come with varied automated shut down mechanisms such as plugs which melt with overheating, allowing the core to drop into a safe containment vessel, and the tendency for some reactors to slow and even shut down automatically if the temperature rises unduly. (203,217)

Waste

A particularly strong attraction is the fourfold promise of amelioration of nuclear waste problems. First, because the fast reactors can use all of the uranium, including U238, they produce 5 times less waste in bulk. Second, some are designed to use existing nuclear waste as fuel. Third, they can be set up as burners to use up their fuel and the long-lived actinides which are left in the waste of slow reactors. Fourth, they can specifically use military stores of plutonium as fuel, and reduce those stockpiles. (203,198,217) However, critics warn that problems still beset these developing technologies.

Disadvantages of Fast Reactors

Challenges abound. Among them are the properties of the metallic coolants. Sodium, though not corrosive, can be explosive in contact with water or air. The sodium becomes radioactive, and, if it leaks, which is hard to always prevent, it has a half-life of 15 hours. Some liquid metal coolants, such as lead, are corrosive. Molten salt reactors, which have all ingredients, such as fuel and coolants, in one container, have as yet unsolved corrosion problems. Molten salt reactors rely on electricity to maintain their salts in a liquid state; an electric power loss could result in a solidification in part of the reactor that would block the flow of coolants, creating the possibility of overheating of the core, and meltdown. Additionally, the automatic shutdown systems can encounter varied technical conditions which undermine their protections. (198,217,218) While ongoing research and development seek to solve or ameliorate these problems, solutions are not expected quickly.

Proliferation and other vulnerabilities of four kinds exist in the very design of fast reactors, with one possible exception (The Hovering Hope described below). First, the necessary level of enrichment for the fuel for fast reactors is close enough to the 20% needed to make fuel for bombs that the product would be of interest to those interested in nuclear weapons. Second, processing plants, previously discussed, a target for bomb makers, are needed for the chemicals of molten salt reactors and to treat nuclear waste for further use in some reactors. Third, those reactors that can be net breeders of plutonium are making fuel that can be used in bombs. Fourth, molten salt reactors which contain all ingredients in a molten state in a container, contain, in essence, liquid bomb ingredients and the structure prevents effective monitoring to determine whether or not the owner is using it to make bombs. (203,198,219)

A Hovering Hope

A recent review of fast reactors found that not only were they not likely to be operational in the near future, but also that they could be, with one exception, considered more dangerous than light water reactors because they had to use start up fuel centrifuged to be close to bomb material and that their promised ability to use nuclear waste and depleted uranium to make fuel also involved processing that created products that were potential bomb ingredients. (198)

The one possible exception was a reactor design that would use nuclear waste and uranium stockpiles as fuel, burn up the plutonium and other actinides inside the reactor, and significantly reduce the volume and radioactivity of the waste, due to actinide absence. The less toxic waste of these “once through” reactors would not be reused as fuel. The claims are for elimination of the need for mining fuel, of proliferation dangers, and of stockpiles of existing very toxic nuclear waste. 198. This “standing wave” technology would employ remotely controlled automation to push the fuel into the very hot burn area, capable of burning the long-lived actinides left in slow reactor wastes. While the benefits of the described technology would address some of the significant problems of slow reactors, electricity dependence remains for pumping and automation, and in general, developers are finding technological problems, such as viable materials for reactor walls, to be recalcitrant. (220)

All reactors

All reactors face the described problems of aging, construction time, earthquakes, extreme weather, dependence on electricity, water and public resistance to their construction due to concerns about radioactivity. Also, they require transmission lines to both send and receive electricity and are vulnerable to existing problems with transmission systems. However, they do not require the transmission build out that wind and solar do. (199)

Any nuclear technology can use small modular reactors (SMR) with their potential offerings of standardized modules, off site production of parts, transportability, more rapid construction, smaller safety zones, and suitability for more locations. As previously discussed, while economies of scale are lost at one level, such as the lower heat transfer due to smaller pipes, the option of smaller investment starts and economies of module construction are on offer as is the opportunity to incorporate learning into newer modules over time. However, the smaller sizes may introduce a degree of compactness that would make monitoring and maintenance more difficult at times. (221,222) Also, economic factors ignored in discussions of SMR’s such as security costs and limits to standardization due to site characteristics can undermine their economic attractiveness. (223)

Any future investment in nuclear electric power production will require stronger investment than indicated by average conditions for protections against earthquakes, flooding and extreme weather and long losses of electric power. Community safety concerns which exist for all forms of electricity are especially difficult for nuclear power and require considerable spending on community education and negotiation.

Conclusion

If we do not expand and also eliminate nuclear, we shall have much more wind and solar to build and maintain, we shall be increasing our dispatchability needs and long-term power gap problems, and we shall have to replace equipment every 25 years. We shall require much more space, have more vulnerability to extreme weather, and are likely to have more power outages. New nuclear power plants are underway, for, globally, there are 50 plants being built with 100 more ordered or planned. But many of the 400 commercial reactors in the world will reach retirement age by 2030. (246,254) Given the threats to the human habitat, the previously described limitations of renewable energies, analysis of how to most safely expand use of the nuclear power option should be part of electric power policy. The need for open discussion is heightened by the recent Indian heat waves of 115 and 120 degrees. High heat degrades solar panel performance, and we cannot predict what will happen to wind patterns. The result may well be increased demand for nuclear power. We also need to understand how such extreme heat affects nuclear power operations and waste storage.

The disadvantages and long construction times of all electric power systems create strong doubt about meeting, within a safe time period, the challenges of climate change through either technological approach, making the topics of carbon pricing and degrowth seem particularly pertinent.

Conclusion: Advisability of Carbon Pricing and Alternate Consumption Patterns Due to Availabilities, Vulnerabilities, and Negativities

Unfortunately, in line with the recent UN IPCC report that the world is not meeting the needed reductions in carbon emissions .(235) The foregoing review of the characteristics of and prospects for developing non-carbon energy to create electric power in time to prevent a climate intolerable for humans identifies three categories of problems that indicate that society should pay attention to carbon pricing and altering global consumption patterns, often called degrowth, to reduce energy demand . Three categories of problems are availabilities, vulnerabilities, and negativities.

Availabilities

The previous analysis has identified **t**wo types of availability limits, those of the non-carbon energy sources themselves and those of their necessary complements.

energy sources.

Both capacity and time constraints check the expansion of some energy sources. Hydro power, geothermal, and biomass, individually or together, lack the capacity to satisfy the need for non-carbon energy. Expanding non-carbon energy sources to meet projected electricity needs happen cannot be done speedily. Wind, solar and biomass can be expanded only slowly, not fast enough to be relied upon to meet decarbonization needs. Fast nuclear power, green hydrogen and green carbon capture are all only in the developmental stages. Furthermore, if green hydrogen and green carbon capture were to scale up, they would require even more expansion of non-carbon energy to facilitate their growth.

energy source complements

Five necessary complements to the expansion of non-carbon electric power also present barriers to a a timely development of a carbon free electric grid: ingredients, space, transmission, storage and regulations. First, ingredients necessary to some technologies do not have the abundance needed for scaling up the technologies of wind, solar, and green hydrogen. Second, spatial conflicts will increase as some technologies expand either due to competing interest for the land or local safety concerns. These will affect nuclear, wind, solar and, due to pipeline use, hydrogen. Third, complex transmission lines and control center equipped with sophisticated hardware and software will take a long time to build, especially in a country like the US without a national grid, characterized by fragmented decision making and a more robust and complex transmission system is a prerequisite to expansion of wind and solar power. The fourth impediment is short- and long-term storage. Even short-term storage will take time to develop, given the assumption of the use of cars and household appliances as batteries. Low incomes may prevent household from making desired investments. Adequate long-term storage is even more difficult to imagine. Green hydrogen, even if developed, is very difficult to transport and store at the required low temperatures. While innovative ideas rise up and are being sought, scaling them up to need is not necessarily possible and will take time to develop, if they have potential. Fifth, effective and compatible laws and regulations conducive to enabling the new technologies and protecting the public will be necessary. Given the fragmented decision-making systems, their development and implementation will be fraught with disagreements. All of these factors will combine to drag the heels of progress towards needed decarbonization goals.

Vulnerabilities

Three sets of vulnerabilities also present challenges to effective progress toward decarbonization goals: incentives, extreme weather, and cybersecurity. First, needed adaptations to change can be impeded both by the profit incentives of the fragmented group of private owners or the budgetary priorities of public owners. Corruption is another unwelcome incentive that could undermine needed alterations to investment patterns. Second, extreme weather can cause system breakdown of any power sources. As discussed, incentives to invest to protect against average rather than extreme conditions can combine with extreme weather to undermine the effectiveness of grid investments. Third, the dependency of the new grid on intermittent and variable power sources requires automated equipment that can respond faster than human monitors and such systems are subject to cyber security attacks that can, if not deterred, cripple the system. Not only is the system vulnerable, but the task of building in tools of prevention is yet another barrier to a timely upgrade of the system.

Given the current fighting in Ukraine around nuclear power plants and the blowing up of oil refineries, war should be added as another vulnerability to all forms of energy. All kinds of infrastructure can be damaged in war, and energy infrastructure is not an exception.

Negativities

Finally, negative impacts of the power sources present two more barriers to swift construction of a non-carbon system. Three that can be identified include ecological effects, proliferation concerns, and spreading of undesired substances. Two examples of the first are cutting of trees for biomass fuel which can undermine valued habitats, and competition of biomass with other needed uses such as food. These effects would give rise to resistance to expansion. Second, concerns about proliferation or use of nuclear power ingredients to make bombs has long produced protest against expansion of that power source. Third, the power sources can introduce a range of undesired substances into the environment including radiation, explosions of escaped hydrogen, unrecycled wind and solar equipment, and waste from poorly run mine areas. All of these lead to resistance to expansion of new technologies even though fossil fuel itself is a very toxic technology.

Price Of Carbon and Altering Its Consumption Patterns

In sum, a technological solution to our climate change needs cannot be counted on to appear quickly or in a timely manner. Given the seriousness of the situation, it would be self-destructive for human society not to consider raising the price of carbon and altering its consumption patterns to lower its energy demands. Discussion of these worthy topics is beyond the scope of this investigation. Below is a beginning list of sources by some who have already delved deep into the issues of both needed approaches. Considering what they have to say would be wise.

Hopefully this guide will help people to ask needed questions about electric power we they work to create a viable way forward.

Sources For Price Of Carbon And Altering Its Consumption Patterns

Carbon Pricing

taxes

https://www.economicshelp.org/blog/2207/economics/carbon-tax-pros-and-cons/
https://environmental-conscience.com/carbon-tax-pros-cons-alternatives/
https://yaleclimateconnections.org/2016/07/pros-and-cons-of-a-carbon-tax-key-issues/

subsidies

https://uspirg.org/feature/usp/end-fossil-fuel-subsidies
https://www.nature.com/articles/d41586-021-02847-2

Altering consumption Patterns and Degrowth

https://regeneration.org/home Regeneration: Ending the Climate Crisis in One Generation
https://cmi.princeton.edu/resources/stabilization-wedges/
https://www.boell.de/en/2020/12/09/societal-transformation-scenario-staying-below-15degc
https://www.degrowth.info/

Tables and Figures

APPENDIX

AVERAGE EXPOSURE TO RADIATION

in Millirems per year *(1 millirem = .01 millisiverts)*

NRC = Nuclear Regulatory Commission (US) ICRP International Commission on Radiological Protection

CUMLATIVE DOSE LIMITS OR OCCURRENCES *(absorbed dose=energy absorbed by human tissue)*

Iranian measured annual background radiation dose	***26000***
Kerala India measured annual background radiation dose	***1250***
NRC annual nuclear work limit	*5000*
ICRP 5yr radiation worker annual limit	*2000*
AVERAGE ANNUAL US DOSE	***620***
(half natural and half human made sources)	
NATURAL ANNUAL BACKGROUND DOSE:	***310***
Includes: water exposure	
EPA Safe drinking water limit	4
INTERNAL BODY DOSE	***40***
COSMIC RAYS	***30***
NRC public dose limit	100
ICRP public dose limit	100

From 2007 study

Coal ash from coal power plant	18
Two nuclear power plants	3 to 6 (waste sealed)

INDIVIDUAL OR ON SITE DOSE OCCURRENCES

CT scan	1000
Chest x-ray	10
Trans-Atlantic Airplane flight	2.5

https://www.radiologyinfo.org/en/info.cfm?pg=safety-hiw_09
https://www.nrc.gov/about-nrc/radiation/around-us/doses-daily-lives.html
(https://www.scientificamerican.com/article/coal-ash-is-more-radioactive-than-nuclear-waste/)
https://www.world-nuclear.org/information-library/safety-and-security/radiation-and-health/nuclear-radiation-and-health-effects.aspx
(https://www.iaea.org/Publications/Factsheets/English/radlife))
https://hps.org/publicinformation/ate/q8900.html
https://www.unscear.org/docs/publications/2017/UNSCEAR_2017_Annex-B.pdf
https://www.nrc.gov/docs/ML1209/ML120970113.pdf
https://www.ncbi.nlm.nih.gov/pubmed/11769138

Acknowledgements

Absolutely all errors in this working paper are due to me. I undertook this project as a matter of honor, intellectual honesty and continued it spurred by puzzlement and curiosity. I had written about nuclear power regarding its problems, but I really did not understand how it worked. A debate about whether nuclear power was necessary because wind and solar could not satisfy our needs made me aware that I did not understand much about the technologies for any energy system that would be used for electric power. I decided to explore the issues, and as is generally true, the more one learns, the more one realizes one does not know. I found that being perplexed motivated me to engage in further inquiry. It all took much more time than I had anticipated. The generous people and institutions acknowledged below assisted me in the varied ways that research requires: asking questions, making introductions, answering questions, providing information and links to information, reviewing drafts, providing encouragement and support, and being patient. To all of them, I say thank you!

Anthony Anderson, Patricia Adams, Janis Barry, Greg Bischak, Nancy Breen, Nancy Butler Ross, Alex Cannara, Helenka Casler, Geert Dhondt, Anthony Gronowicz, Jay Hamilton, Jack Hammond, Irving Institute For Energy And Society, Carol Kahn, Philip Kahn, Kewulay Kamara, Pushker Karecha, Lindsey Kayman, Kit Kennedy, Kent Klitgaard, Adam Koranyi, Gary Krellenstein, Dick Lahey, Karen Malpede, Robert J. Messinger,Kimberly Ong, Natural Resource Defense Council (NRDC), Christian Parenti, Ross Pinkerton, PSC-EJWG (Professional Staff Congress-Environmental Justice Working Group), Keith Rodan, Len Rodberg, Nancy Romer, Kate Salamido, Alexander Schlutz, Sandra Swenson, Conrad Weiffenbach

REFERENCES

1. *https://www.boell.de/en/2020/12/09/societal-transformation-scenario-staying-below-15degc*
2. *https://irving.dartmouth.edu/education/energy-101 power point deck session 1*
3. *https://www.powermag.com/did-you-know-there-are-60000-u-s-citizens-who-lack-access-to-electricity/#:~:text=%E2%80%9CWe%20have%20about%2015%2C000%20families,is%20a%20licensed%20professional%20engineer.*

4. https://www.iea.org/reports/electricity-information-overview ; https://ourworldindata.org/electricity-mix

5. https://flowcharts.llnl.gov/content/assets/images/energy/us/Energy_US_2019.png
6. https://www.2035report.com/
7. & https://www.rewiringamerica.org/handbook
8. https://environmenthalfcentury.princeton.edu/sites/g/files/toruqf331/files/2020-12/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf
9. 2014 IPCC, Global warming potential of selected electricity sources
10. https://www.lazard.com/media/451881/lazards-levelized-cost-of-energy-version-150-vf.pdf
11. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php
12. . https://www.eia.gov/electricity/annual/html/epa_01_01.html
13. Rodberg
14. https://blogs.scientificamerican.com/plugged-in/renewable-energy-intermittency-explained-challenges-solutions-and-opportunities/;
15. https://www.energy.gov/eere/articles/how-do-wind-turbines-survive-severe-storms
16. *NYS, Climate Action Council.Power Generation advisory panel, meeting 1 Sept 16, 2020*
17. *https://www.newscientist.com/article/2174262-weird-wind-drought-means-britains-turbines-are-at-a-standstill/*
18. https://www.ourenergypolicy.org/wp-content/uploads/2014/04/wind-predictions.pdf
19. *http://www.caiso.com/documents/resourceinterconnectionfaqs.pdf*
20. https://blogs.scientificamerican.com/plugged-in/renewable-energy-intermittency-explained-challenges-solutions-and-opportunities/
21. https://blog.oup.com/2017/10/solar-wind-energy-carbon-dioxide-emissions/
22. https://www1.ncdc.noaa.gov/pub/data/ccd-data/clpcdy18.dat
23. https://www.windsolarenergy.org/best-regions-for-solar-power.htm
24. https://www.ewea.org/wind-energy-basics/faq/
25. https://www.eia.gov/energyexplained/wind/where-wind-power-is-harnessed.php
26. https://www1.ncdc.noaa.gov/pub/data/ccd-data/wndspd18.dat
27. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b
28. capacity https://www.eia.gov/electricity/annual/html/epa_04_03.html
29. https://www.eia.gov/electricity/annual/html/epa_01_01.html
30. https://environmenthalfcentury.princeton.edu/sites/g/files/toruqf331/files/2020-12/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf
31. http://euanmearns.com/how-long-does-it-take-to-build-a-nuclear-power-plant/
32. https://www.ewea.org/wind-energy-basics/faq/
33. https://en.wikipedia.org/wiki/Chokecherry_and_Sierra_Madre_Wind_Energy_Project
34. https://www.seia.org/research-resources/development-timeline-utility-scale-solar-power-plant
35. https://amperem17.imanengineer.org.uk/question/how-long-does-it-take-to-build-one-wind-turbine/
36. https://www.energycentral.com/c/ec/how-long-does-it-take-build-wind-farm
37. https://www.seia.org/research-resources/development-timeline-utility-scale-solar-power-plant
38. https://www-pub.iaea.org/MTCD/Publications/PDF/te_1555_web.pdf
39. https://www.nytimes.com/2021/02/21/us/texas-electricity-ercot-blackouts.html?action=click&module=Spotlight&pgtype=Homepage
40. https://www.nytimes.com/2021/02/16/climate/texas-power-grid-failures.html

41. https://www.scientificamerican.com/article/lightning-strikes-are-a-big-problem-for-wind-turbines/
42. https://www.energy.gov/eere/articles/how-do-wind-turbines-survive-severe-storms
43. https://www.energy.gov/eere/articles/wind-turbines-extreme-weather-solutions-hurricane-resiliency
44. https://www.bbc.com/future/article/20200903-the-wind-turbines-standing-up-to-the-worlds-worst-storms
45. https://www.nytimes.com/2021/02/16/climate/texas-power-grid-failures.html
46. https://grist.org/article/can-solar-panels-handle-the-heat-of-a-warming-world/
47. https://www.sciencedaily.com/releases/2021/08/210824121028.htm
48. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1108r4.pdf
49. https://www.energy.gov/sites/prod/files/2017/03/f34/quadrennial-technology-review-2015_1.pdf page 390
50. https://www.bbc.com/news/science-environment-46455844 Climate change: The massive CO2 emitter you may not know about
51. https://www.ovako.com/globalassets/downloads/products/cradle-to-gate--understanding-co2-footprint.pdfhttps://www.ovako.com/globalassets/downloads/products/cradle-to-gate--understanding-co2-footprint.pdf
52. Environmental Justice Along Product Life Cycles: Importance, Renewable Energy Examples, And Policy Complexities. Local Environment. (June 2017) Vol 0 Issue 0.0 Routledge DOI 10.1080/13549839.2017.1329285
53. http://css.umich.edu/factsheets/critical-materials-factsheet
54. CUNY does this for the City of New York
55. https://www.eia.gov/energyexplained/hydropower/where-hydropower-is-generated.php
56. https://www.nytimes.com/2021/07/14/climate/renewable-energy-batteries.html
57. .https://www.sciencedirect.com/topics/engineering/distributed-power-source
58. https://www.epa.gov/energy/distributed-generation-electricity-and-its-environmental-impacts
59. https://en.wikipedia.org/wiki/Distributed_generation
60. *https://ieeexplore.ieee.org/abstract/document/9112707*

61. https://blogs.scientificamerican.com/plugged-in/renewable-energy-intermittency-explained-challenges-solutions-and-opportunities/

62. http://electricalarticle.com/overview-power-system/
63. https://www.explainthatstuff.com/transformers.html
64. https://atos.net/en/blog/why-local-load-balancing-is-vital-for-managing-the-grid-in-the-new-energy-world
65. Energy Internet blockchain technology Yin Cao, in The Energy Internet, 2019
66. https://www.landisgyr.eu/ezine-article/making-way-two-way-power-flows-planning-control-matters/#
67. https://www.eee.hku.hk/doc/ffwu/WuMoslehiBose.pdf
68. https://electricenergyonline.com/energy/magazine/491/article/A-Brief-History-of-Electric-Utility-Automation-Systems.html
69. https://www.energy.gov/articles/war-currents-ac-vs-dc-power
70. https://www.nrel.gov/grid/cybersecurity.html
71. Dawson, Ashley. People’s Power (Reclaiming the Energy Commons). 2020. QR: New York
72. https://www.eia.gov/energyexplained/hydropower/where-hydropower-is-generated.php
73. https://www.energy.gov/sites/prod/files/2018/02/f49/Hydropower-Vision-021518.pdf
74. https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf
75. Sankey diagram
76. https://www.nationalgeographic.org/encyclopedia/geothermal-energy/

77. https://www.vox.com/energy-and-environment/2020/10/21/21515461/renewable-energy-geothermal-egs-ags-supercritic al
78. https://www.ucsusa.org/resources/environmental-impacts-geothermal-energy#:~:text=In%20open%2Dloop%20geothermal%20systems,dioxide%20equivalent%20per%20kilowatt%2Dhour
79. https://www.eia.gov/energyexplained/geothermal/geothermal-energy-and-the-environment.php
80. https://geo-nii.org/reducing-electricity-demand-with-geothermal-heat-pump-systems/
81. https://www.energy.gov/eere/bioenergy/biopower-basics#:~:text=Most%20electricity%20generated%20from%20biomass,drives%20a%20generator%2C%20producing%20electricity.
82. https://www.syntechbioenergy.com/blog/biomass-advantages-disadvantages
83. https://www.eia.gov/energyexplained/biomass/
84. https://www.britannica.com/technology/biofuel
85. https://letstalkscience.ca/educational-resources/backgrounders/generating-electricity-biomass
86. https://www.nrdc.org/experts/sasha-stashwick/how-biomass-industry-sent-sustainability-smoke
87. https://www.tandfonline.com/doi/full/10.1080/10934529.2018.1459076
88. https://theconversation.com/biofuels-turn-out-to-be-a-climate-mistake-heres-why-64463
89. https://www.boell.de/sites/default/files/bigbadfix.pdf?dimension1=division_iup
90. https://www.nytimes.com/2021/06/23/magazine/interface-carpet-carbon.html
91. https://energypost.eu/10-carbon-capture-methods-compared-costs-scalability-permanence-cleanness/
92. https://www.nytimes.com/2021/01/18/climate/carbon-removal-technology.html?action=click&module=Top%20Stories&pgtype=Homepage
93. https://www.nationalgrid.com/stories/energy-explained/what-is-ccs-how-does-it-work
94. https://theicct.org/blog/staff/carbon-capture-storage-and-leakage
95. https://www.energy.gov/carbon-capture-utilization-storage#:~:text=Carbon%20capture%2C%20utilization%20and%20storage,will%20not%20enter%20the%20atmosphere.
96. https://www.konsyse.com/articles/pros-and-cons-of-carbon-capture-and-storage/
97. https://eos.org/articles/basalts-turn-carbon-into-stone-for-permanent-storage
98. *https://www.sdu.dk/en/nyheder/forskningsnyheder/beton-opsuger-co2*

99. https://www.pnnl.gov/carbon-utilization
100. https://www.nytimes.com/2021/10/31/climate/is-carbon-capture-here.html
101. https://spectrum.ieee.org/energywise/energy/fossil-fuels/carbon-capture-power-plant-co2-concrete
102. CO2 Capture, Use, and Storage in the Cement Industry - MDPI
103. https://www.nytimes.com/2021/01/18/climate/carbon-removal-technology.html?action=click&module=Top%20Stories&pgtype=Homepage

104. https://www.cnbc.com/2021/01/31/carbon-capture-technology.html
105. Parenti, Christian. "A Left Defense of Carbon Dioxide Removal: the state must be forced to deploy civilization saving technology," in J.P. Sapinski, Holly Jean Buck and Andreas Malm, (ed.s), *Has it Come to This? The Promises and Pitfalls of Geoengineering*, Rutgers University Pres
106. https://www.scientificamerican.com/article/solar-and-wind-power-could-ignite-a-hydrogen-energy-comeback/

107. https://www.acs.org/content/acs/en/climatescience/climatesciencenarratives/its-water-vapor-not-the-co2.html
108. https://www.sciencedirect.com/science/article/pii/S0301421513003856
109. https://nelhydrogen.com/podcasts/the-many-colours-of-hydrogen/
110. https://www.globalccsinstitute.com/wp-content/uploads/2021/04/Circular-Carbon-Economy-series-Blue-Hydrogen.pdf
111. . *https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-one-the-supply-side/*
112. https://energypost.eu/hydrogen-production-in-2050-how-much-water-will-74ej-need/
113. https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook Outlook
114. . https://www.iea.org/reports/the-future-of-hydrogen
115. https://www.nrel.gov/news/program/2020/study-shows-abundant-opportunities-for-hydrogen-in-a-future-integrated-energy-system.html
116. . https://www.forbes.com/sites/mikescott/2020/12/14/green-hydrogen-the-fuel-of-the-future-set-for-50-fold-expansion/

117. https://news.climate.columbia.edu/2021/01/07/need-green-hydrogen/

---

118. https://cen.acs.org/business/petrochemicals/ammonia-fuel-future/99/i8
119. Hydrogen https://www.powermag.com/countries-roll-out-green-hydrogen-strategies-electrolyzer-targets/
120. https://www.frontiersin.org/articles/10.3389/frsus.2020.612762/full
121. Life Cycle Assessment and Water Footprint of Hydrogen ...https://www.mdpi.com › pdf
122. . https://electrek.co/2021/08/16/worlds-largest-solar-powered-battery-system-is-now-75-complete/
123. https://www.greentechmedia.com/articles/read/nextera-inks-even-bigger-windsolarstorage-deal-with-oklahoma-cooperative).
124. . https://www.energy.gov/eere/fuelcells/articles/apply-funding-opportunity-advance-technologies-integrating-hydrogen-and
125. , https://kleinmanenergy.upenn.edu/news-insights/renewable-hydrogen-the-future-of-storage-and-fuel-of-the-future/
126. . https://dailyhive.com/vancouver/ubc-renewable-energy-hub-solar-farm-hydrogen-station
127. . https://www.pv-magazine.com/2021/05/29/the-weekend-read-age-of-green-hydrogen-causes-co-location-rethink/
128. . https://www.icax.co.uk/Advantages_Burning_Hydrogen_Heating.html
129. https://spectrum.ieee.org/hydrogen-batteries-solar-energy
130. https://www.sciencedirect.com/science/article/pii/S0360319919302368
131. https://www.norvento.com/en/blog/hydrogen-storage/
132. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/11/Ammonia-as-a-storage-solution-for-future-decarbonized-systems-EL-42.pdf
133. https://www.intechopen.com/chapters/40233
134. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter7.pdf
135. https://www.frontiersin.org/articles/10.3389/fenrg.2021.580808/full ammonia
136. https://pubs.rsc.org/en/content/articlelanding/2020/gc/d0gc02301a

137. https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf
138. https://www.science.org/content/article/ammonia-renewable-fuel-made-sun-air-and-water-could-power-globe-without-carbon
139. https://www.iea.org/reports/the-future-of-hydrogen
140. Intro 1: "IPCC Working Group III – Mitigation of Climate Change, Annex III: Technology - specific cost and performance parameters - Table A.III.2 (Emissions of selected electricity supply technologies (gCO 2eq/kWh))" (PDF). IPCC. 2014. p. 1335. Archived (PDF) from the original on 14 December 2018. Retrieved 14 December 2018.
141. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php
142. https://www.nei.org/news/2015/land-needs-for-wind-solar-dwarf-nuclear-plants#:~:text=Wind%20farms%20require%20up%20to,75%20times%20the%20land%20area.
143. How Long Can a Nuclear Reactor Last? - Scientific American https://www.scientificamerican.com › article › nuclear-p...
144. https://www.scientificamerican.com/article/how-long-can-nuclear-reactors-last/
145. https://www.nrc.gov/reactors/operating/licensing/renewal/overview.html
146. https://www.power-technology.com/features/worlds-oldest-nuclear-power-plant/
147. https://www-pub.iaea.org/MTCD/publications/PDF/Pub1382_web.pdf
148. https://digital.library.unt.edu/ark:/67531/metadc692454/
149. https://neinuclearnotes.blogspot.com/2015/07/how-much-land-does-nuclear-wind-and.html
150. https://www.nei.org/resources/reports-briefs
151. https://web.evs.anl.gov/uranium/faq/uproperties/faq5.cfm
152. https://www.nrc.gov/reactors/operating/ops-experience/reactor-vessel-integrity.html
153. https://www.nature.com/articles/s41560-021-00849-y
154. https://www.nrdc.org/experts/rachel-fakhry/myth-247365-power-plant
155. https://www.iaea.org/newscenter/news/new-iaea-publications-highlight-importance-of-seismic-safety-for-nuclear-power-plants
156. https://www.iaea.org/publications/13478/methodologies-for-seismic-safety-evaluation-of-existing-nuclear-installations
157. https://www.iaea.org/publications/14744/probabilistic-safety-assessment-for-seismic-events
158. https://www.forbes.com/sites/jamesconca/2019/03/05/nuclear-power-always-ready-for-extreme-weather/?sh=35a3f2f12de4
159. https://www.oecd-nea.org/jcms/pl_61802/climate-change-assessment-of-the-vulnerability-of-nuclear-power-plants-and-approaches-for-their-adaptation
160. https://www.nirs.org/wp-content/uploads/radiation/radstds/radiationandanimals.pdf
161. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4157184/
162. https://cancer.ca/en/treatments/treatment-types/radiation-therapy/side-effects-of-radiation-therapy
163. https://www.epa.gov/radiation/radiation-health-effects
164. https://www.ucsusa.org/resources/safer-storage-nuclear-waste#:~:text=These%20pools%20are%20designed%20to,to%20store%20it%20in%20pools
165. https://www.sciencedirect.com/science/article/pii/S173857331830737X
166. https://www.world-nuclear.org/information-library/safety-and-security/radiation-and-health/nuclear-radiation-and-health-effects.aspx
167. https://www.epa.gov/radiation/where-does-radon-gas-come

168. https://www.epa.gov/radiation/what-radon-gas-it-dangerous#:~:text=Breathing%20radon%20over%20time%20increases,causes%20more%20lung%20cancer%20death
169. https://www.epa.gov/radtown/radioactive-waste-uranium-mining-and-milling
170. https://cdn.greenpeace.fr/site/uploads/2019/01/REPORT_NUCLEAR_WASTE_CRISIS_ENG_BD-2.pdf
171. https://justenergy.com/learning-center/electricity/
172. https://energyeducation.ca/encyclopedia/Light_water
173. https://www.nrc.gov/about-nrc/radiation/health-effects/radiation-basics.html
174. https://www.cdc.gov/nceh/radiation/ionizing_radiation.html#:~:text=Ionizing%20activity%20can%20alter%20molecules,produce%20skin%20or%20tissue%20damage.
175. https://www.britannica.com/science/actinoid-element
176. http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-wastes-myths-and-realities.aspx#:~:text=The%20radioactivity%20of%20nuclear%20waste,of%20the%20originally%20mined%20ore.
177. https://www.forbes.com/sites/christinero/2019/11/26/the-staggering-timescales-of-nuclear-waste-disposal/
178. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/the-cosmic-origins-of-uranium.aspx
179. https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx
180. https://www.gao.gov/nuclear-waste-disposal#t=0
181. https://www-pub.iaea.org/MTCD/Publications/PDF/te_1591_web.pdf
182. 182 https://www.forbes.com/sites/jamesconca/2021/04/27/do-new-nuclear-reactor-designs-change-the-nuclear-waste-issue/
183. https://newmdb.iaea.org/profiles.aspx?ByCountry=US
184. https://www.gao.gov/key_issues/disposal_of_highlevel_nuclear_waste/issue_summary#t=0
185. https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-wastes-myths-and-realities.aspx
186. https://www.ucsusa.org/resources/safer-storage-spent-nuclear-fuel
187. https://www.nwmo.ca/en/Canadas-Plan/What-Other-Countries-Are-Doing
188. https://www.reuters.com/markets/commodities/biden-renews-hunt-willing-hosts-nuclear-waste-storage-sites-2021-11-30/
189. https://nuclear.duke-energy.com/2014/01/22/importance-of-water-at-nuclear-plants
190. https://www.britannica.com/event/Fukushima-accident
191. https://www.iaea.org/publications/8635/meteorological-and-hydrological-hazards-in-site-evaluation-for-nuclear-installations
192. https://allthingsnuclear.org/dlochbaum/nuclear-powerless-plants/
193. https://nuclearsafety.gc.ca/eng/resources/fact-sheets/natural-background-radiation.cfm
194. https://www.scientificamerican.com/article/how-to-cool-a-nuclear-reactor/
195. https://www.nrc.gov/reading-rm/basic-ref/glossary/containment-structure.html
196. https://thesurvivalmom.com/long-term-blackout-nuclear-meltdown/
197. https://energypolicy.columbia.edu/sites/default/files/A%20Comparison%20of%20Nuclear%20Technologies%20033017.pdf
198. https://www.ucsusa.org/resources/advanced-isnt-always-better
199. https://www.forbes.com/sites/jamesconca/2021/04/27/do-new-nuclear-reactor-designs-change-the-nuclear-waste-issue/

200. https://www.nationalgeographic.com/culture/article/chernobyl-disaster
201. https://www.ucsusa.org/resources/brief-history-nuclear-accidents-worldwide
202. https://www.koreatimes.co.kr/www/news/biz/2016/10/123_215869.html
203. https://world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx
204. https://www.scientificamerican.com/article/nuclear-power-looks-to-regain-its-footing-10-years-after-fukushima/
205. https://www.energy.gov/ne/articles/3-ways-make-nuclear-power-plants-faster-and-more-affordable-build
206. http://www.nuclearny.org/indian-point/
207. https://www.forbes.com/sites/jamesconca/2021/07/20/new-nuclear-fuel-can-be-here-even-faster-than-new-reactorsaneel/
208. https://www.scientificamerican.com/article/eroi-behind-numbers-energy-return-investment/
209. https://www.radioactivity.eu.com/site/pages/Uranium_238_235.htm
210. https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx
211. https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx
212. https://world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/uranium-and-depleted-uranium.aspx
213. https://www.energy.gov/ne/articles/whats-lifespan-nuclear-reactor-much-longer-you-might-think
214. https://www.forbes.com/sites/jamesconca/2021/07/20/new-nuclear-fuel-can-be-here-even-faster-than-new-reactorsaneel/
215. https://whatisnuclear.com/thorium.html
216. https://www.enggarena.net/gas-cooled-reactors-power-plant/
217. https://www.enggarena.net/gas-cooled-reactors-power-plant/
218. https://www.sciencedirect.com/science/article/pii/S2666032620300259/pdfft?isDTMRedir=true&download=true
219. https://whatisnuclear.com/msr.html
220. https://www.epj-n.org/articles/epjn/full_html/2019/01/epjn190010/epjn190010.html
221. https://www.sciencedirect.com/science/article/pii/S2666032620300259/pdfft?isDTMRedir=true&download=true
222. https://www.sciencedirect.com/science/article/pii/S2666032620300259
223. https://cleantechnica.com/2021/05/03/small-modular-nuclear-reactors-are-mostly-bad-policy/
224. https://www.ocregister.com/2019/07/08/earthquakes-radioactive-waste-and-that-nuclear-plant-on-the-orange-county-coast/
225. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3653646/
226. https://www.nrc.gov/docs/ML0523/ML052350537.pdf
227. https://www.neimagazine.com/features/featurepassive-cooling-systems-for-spent-fuel-pools-4551654/
228. https://www.ans.org/news/article-1191/spent-fuel-pool-at-oyster-creek/
229. https://www.armscontrol.org/act/2005-09/features/us-reprocessing-worth-risk
230. https://www.gao.gov/assets/emd-80-38.pdf
231. https://www.neimagazine.com/features/featurerenewal-by-annealing-7171272/
232. . https://energycentral.com/c/ec/small-modular-reactors-raise-nuclear-waste-risk-distract-real-climate-solutions

233. https://www.iaea.org/newscenter/news/small-modular-reactors-a-challenge-for-spent-fuel-management
234. https://cleantechnica.com/2021/05/03/small-modular-nuclear-reactors-are-mostly-bad-policy/
235. https://www.ipcc.ch/report/ar6/wg2/
236. https://www.bitlyft.com/resources/cybersecurity-for-utilities
237. https://dailyenergyinsider.com/infrastructure/22281-survey-56-percent-of-utilities-have-faced-a-cyberattack-in-the-last-year/
238. https://www.purdue.edu/discoverypark/energy/assets/pdfs/History.pdf
239. https://www.atlanticcouncil.org/blogs/energysource/cyberattacks-on-our-energy-infrastructure/
240. https://www.nrdc.org/experts/caroline-reiser/win-proper-nuclear-safety
241. https://www.energy.gov/ne/articles/whats-lifespan-nuclear-reactor-much-longer-you-might-think
242. https://www.washingtonpost.com/opinions/2022/01/01/germany-is-closing-its-last-nuclear-plants-what-disaster/
243. https://techxplore.com/news/2022-01-france-germany-nuclear-power.html
244. https://www.nrc.gov/docs/ML2111/ML21117A007.pdf
245. https://www.jdsupra.com/legalnews/nrc-ordered-updated-environmental-5954782/
246. https://cen.acs.org/energy/nuclear-power/Combating-corrosion-worlds-aging-nuclear/98/i36
247. https://www.materialsperformance.com/articles/material-selection-design/2020/10/new-solution-to-stop-corrosive-buildup-in-nuclear-systems
248. https://www.energy.gov/ne/articles/10-big-wins-nuclear-energy-2021
249. https://www.nrdc.org/experts/caroline-reiser/win-proper-nuclear-safety
250. https://www.bloomberg.com/news/articles/2022-02-28/delaying-germany-s-nuclear-phase-out-is-easier-said-than-done
251. https://www.forbes.com/sites/michaelshellenberger/2018/06/11/if-nuclear-power-is-so-safe-why-are-we-so-afraid-of-it/?sh=57a7ea026385
252. https://world-nuclear.org/nuclear-essentials/what-are-the-effects-of-nuclear-accidents.aspx
253. https://www.nejm.org/doi/full/10.1056/nejmra1103676
254. https://www.france24.com/en/france/20211013-france-unveils-nuclear-power-overhaul-with-eye-on-china
255. https://www.energy.gov/ne/articles/3-ways-make-nuclear-power-plants-faster-and-more-affordable-build
256. https://www.mdpi.com/2071-1050/13/12/6871/htm
257. https://energyinnovation.org/2021/11/01/how-agrivoltaics-can-provide-more-benefits-than-agriculture-and-solar-photovoltaics-separately/
258. https://www.nrdc.org/stories/made-shade-promise-farming-solar-panels
259. https://www.viite.fi/2021/01/20/nuclear-qa/
260. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-wastes-myths-and-realities.aspx
261. https://blogs.scientificamerican.com/guest-blog/natures-nuclear-reactors-the-2-billion-year-old-natural-fission-reactors-in-gabon-western-africa/
262. https://www.iaea.org/newscenter/news/meet-oklo-the-earths-two-billion-year-old-only-known-natural-nuclear-reactor

263. https://www.deepisolation.com/wp-content/uploads/2021/01/SpentFUEL-Deep-BoreholeDisposal-could-be-a-Path-for-BackEnd-FuelCycle.pdf
264. https://www.cnbc.com/2022/04/04/deep-isolation-aims-to-bury-nuclear-waste-using-boreholes.html)
265.
266.