CLEAN ELECTRIFICATION OF THE U.S. ECONOMY

A crash course on the renewable revolution

Foreword

December 30th, 2021

The global energy system is undergoing the largest and fastest transformation since the Industrial Revolution. Breakthroughs in renewable production and storage have made solar and wind the cheapest and cleanest energy ever available. Consequently, solar, wind, and batteries now make up more than 90% of all new energy production built each year. Because the energy scene is changing so rapidly, there is a lot of misunderstanding and misinformation (just YouTube "renewables" and you'll see what we mean). Even those of us in the industry can get out of date in a matter of months. As a group of researchers, students, and community members, we prepared this overview of the *renewable revolution* based on more than 300 peer-reviewed studies, technical reports, and public articles. We were asked by local and state lawmakers to prepare this report, but we received no funding to do this research.

America is known for its innovation and leadership. If we apply these virtues now, clean electrification could solve air pollution and climate change while revitalizing our economy, saving American families thousands of dollars every year, and protecting our local ecosystems. Thank you for taking the time to consider this information, and please reach out if you have questions or find any errors.

Sincerely,

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Wind turbines, solar panels, and a biogas farm north of Milford, Utah. (Trent Nelson, Salt Lake Tribune)

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Rooftop solar on homes in the Red Oak Park affordable housing development in Colorado. (Dennis Schroeder, National Renewable Energy Laboratory)

Executive Summary

1. **Clean energy, clean air.** Air pollution causes death, illness, and economic damage at enormous scales. Globally, air pollution from fossil fuels causes 1 in 5 deaths and $10 trillion in economic damage annually[1–4]. In the U.S., air pollution causes 200,000 premature deaths and $933 billion in economic losses each year, including 2,500 to 8,000 premature deaths in Utah[1–5]. It is a moral duty to protect the health and prosperity of our communities by transitioning to clean energy as fast as possible (Fig. 1).
2. **Renewables are cheaper than fossil fuels.** Solar PV and wind prices have plummeted 91% and 71%, respectively since 2009 and are still dropping (Fig. 2). Renewable price reductions are 20 to 30 years ahead of schedule, making solar and wind the cheapest and cleanest energy sources ever available[5–7]. Global markets have already responded, and 90% of all new energy capacity built in 2021 was renewable (92% in the U.S.)[8–13]. The global capacity of solar is doubling every 1.9 years, and wind is doubling every 3.7 years, putting renewables on track to meet nearly all electricity demand in 10 years and all primary energy demand (transportation, heating, manufacturing, etc.) in 20 years[6,7,14].
3. **Solutions to intermittency are mature and cost competitive.** Diverse regions around the U.S. and the world have demonstrated that renewables can provide reliable 24/7 power year round[5,6,14–17]. The intermittency of solar and wind has been solved using a combination of energy transmission, energy storage, excess generation, and electrification of other economic sectors[5,7,18–20]. Lithium battery prices have dropped 93% since 2009, making battery peaking cheaper than natural gas peaking (Fig. 2)[21,22]. This triggered a 20-fold increase in U.S. battery storage since 2019[23–25]. Transmission and storage projects have short payoff periods (1 to 3 years) because they allow greater incorporation of cheap renewables and decreased operating costs[19,26].
4. **Clean electrification creates jobs and saves money.** Electrifying transportation, heating, and industry will require a doubling of electrical production in the U.S.[5] and a major expansion of domestic manufacturing[27–30]. This is projected to create 25 million new jobs distributed across every job sector and region of the U.S. during the transition (2020-2040; Fig. 3)[28,29,31], and 4.7 million more permanent jobs in the energy sector[5]. Additionally, clean electrification of heating and transportation decreases energy costs by 63%[5], saving each American family $1,000 to $2,000 per year[27,32]. Regions with pro-renewable policies will see the greatest employment and economic benefits during this transition[33,34].
5. **China is winning the clean energy race.** Widening its lead, China deployed 3-times more renewable energy than the U.S. last year (Fig. 4)[10,12]. Globally, China produces 65% of lithium batteries, 67% of solar panels, and 54% of wind turbines, compared to 6%, 0.7%, and 19% by the U.S.[10,35]. While most Chinese production is currently being deployed within its borders, China is set to dominate the global renewable energy market after fulfilling its energy needs[36,37]. China invests more in renewable research, development, and deployment than the U.S. in absolute and relative terms[10,38].
6. **U.S. leadership in the renewable revolution.** With its robust high-tech sector, research capacity, and investment base, the U.S. is well positioned to compete in the renewable transition, but only if we are strategic[39,40]. For example, Utah and other western states are updating policy to develop their enormous renewable potential[34,41–48]. Rapid deployment of renewable energy systems domestically would spur innovation, create jobs, improve energy resilience, and enhance national security[28,29,31,49–52]. Direct support or low-cost financing for construction of large *gigafactories* could take advantage of the intense global demand for solar panels, wind turbines, and batteries, creating high-quality jobs in economically vulnerable areas[25,28,53–56]. Specifically, the U.S. could update regulation to allow expansion of transmission and distributed generation[26,57–59], level the economic playing field via pollution pricing[60–62], and create a comprehensive, forward-looking strategy for leading in new energy markets[19,27].

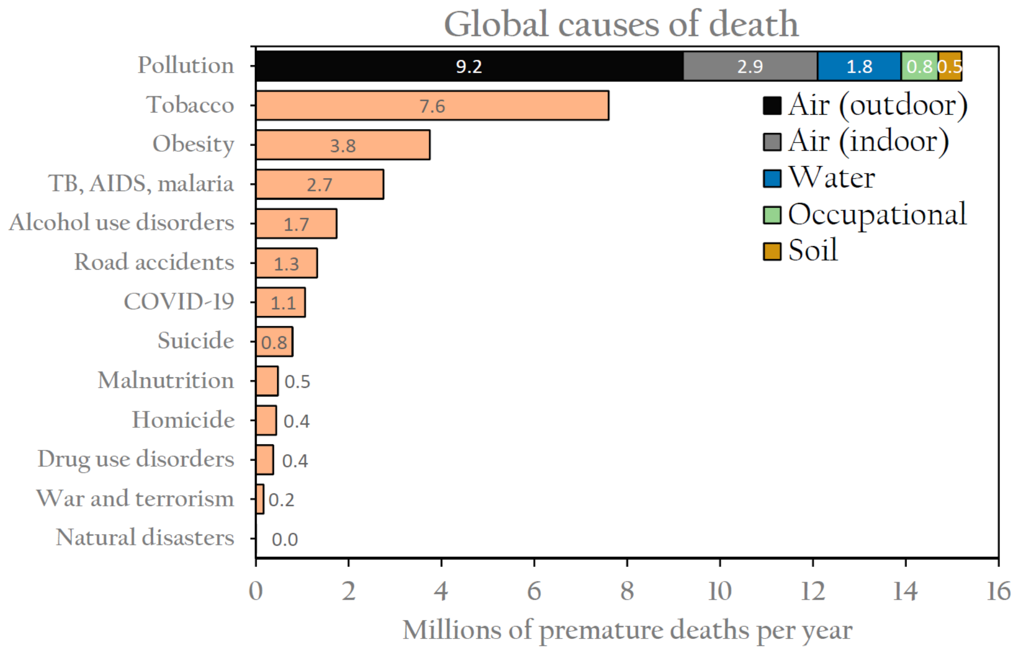

Figure 1. *Estimates of premature deaths caused by pollution compared with other causes and risk factors worldwide[63]. Approximately 10.2 million of air pollution deaths are caused by fossil fuels[3]. (Errigo et al. 2020)*

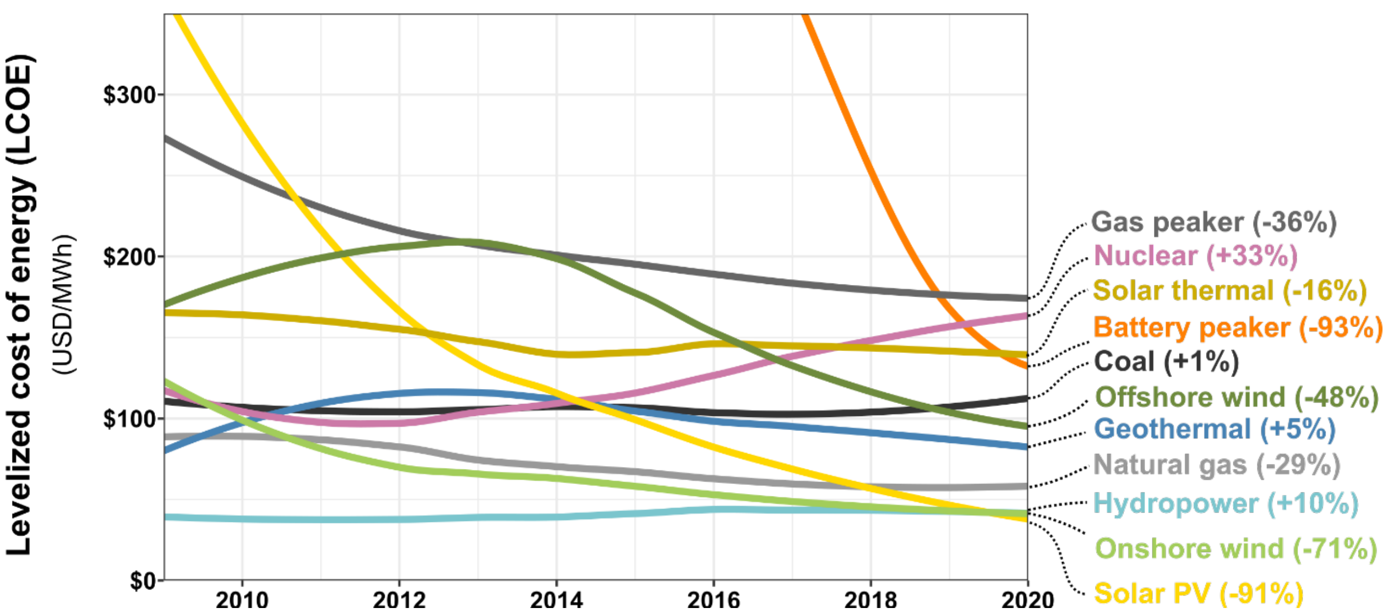

Figure 2. *Global prices of 11 energy sources[7,10,17,35]. The lines show the average levelized cost of energy, which includes the combined cost of fabrication, installation, operation, and retirement. This comprehensive metric allows comparison of different energy sources. The numbers in parentheses show the percent change in cost from 2009 to 2020, with negative numbers representing a decrease in cost and positive numbers indicating an increase. "Peaker plants" (both gas and battery) are cycled on and off to supply power during periods of high demand.*

Renewable FAQs:

Q1. Why should we transition to renewables?

The free market has already decided on renewables. Solar and wind now account for 90% of new energy globally and in the U.S.[9,10,64]. Rapidly transitioning to renewables could allow the US to reduce energy prices, increase human health, grow domestic manufacturing, and strengthen the reliability and security of the U.S. energy system[26,27,65]. A modernized transmission grid with distributed storage and production will prevent disasters like the Texas power outages in February 2021, which killed hundreds and caused $200 billion dollars of damage[5,66–68]. With the transition to renewables already underway, the question is, will the U.S. take this opportunity to dominate energy markets at home and abroad, or let other countries (especially China and the European Union) take the lead?

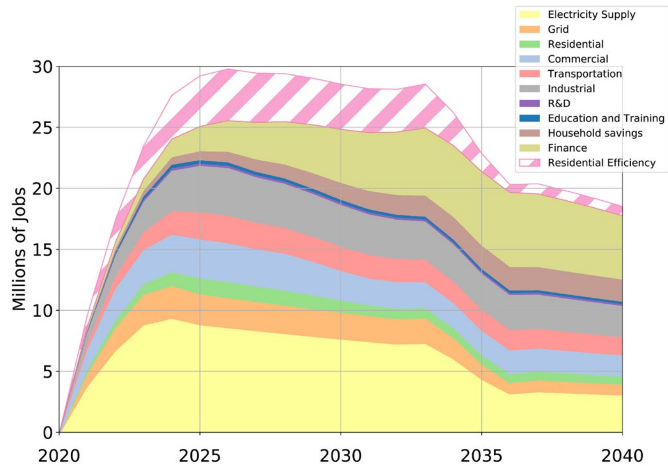

Figure 3. *Estimates of job creation caused by clean electrification in the U.S. were we to commit to halving greenhouse gas emissions each decade until reaching zero emissions. (Griffith and Calisch 2020)*

Q2. What about when the sun doesn't shine, and the wind doesn't blow?

The intermittency of wind and solar energy was initially a major obstacle (see section 2). Five proven and cost-effective approaches are now being used to overcome intermittency: 1. regional transmission, 2. operational flexibility (storage and demand response), 3. excess generation, 4. distributed energy resources, and 5. electrification of other sectors of the economy[30,69]. Energy storage costs (especially lithium-ion batteries) have declined decades faster than projected (Fig. 2)[70–72], which allows us to cheaply and reliably back up intermittent renewables[24,26,73]. Current technologies allow us to meet 80% of our energy needs with intermittent renewables at a lower cost than fossil fuels[5,6,16,26,74]. Developing technologies are on track to meet the remaining demand cost-effectively within the decade[16,75,76]. Potential clean energy technologies to replace the final 20% of fossil fuel production include advanced batteries, enhanced geothermal, biogas captured from agricultural and urban waste, green hydrogen produced with renewable energy, next-generation nuclear, and other types of bioenergy[6,14,15,65,77–79]. In summary, intermittency is no longer a technical or economic bottleneck to taking advantage of cheap and clean renewable energy.

Q3. How much land and water would it take if we switched to solar panels and wind turbines?

Renewables use much less land and water than our current fossil fuel energy system. It would take around 8 million acres to power the entire U.S. economy only with solar panels or 56 million acres with wind turbines (0.3% and 2.3% of the U.S. total surface area, respectively)[5,19,27,80]. The U.S. fossil fuel footprint (drilling pads, pipelines, access roads, etc.) is 81 million acres (3.3% of the U.S surface area), with an expansion of about 7 million acres per decade[5,81]. Some of the land disturbed by fossil fuel extraction and transport can be restored, but most of this damage is effectively permanent[82–84]. This means that a renewable economy will use 31% to 90% less land than our current energy system, while eliminating the need for future expansion. Deploying solar on rooftops, parking lots, canals, landfills, and in agrivoltaic setups further reduces new land use. Additionally, renewables reduce water used in energy production (the single largest category of water use in the U.S.) by more than 70%[85], substantially strengthening our water security[19].

Q4. How big is the environmental footprint of wind, solar, and batteries?

Renewables typically produce less than 1% of the waste and pollution associated with fossil fuels for the same amount of energy[19,86–90]. For example, current electricity production in the U.S. creates more than 6 tons of waste per person per year (air pollution, waste coal, coal ash, formation water, radioactive brine, tar, etc.)[19,91]. Renewables could provide the same electricity while producing only a few pounds of non-recyclable waste[19,27,92]. Electrification of transportation yields similar savings—62 tons of fuel waste over the life of a fossil car versus less than 70 pounds for an electric vehicle (EV) charged with renewable energy[86,92,93]. The already small footprint of renewables is shrinking further as we implement reuse and recycling of batteries, solar panels, and wind turbines, and use renewable energy to manufacture these devices (details in section 5). Renewables aren't a free lunch, but they produce much less waste than fossil fuels.

Q5. What about China and the developing world?

China is currently dominating the manufacture and deployment of renewable technology (Fig. 4)[10,36,37]. Though the U.S. invented both solar panels and lithium-ion batteries, we have let manufacturing move overseas and fallen behind on deployment[36,94]. China, the E.U., India, Vietnam, Australia, and other countries are choosing renewable energy because of its low cost, easy deployment, clean operation, and built-in energy independence[10,40,95]. Increasing renewable energy production represents one of the greatest economic opportunities for our states and country (see section 3)[96]. Creating an economy that doesn't rely on fossil fuels will protect us from the economic shocks of changing foreign oil and gas production[52,97] and free us from the scarcity inherent in nonrenewable energy sources[19]. Because international demand for solar panels, wind turbines, and batteries is skyrocketing[8,10,25,55], developing energy system prowess and cultivating domestic manufacturing could reestablish the U.S. as an energy powerhouse in the 21st century. Failure to anticipate the energy transition will miss this economic opportunity and increase dependence on foreign supply chains with their associated vulnerabilities[98,99]. Transitioning to renewable energy sources will allow continued economic growth domestically and abroad while keeping our air clean and our citizens healthy[3,4,63].

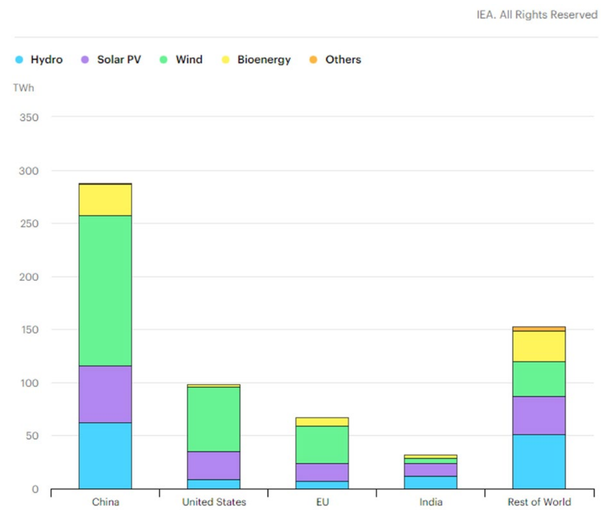

Figure 4. *Renewable electricity production added in 2021 by technology and region. ([IEA](IEA) 2021)*

Q6. What about nuclear?

Nuclear energy is much cleaner than fossil fuels, and until a few years ago, most researchers believed it was the most likely pathway toward economy-wide clean electrification[100–103]. However, nuclear power has become 33% more expensive over the past decade, while renewable costs have dropped ~90% (Fig. 2). With cost overruns and development delays in next-generation nuclear technology (no working *4th gen* prototypes have been constructed), many now question if nuclear is a worthwhile investment[104–107]. Even for the most optimistic scenarios, new nuclear plants won't be completed for 10 to 20 years, and their electricity costs in 2040 are expected to be at least double what renewables are already delivering today[108]. If our goals are to reduce pollution and deliver reliable energy to more of the Earth's population as quickly and economically as possible, nuclear is a hard sell given its high price, slow rollout, and continued global decline[10]. However, maintaining our current second and third generation nuclear plants during the renewable transition is highly desirable because they are cheap to run and produce little pollution[19,65].

Q7. Aren't renewables only winning because of massive government subsidies?

No, fossil fuels receive 3.5-times more direct subsidy (tax breaks, public financing, royalty exemptions, etc.) than renewables and 34-times more indirect subsidy by not having to pay for air pollution[38,109–112].

Q8. Why is renewable energy a partisan issue?

Thankfully, it isn't. Both Republicans and Democrats are working on solutions to reduce air pollution and address climate change. For example, Representative John Curtis from Utah created the Conservative Climate Caucus in 2021, which is supporting "practical and exportable" energy solutions to reduce emissions[113]. Likewise, Democratic Senator Martin Heinrich from New Mexico created the bicameral Electrification Caucus to help American families electrify their homes, buildings, and vehicles to reduce costs and pollution[114]. There is no partisan disagreement about a cleaner and more abundant future for our children. We hope and pray that the renewable revolution will be an opportunity for our country to unite and face the triple threats of air pollution, climate change, and declines in quality of life, especially for the working class.

1. The unexpected rise of renewables

Ten years ago, the prevailing view was that thermal plants (coal, natural gas, and nuclear) and hydroelectric power would provide the bulk of the world's growing energy demand for decades into the future[65,103,115]. Low-carbon energy sources were desperately needed to reduce local air pollution and slow climate change, but there didn't seem to be a viable way forward except for regions with hydropower or geothermal resources[116]. Nuclear energy had grown quickly in the 1980s[100], but it stalled and then declined in the 90s because of high-profile accidents and cost overruns[104,105]. Wind power had been growing rapidly since 2000, but most people assumed that intermittent renewables would remain marginal[103]. Indeed, in 2010, wind and solar produced only 1.7% of global electricity[9,115,117].

Behind the scenes, there was a revolution brewing. Prices of solar panels, wind turbines, and lithium-ion batteries were in freefall (Fig. 2). Though nearly three-times more research funding was going into nuclear energy, and fossil fuels were receiving 34-times more government subsidy ($140 billion for renewables versus $4.7 trillion for fossil fuels in 2015)[38,109,110], renewable technology was progressing in leaps and bounds. Renewables took the lead in the global energy race in 2015, when construction of new wind and solar exceeded that of new fossil fuels for the first time (Fig. 5). Every year since 2015, renewables have widened their lead, now constituting more than 90% of new electrical production built each year[8,9,118].

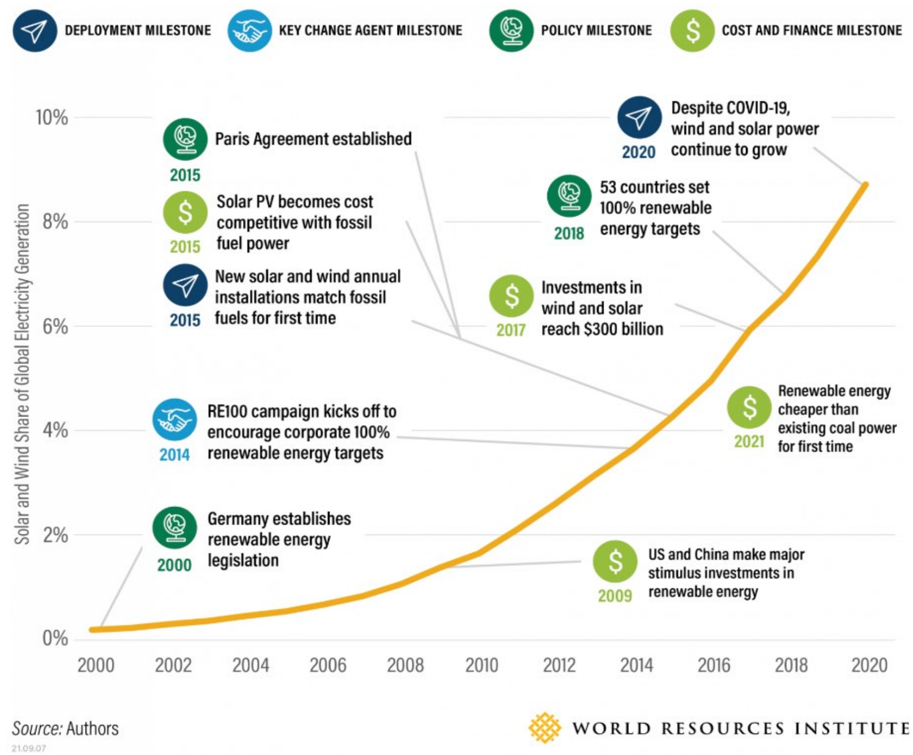

Figure 5. *Milestones in the growth of solar and wind. (Jaeger 2021)*

The expansion of renewable energy is decades ahead of predictions and is following an exponential trend rather than a linear one (Fig. 5)[8,14,117,119]. Globally, wind and solar now produce more electricity than nuclear, and they are on track to overtake hydropower, coal, and gas within two years[8,10,120]. Since 2000, wind capacity has doubled every 3.7 years and solar capacity has doubled every 1.9 years, putting these technologies on track to meet nearly all global electricity demand within 10 years and to produce enough energy to run the entire global economy within 20 years[6,7,14].

The continued dominance of renewables is now projected by nearly all investment groups, economic forecasts, and energy system models (the computer simulations used to design and test electricity production and transmission)[6–9,15,17,49,118,119,121–123]. In late 2021, the International Energy Agency projected that more than 95% of all new energy production built through 2025 will be renewable[119,124]. Another 50% cost decrease is projected for solar by 2030, and a 90% cost decrease is projected for batteries by 2040[39,75,125]. Indeed, national and international energy system models now predict that solar and wind will provide 90% or more of the total energy needed for all electricity, transportation, heating, and manufacturing by 2040[6,7,15,121,122].

The reasons for this explosive growth have been analyzed in detail elsewhere (see Box 1 and Figure 5), but there are at least four distinct factors that have contributed to the meteoric rise of renewables[39,115,121].

1. The intermittency problem of renewables has been solved with transmission between regions, energy storage, demand shifting, overbuilding, and sector coupling (details in section 2).
2. Because wind and solar units are modular and built in factories, their manufacturing processes can be improved much faster than fossil fuel, hydroelectric, and nuclear plants, which must be custom designed and built on site over a period of years to decades[39,75,126].
3. Renewables are extremely cheap to manufacture, install, and operate[127]. They require a fraction of the capital expenditure of a power plant, which decreases financing and permitting costs. Most importantly, these technologies require no fuel and have long operational lives (25-50 years), with minimal maintenance[127].
4. Growing awareness of the negative effects of air pollution and climate change has increased public pressure to transition to clean energy (see section 3). This pressure will only intensify domestically and internationally in coming years. For example, 165 countries have renewable energy targets, 30 U.S. states have binding renewable portfolio standards, and more than 600 cities have committed to 100% renewable energy[9,33,118,128,129].

Box 1. Don't take our word for it

The research cited in this report comes from independent teams working across the U.S. and the globe. We have tried to represent the consensus view, but there is no substitute for diving into the references yourself. Here are 24 resources we found helpful:

Written resources:

1. This World Resources Institute report explains the drivers and consequences of growth in renewable energy.
2. *Electrify*, by engineer Saul Griffith, explores potential American leadership in the renewable revolution.
3. The 2035 Report provides an economic and engineering analysis of clean electricity and transportation.
4. The Rural Renewable Energy report by The Western Way lays out how renewables are affecting rural regions.
5. The REN2021 Global Status Report is the definitive resource about renewable market trends and technologies.
6. Rewiring America's data viewer lets you explore savings and health benefits of electrification for every U.S. county.
7. Project Drawdown is the most comprehensive resource on climate solutions, including renewables.
8. The Rocky Mountain Institute (RMI) has in-depth resources on renewable technology, policy, and market dynamics.
9. GridLab is one of the most comprehensive and comprehensible resources about the energy transition.
10. This book chapter by Christian Breyer explains operation and cost of 100% renewable energy economies.
11. This peer-reviewed paper by Mark Jacobson is a deep dive into renewable costs, reliability, and impacts.
12. The Oxford Energy Transition Study explores how low renewable costs affect economics and financing.

Podcasts and Videos:

13. Creating New Clean Energy Solutions (RMI)
14. How to decarbonize America and create 25 million jobs (Griffith)
15. The benefits of carbon pricing (Citizens' Climate Lobby)
16. Can solar power save our economy? (Kennedy)
17. How solar energy got so cheap, and why it's not everywhere…yet (DW Planet A)
18. 100% of our energy from renewable sources? (Breyer)
19. Renewables vs. Fossil Fuels: The True Cost of Energy (Rosie)
20. Viable pathways to a Decarbonized Future (Baldwin)
21. Short circuiting policy changes to U.S. energy law (Stokes)
22. Legal issues impacting the clean energy transition (Hayes)
23. 100% wind and solar energy with pumped hydro (Blakers)
24. It's time to rewire America and electrify everything (Griffith)

2. Solving intermittency

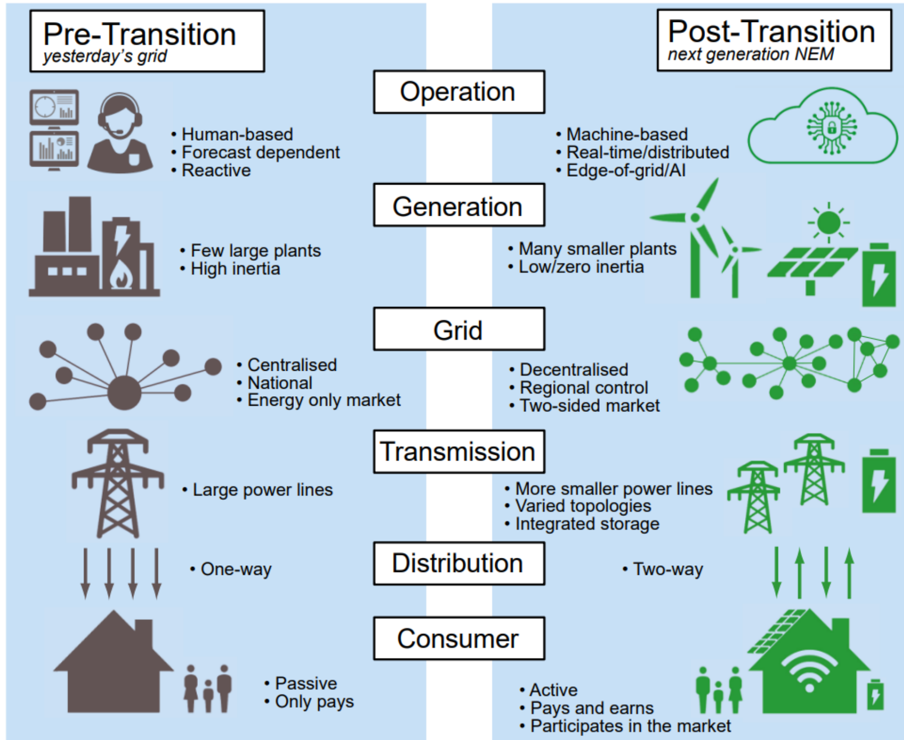

***Figure 6**. Comparison of electrical grid design and operation before and after the transition to clean energy. ([Finnigan](#) 2021).*

Wind and solar energy aren't *dispatchable*, meaning you can't turn them on at will. This intermittency was initially expected to be a major challenge for providing grid-stable electricity 24/7 throughout the year[5,19,65,130]. The primary concern has always been how to provide energy during dips in renewable production, but there is also the problem of what to do with excess power during periods of overproduction[65,69,131]. Solutions to intermittency have been simulated by energy system models for years [18,69,117,121], and we are now seeing them solved in the real world, in diverse regions such as Iowa, Australia, the U.K., Denmark, China, Germany, Brazil, Vietnam, and India[26,73,95,132]. While each of these regions is solving intermittency differently, there are five common approaches that have proven extremely reliable and economical (see section 8). In general, the more of one approach you have, the less of the others you need:

1. Expand electricity transmission
2. Increase flexibility of supply and demand
3. Build excess generation capacity to limit dips
4. Deploy distributed energy resources such as rooftop solar and household batteries
5. Electrify other economic sectors such as transportation, heating, and manufacturing

Approach 1: Expand transmission. Regional transmission of electricity smooths out variation in energy production and demand[6,69], reducing the need for energy storage[69,79]. When a city or region has an excess, it exports power, and when it is in deficit, it imports power. The value of transmission is even greater with a mix of wind and solar, which have very different production profiles[26,30,51]. For example, robust, inter-state transmission would allow Utah to buy wind power from Wyoming at night and then sell solar power to Iowa during wind dips in the afternoon.

> "A piecemeal approach to expanding the transmission system is not going to get the job done. We must take steps today to build the transmission that tomorrow's new generation resources will require."
>
> FERC Chairman Rich Glick [July 15 2021](#)

In addition to allowing greater integration of renewables, electrical transmission decreases electricity costs and makes the grid more resilient to outages (Fig. 6)[5]. Interconnections can maintain power when disasters hit part of the country—such as the Texas outage in February of 2021, which killed 150 to 700 people and caused more than $200 billion dollars of damage[5,66]. Unfortunately, regulatory hurdles currently make it extremely difficult to expand electrical transmission. While the Federal Energy Regulatory Commission (FERC) is authorized by the Natural Gas Act to exercise eminent domain when building pipelines, there is no such authority for electrical transmission lines[57]. Modern transmission is highly efficient but can only move electricity where it exists.

Approach 2: Increase flexibility in demand and delivery. On the power consumption side, *load shifting* or *demand response* can decrease storage needs and electricity costs substantially by matching demand with supply[32,133]. Load shifting is already common in many regions, where time-of-day pricing allows consumers to reduce energy expenses by programing water heaters, electric vehicles, and other high-load appliances to take advantage of periods of low energy cost[19]. In fossil-fuel and nuclear-dominated grids, electricity prices usually drop at night when demand decreases but baseload generating equipment can't be fully throttled[19]. In renewable-dominated grids, prices are often lower midday, when solar production peaks[26]. Allowing the price of electricity to reflect its cost is a market principle that synchronizes demand with supply and encourages innovation (see section 8)[19,134,135]. The capacity for demand response to solve intermittency will increase substantially as transportation, heating, and manufacturing are electrified (see approach 5). Clean electrification of the entire economy will add large commercial and industrial loads to the grid that are often more flexible than residential electricity use[26,69].

On the power production side, flexibility can be added through energy storage[5,19,136]. Perhaps counterintuitively, intermittent renewables don't need baseload power[32,102,130,137]. Wind and solar produce more than enough energy to power the whole grid most of the time[19,26]. Renewables benefit most from flexible backup power that can be turned on to fill dips in production[6,19,69,138]. The cheapest and highest performance dispatchable energy sources are currently pumped hydro and chemical batteries[5,18,58,139].

Pumped hydro uses reversible water turbines to move water uphill to store energy and let it run downhill to produce it (Fig. 7). This mature technology accounts for most energy storage currently on the grid[18,71,140]. Batteries store energy chemically, most commonly by moving lithium ions[121]. Utility-scale batteries use lithium-iron-phosphate chemistry, which has no toxic or rare ingredients and provides superior longevity and safety (see section 5).

***Figure 7.** An off river pumped hydro facility in Italy consisting of two reservoirs separated by 1,600'. The cost of pumped hydro is lowest in areas with high topographic relief such as this because more energy can be stored by smaller reservoirs. ([Blakers et al](#). 2021)*

Although these two technologies are very different, both pumped hydro and batteries deliver bulk electricity storage economically with round-trip efficiencies of around 80% (you get back ~80% of the energy you put in)[18,75,127,141]. Importantly, these storage solutions are extremely responsive, allowing much faster and finer control of power delivery than currently possible even with natural gas peaker plants[21], reducing issues caused by abrupt changes in demand (Fig. 9)[19,142,143].

Because of continued advances in performance and economy, batteries account for nearly all growth in energy storage[23,139,140]. In the U.S., the use of batteries has exploded since 2019 when battery peaking became cheaper than natural gas peaking (Fig. 2). Consequently, the U.S. added 2.9 GWh of battery storage in 2020 and will likely add 13.9 GWh in 2021 (a 20-fold increase since 2019)[23,139,140]. 34 states now use grid-scale battery storage for peaking[23,24,138].

Adding energy storage to the grid has major advantages besides solving intermittency. By allowing the capture of low- or no-cost electricity produced during periods of excess production, batteries and pumped hydro can decrease electricity rates[5,26,40,49,131]. Additionally, because of their responsive, two-way energy flow, batteries reduce costs associated with electrical conditioning and voltage control[26,49]. For example, Australia's 100 MW Hornsdale Power Reserve was the largest chemical battery on Earth when completed in 2017 (it has lost its place every year since then to larger installations). The project was completed by the American company Tesla in less than 100 days at a cost of $66 million. Within two years, the battery had paid for itself, slashing grid service costs by 90% and allowing greater use of low and negative pricing events[26,73]. The project was so successful that South Australia expanded the reserve's capacity by 50% in 2020. This 2021 report by Bowyer and Kuiper provides a detailed view of Australia's energy transition.

A large range of more exotic energy storage solutions are currently under development, some of which may be economical in the next decade—precisely when renewable production will be reaching 80% or more in many regions[5,121]. Potential storage options include compressed air, advanced batteries (flow, solid state, etc.), mechanical storage (lifting of concrete blocks), biogas, hydrogen, and synthetic fuels (see section 8). So far, none of these options are following the rapid price declines or scalability of lithium-ion batteries and pumped hydro, which appear to be the clear winners in the race for energy storage[5,75,121,144,145].

Approach 3: Overbuild power generation. Producing more power than you need makes short-term dips less likely to impact supply. Scaling renewable systems to the lowest-productions periods of the day or year creates more electricity than needed during high-production periods, which would never be economical in fuel-based power systems[5,130]. However, because wind and solar are so cheap and require no fuel, overbuilding by a factor of 1.2 to 4 can reduce the amount of needed transmission and storage[5,7,14,19]. Excess electricity is currently treated as a liability, triggering negative pricing events where producers pay to shunt power[146]. However, in overbuilt renewable energy systems, excess power is produced frequently and predictably (e.g., midday peaks in solar). This abundant "free" electricity creates new economic opportunities and will become even more valuable as we electrify other parts of the economy (see approach 5)[19,147,148]. For example, excess electricity can be used for inefficient and time-insensitive applications such as warehouse refrigeration, water heating, hydrogen production, carbon dioxide recapture, and advanced manufacturing processes that are currently impractical because of energy costs[65,149–152].

Approach 4: Distributed energy. While most electricity in the U.S. is produced in centralized power plants, it is now possible to generate and store power throughout the grid (Figs. 6 and 8). Rooftop solar and household batteries are *distributed energy resources* that can reduce problems of intermittency and provide major economic and resilience benefits[19,26,138,153,154]. When power production, storage, and consumption are colocated throughout the network, the grid doesn't have to distribute as much energy, reducing strain substantially compared to centralized production[19,26,154–158]. Early fears that distributed energy would overload or degrade the grid have proven unfounded. Regions with high levels of distributed energy have maintained or increased electricity quality, reliability, and resilience[26,155,159]. In fact, distributed energy can now be controlled by smart grids, making residential solar and batteries dispatchable. This allows smoothing of demand and greater responsiveness during abrupt changes in load (Fig. 9)[26,154,156,160–162].

Figure 8*. An example of distributed energy production and sector coupling. (Roberts 2021)*

Distributed energy resources are often criticized because of higher per-watt cost and lower capacity factor compared to utility-scale deployments[58]. However, multiple studies and real-world examples show decreased cost and increased reliability for systems with distributed energy[5,19,58,154]. Indeed, the more residential storage and batteries in the system, the lower energy prices become for all users[154]. One reason for this is that rooftop solar and household battery storage units are usually paid for by end users, eliminating the capital expenditure for utilities. Combined with less need for distribution, this can reduce retail rates for consumers and operating costs for producers[27,136,154]. For example, households with rooftop solar are paying an average retail price of 6¢/kWh in Australia where more than 76% of solar production is rooftop[19,26,27,49,163,164]. This is less than the 7.8¢/kWh average cost of distribution in the U.S. (the expenses required to move the electricity from the plant to the consumer)[19].

There is currently a major price penalty associated with rooftop solar in the U.S.—though not because of problems with the technology[19]. *Soft costs* including convoluted permitting and outdated regulation make U.S. rooftop solar approximately 3-fold more expensive than in other countries such as Australia, Mexico, and Germany (see section 4 for possible solutions)[165–168]. Additionally, the current business model of public and private utilities as regulated monopolies can create a tendency to centralize all solar production[65]. Because we need to double the electricity supply to fully electrify the economy[5], we need to encourage both utility-scale and distributed renewables[154]. Relying exclusively on centralized production increases costs, requires more land, and puts more strain on the grid. The consensus view is that centralized and distributed production are highly complementary, with the lowest cost and highest performance grids taking advantage of both[52,58,79,154,157,158,160,163,169,170].

Approach 5: Electrify all sectors of the economy. Electrifying transportation, heating, and manufacturing has multiple benefits, including eliminating >95% of air pollution, improving overall energy efficiency by 57%, and reducing energy costs by 63%[5,19,27]. Full electrification of transportation, heating, and manufacturing will require a doubling in electrical production in the U.S. and a 5.4-fold increase worldwide[5,27,30,127].

Electrifying everything helps solve intermittency because many economic sectors have built-in storage and greater flexibility in power demand compared with domestic and commercial use[19,171,172]. For example, energy for home cooking or office lighting is difficult to shift in time. However, heating water or cooling a refrigerated warehouse can occur anytime as long as the required conditions are maintained[19]. Economy-wide electrification allows greater load shifting and more total power in the system, reducing production dips (see approaches 2 and 3 above)[19,76].

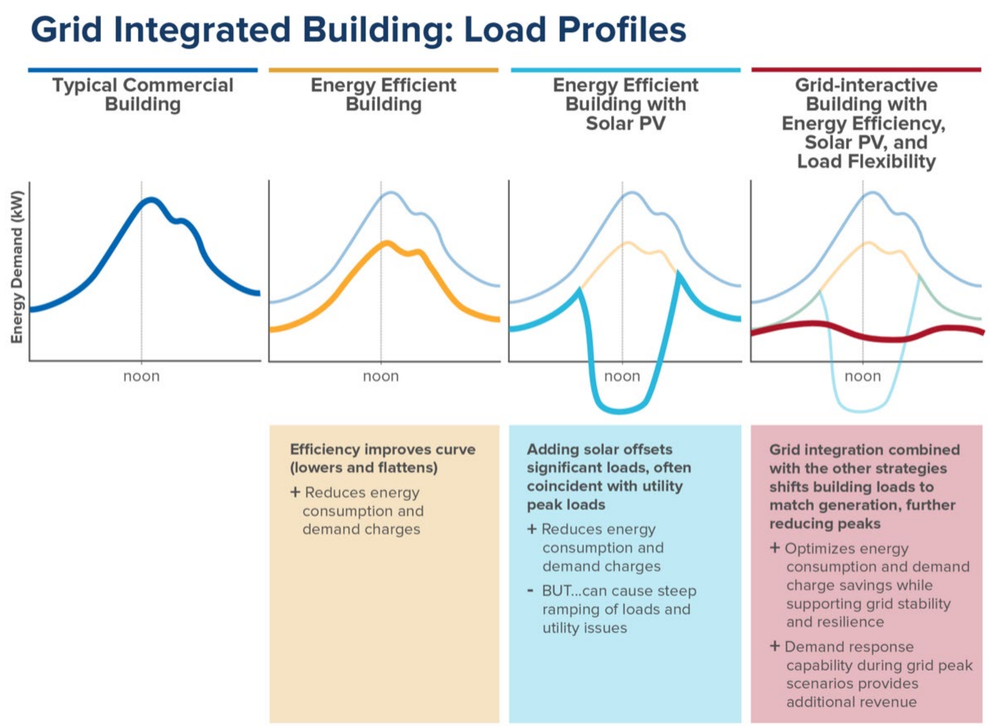

Figure 9*. Schematic diagram showing how efficiency, distributed energy, and grid integration can match supply and demand. (RMI 2021)*

Electrifying transportation is particularly important as it is a third of total energy use and the single largest source of air pollution and greenhouse gas emissions in the U.S. (Fig. 11)[63,87,172]. For example, gasoline and diesel vehicles create 48% of the air pollution in northern Utah[63,64,173]. In addition to not producing air pollution[87,93], EVs are effectively batteries on wheels. As charging stations become more available at work and in public spaces, EVs can soak up excess production during the midday solar maximum and then feed power back to the grid to meet peak demand in the evening[19,76,123,172,174]. Two-way charging is already available for the Ford F150 Lightning, GM Hummer EV, and Nissan Leaf (Fig. 10)[175,176]. Once all U.S. vehicles are electric and integrated into the grid, their storage capacity alone could bridge daily fluctuations in power production, complementing utility-scale storage and transmission[19,123,174]. Electrification of transportation creates a highly efficient, cheap, and resilient grid[19,123].

Figure 10. *New electric vehicles such as the Ford F150 Lightning feature two-way charging, allowing their battery to feed power back to the grid. (Ford)*

Heat pumps are less sexy than EVs, but they are the key to electrifying air and water heating[177–180]. Currently, heating and cooling account for 13% of total energy use in the U.S. and 39% of air pollution in cold-climate regions such as Utah[63,64,173]. Because of their efficient, all-electric operation, heat pumps simultaneously decrease energy use (>70% savings), reduce consumer heating costs, and eliminate local air pollution and housing hazards from natural gas furnaces and water heaters (details in section 8)[27,179,181]. Because of their high thermal mass, electrified buildings act as thermal batteries, allowing substantial load shifting to match supply (Fig. 9)[182,183]. Consequently, heat pumps are being encouraged by utilities and governments around the world, including in the U.S., Ireland, China, Norway, and Italy[142,180,184,185].

The electrification of transportation, heating, and industry will increase both demand response and energy storage[123,158,186]. Because grid interactivity is so beneficial for energy prices and grid performance (Fig. 9), it is worth encouraging or requiring[154]. This is already being done with air conditioning at local and state levels, with utilities offering rate cuts for some degree of remote control[187]. Making federal and state subsidies for EVs, heat pumps, and solar panels conditional on such grid integration would incentivize uptake.

In conclusion, Intermittency is no longer a bottleneck to taking advantage of the health, economic, and environmental benefits of renewables[6,30,65,69,131,171,188]. The most recent research and real-world applications show that a fully renewable grid is possible with already existing technologies at lower energy costs than we are paying now[5,16,19]. In general, the lowest-cost solutions use solar panels and wind turbines for energy production, batteries for day-night variability, and pumped hydro for weekly fluctuations[5,6,121,144]. However, the five approaches above can be combined in various proportions depending on local conditions. For example, a region with abundant hydropower (such as Idaho) or enhanced geothermal potential (such as Utah) could include those energy sources as a part of their flexible backup for solar and wind[18,189–191]. Likewise, agricultural regions that produce large amounts of organic waste may use the biogas produced in digestors to provide electricity during dips in intermittent renewable production (section 8)[77].

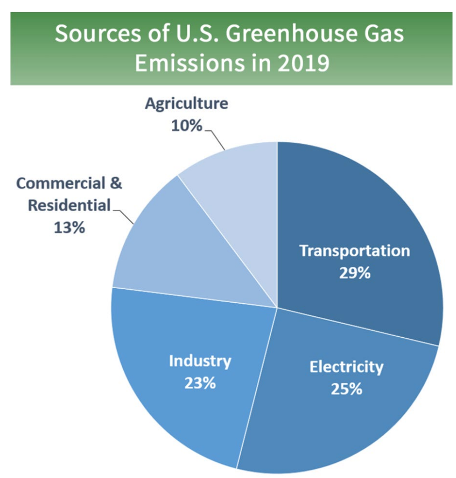

Figure 11. *Greenhouse gas emissions in the U.S. by sector. Total emissions in 2019 were 6.6 billion metric tons of CO_2 equivalent. (EPA)*

3. Health and economic benefits of clean electrification

Clean electrification of the entire economy is one of the most exciting parts of the renewable revolution because it will increase quality of life and decrease environmental degradation[19,192]. The transition to clean and abundant renewable energy will eliminate almost all air pollution (Fig. 11), increase the reliability and resilience of the grid, and decrease energy costs by 63%[2,5,27,32,63]. While there are dozens of reasons to accelerate this transition, here are four major upsides.

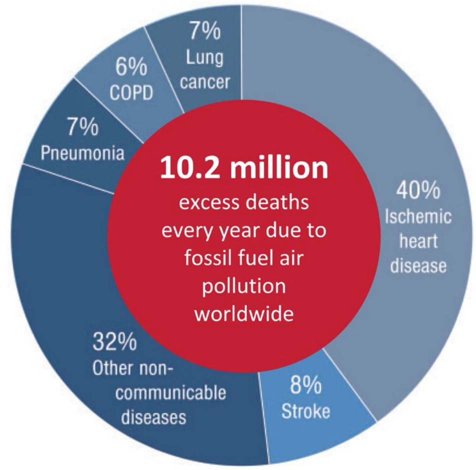

***Figure 12**. Estimates of excess deaths and the health conditions created by fossil fuel air pollution. (Adapted from Lelieveld et al. 2019, Errigo et al. 2020, and Vohra et al. 2021)*

The **first** and most important benefit of clean electrification is the improvement of human health. Air pollution from fossil fuels causes 10.2 million premature deaths each year (Fig. 12)[3,63,193]. That enormous number represents one in five deaths globally—individuals whose lives were cut short because of our current energy system. In the U.S., clean electrification could prevent 100,000 to 300,000 premature deaths every year and save nearly a trillion dollars annually in avoided air pollution costs[2,5,63]. Nationally, every gasoline or diesel car replaced with an EV provides approximately $10,000 of value in avoided health costs[87]. In Utah alone, eliminating air pollution would prevent 2,500 to 8,000 premature deaths, extending our average life expectancy by 1.1 to 3.6 years and yielding an economic benefit of $1.8 to $7.4 billion every year[63]. Electrifying household heating and cooking could reduce childhood asthma rates by 42% by eliminating the most serious source of indoor air pollution: gas stoves[171,194]. For a deeper dive into the benefits of reducing air pollution, check out this report on air quality[1] prepared by researchers from the western U.S. in 2020.

Second, clean electrification saves a lot of money. EVs and heat pumps are much more efficient and cost much less to operate than internal combustion engine vehicles and natural gas furnaces[171,180,195–197]. Switching to electric heating and transportation would save each American household $1,000 to $2,000 annually[5,27]. Check out these independent resources to explore how much you could save by electrifying heating and transportation[27,93,197] based on local energy prices in your state or county.

***Figure 13.** Workers install monocrystalline solar panels on a commercial rooftop. (U.S. Department of Energy)*

Third, clean electrification creates jobs. We will need to replace approximately one billion machines to fully transition from a fossil fuel economy to a clean electric economy[27,32]. This transition will create approximately 25 million jobs through 2040 in every sector of the economy, from mining and manufacturing to financing and refurbishments (Fig. 3)[29,56]. Additionally, a renewable energy economy will create 4.7 million more permanent jobs in the energy sector than at present[5], creating a pathway to long-term prosperity for rural regions across the U.S.[41]. These full-time jobs will not be subject to the boom-and-bust cycles that have created so much uncertainty for our rural communities that depend on resource extraction and energy production[198].

Box 2. American renewables

Sun power: The modern solar cell was patented in 1941 by Russel Ohl, an American engineer working for AT&T's Bell Labs in New Jersey. Bell Labs built the first commercially viable cell in 1954. Because of their high cost, solar cells were initially constrained to the space industry and low-current applications such as watches and calculators. American investment in solar R&D in the 90s and 2000s, combined with international demand for solar panels (Fig. 5) caused plummeting costs and soaring efficiency. Solar is now the fastest growing energy source in the U.S. Unfortunately, the U.S. lost its early lead in solar manufacturing, dropping from 20% to <1% market share from 2000 to 2021.

Wind power: Wind has been used to generate mechanical energy for thousands of years (the Babylonian King Hammurabi talked about it in 1700 BC). The first electric wind turbine was invented in Glasgow Scotland in 1887 by James Blyth. The very next year, the first wind turbine was built in the U.S. to power a mansion in Ohio. In the early 2000s, research and economic investment from the public and private sectors led to rapid growth of U.S. wind power. California was the early leader, but Texas, Iowa, Oklahoma, and Kansas now produce most of the nation's wind power. Strong domestic and international demand have led to extensive job creation and growth in manufacturing. The U.S. company GE Wind Energy is the largest producer of wind turbines globally, with a 19% market share.

Storing power: The basis for lithium-ion batteries was developed in the U.S. in the 70s and 80s. Professors John Goodenough at University of Texas at Austin and M. Stanley Whittingham at Binghamton University in New York were researching advanced materials to improve performance of EVs. They discovered that lithium could be used as a lightweight and energy-dense cathode. This research led to the first commercial lithium-ion cell, which was built by Sony in 1991. The U.S. has remained a leader in batteries, with the Department of Energy supporting research and manufacturing through universities, national labs, and private-public partnerships. Today, the battery industry is robust and rapidly growing in the U.S., providing much of the domestic demand for electric vehicles (Tesla, General Motors, and Ford) and stationary batteries.

This brings us to the **fourth** benefit of clean electrification: maintaining American leadership abroad and ensuring continued economic prosperity at home. The U.S. invented many of the technologies that are powering the renewable revolution (Box 2). However, we are lagging many nations in deployment of these innovations[10]. It is particularly troubling that the U.S. is falling so far behind China, which is manufacturing and deploying renewable tech three times faster than we are (Fig. 4)[10,35]. China now invests more research and development in renewable technology than the U.S., in both absolute and relative terms[10,38]. This research and deployment has contributed to enormous growth in the Chinese economy and international influence[72,199]. Currently, most of the solar panels, wind turbines, and batteries manufactured by China are being deployed domestically to meet soaring internal demand for electricity[10,38]. However, foreign policy and national security experts are very concerned about growing Chinese influence as China begins exporting more renewable technology[10,35,199].

The U.S. is at a crossroads. We could double-down on outdated and expensive fossil and nuclear technologies, with their dwindling international market and environmental costs[104–108]. Or we unleash American innovation and industry to take advantage of skyrocketing domestic and international demand for renewables. The market advantages of renewables are so strong that the clean energy transition will move forward with or without U.S. participation. The question is will we produce the tech fueling this transition or purchase it from other countries?[37]

To compete in the renewable revolution, we need strategic planning and investment (this [interview with Saul Griffith]() provides one version of how this could play out). America has played a pivotal role in past global crises, including World Wars I and II. Now, we could lead the world in disarming the threats of pollution and climate disruption while growing our economy and healing our cultural divides[19].

Although we currently have almost no domestic solar manufacturing (0.7% of global market share), we still have robust capacity in wind and batteries (19% and 6% market share)[10,35]. With strategic investment and clear priorities, we could reinvigorate domestic manufacturing and ensure U.S. competitiveness. One

Figure 14. *Workers from Wanzek Construction and Siemens finish construction of the "Top of the World" wind farm near Casper, Wyoming. (Duke Energy)*

option would be to invest in large renewable manufacturing facilities or *gigafactories*[53]. The largest such factory is currently being built in Hefei province in China at a cost of $2.5 billion. Once completed, it will manufacture 60 GW of solar panels every year, increasing global manufacturing of all intermittent renewables by 25%[53]. Providing low-cost financing or direct support to construct several such gigafactories would immediately put the U.S. back in the solar manufacturing game[53,200] at a relatively low cost compared to current domestic spending levels.

An important co-benefit of investment in domestic manufacturing is that it creates rural mining jobs to replace flagging demand for coal and natural gas[48,79,201]. This could help ensure a fairer and less disruptive transition for miners and other energy workers who could continue working in their areas of expertise during and after the renewable transition[19,31]. In many cases workers won't even need to change companies (Fig. 14), as fossil fuel corporations and logistics providers pivot toward renewable energy[19,202].

4. Better energy policy

> "Utah's renewable energy sector is a growing force driving the state's rural economies with 4,368 construction jobs, an annual output of $154.4 million, and nearly $25 million in annual property tax revenue."
> Utah Rep. Steve Handy [Dec 21 2021]

The remaining obstacles to taking advantage of clean and cheap renewable energy are political[65,69,164,201]. Both internationally and in the U.S., regions with updated policies are seeing the greatest benefits from renewables, while those with outdated regulations are largely being left behind[26,45,65,73,132,203]. For example, Iowa and Wisconsin have similar energy needs and resources. However, Iowa has the most intermittent renewables in the U.S. (58%), while Wisconsin has almost the least (3%)[20], partly because of lobbying of the coal industry in Wisconsin[204]. As a result, Iowa now has cleaner air and 27% cheaper electricity than Wisconsin[204].

A similar dynamic has played out on the East Coast. Florida produces less solar power than New Jersey, despite having more than 10-times the solar potential[205]. New Jersey has an ambitious renewable portfolio standard and energy master plan to "lessen dependence on fossil fuels, help grow the state's economy, reduce emissions and combat climate change"[206]. Conversely, Florida has no binding renewable targets and a high level of influence from fossil fuel interests[203,207]. This has curtailed energy freedom and discouraged private and public investment in clean energy[203,208,209].

Nationwide, energy choices have been greatly diminished by lobbying networks funded by the fossil fuel industry and utility trade groups[65,207]. These special interests, legislative exchange councils, and professional lobbyists have spread disinformation and codified preferential treatment for fossil fuels in state and federal law[65,207,210–212]. Unfair regulations and incentives undermine the free market, limiting competition even if it offers lower prices and cleaner operation[65,204,207,208,213]. This leaves most states—including those with stated "all of the above" or "balanced" policies—with energy systems not optimized for cost and reliability[65,115].

In the case of Utah, our state has some of the best solar and geothermal potential in the country, but renewables only make up 1.4% of total energy use and 10.4% of electricity production[33,34,203,214]. This puts

Utah 25th nationally for renewable energy but 7th nationally for air pollution emissions per kWh[19,65,201]. With its combination of technological assets, rapid economic growth, and renewable resources, Utah could be a world leader in renewable energy production, storage, and manufacturing[47,169,173,215]. Thankfully, Utah and other states are updating policies and investing in clean infrastructure, providing multiple examples to learn from and compare[41,43,65,216]. Drawing on successes from other regions, here are six policy recommendations:

__1. Put a price on pollution__. The failure to make polluters pay for their air pollution has been described as the biggest market failure in economics[60,217–221]. By not requiring payment for the negative effects of pollution on human health and environment, we are giving fossil fuel companies a "pollute for free" pass that is likely worth at least $10 trillion globally each year[38,109–112]. In the words of former South Carolina congressman Bob Inglis, fossil fuel polluters are "dumping into the trash dump of the sky without paying tipping fees." This *economic externality* creates a highly tilted playing field, where the full costs and benefits of energy choices are not fairly compared[63,217,222,223]. We cannot benefit from free market innovation and efficiency as long as the price of energy doesn't reflect its full cost[62,219]. The preferred market-based solution to this problem is a carbon fee and dividend, endorsed by 3,600 American economists and politicians from both major parties[60]. This approach collects a fee from fossil fuel companies based on their emissions, correcting the market failure, and leveling the playing field. The proceeds from the fee are distributed equally among all U.S. citizens to offset potential increases in energy prices (these explainers by the Citizens' Climate Lobby and Center for Climate and Energy Solutions are great). A border adjustment tax makes sure the carbon pricing does not drive manufacturing offshore, and it exerts economic pressure on other countries to reduce emissions[61,62,221]. While pollution pricing doesn't solve pollution and climate change itself, it unleashes market forces to encourage faster reduction of emissions through clean energy production, increased efficiency, and technological innovation[19]. Consequently, states and countries around the world have implemented a price on carbon (Fig. 15), and many corporations are opting into voluntary carbon markets[220,221].

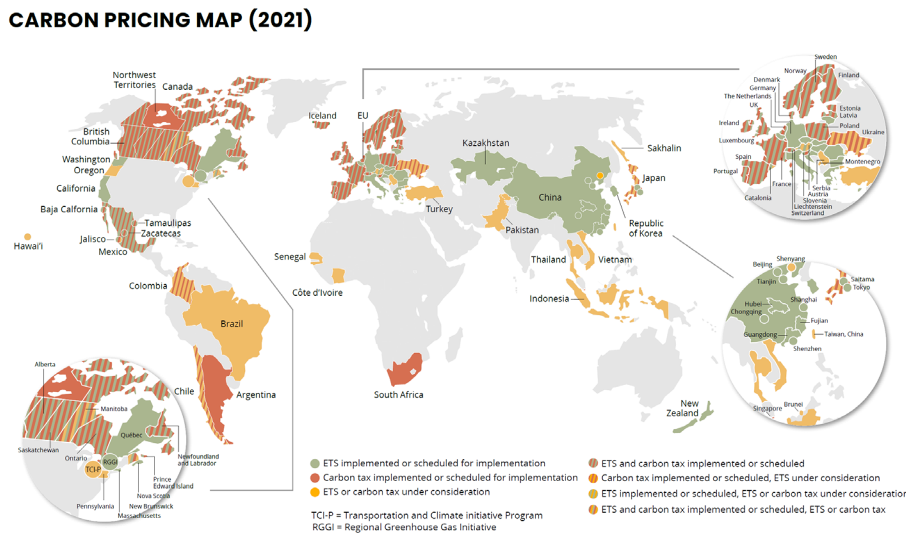

***Figure 15.** Countries and states with carbon pricing. (World Bank 2021)*

__2. Set binding renewable portfolio standards (RPS)__. Even when fair pricing of fossil fuels isn't politically feasible, state and local RPS have proven highly effective at reducing energy costs and pollution[65,128,206]. Setting timelines and binding commitments creates a stable regulatory environment that encourages utilities, businesses, and individuals to deploy renewables[65]. At the municipal level, more than 600 cities worldwide have 100% renewable goals[118], including more than 20 in Utah. This was made possible by the 2019 law H.B. 411 sponsored by Representative Handy and Senator Hemmert that allowed cities to opt into renewable energy agreements with Rocky Mountain Power[224]. A state RPS could ensure faster and more efficient transition to renewable energy[65]. Conversely, continuing to legislate an "all-of-the-above" energy strategy[213] subsidizes technologies that are no longer competitive and lets regional power providers leave stranded assets in Utah while other states demand cheaper and cleaner energy[19,207]. Utah's nonbinding goal of 20% renewable by 2025 makes it one of only 20 states without a binding RPS[33,34,128].

> "There is no way we win this war without the utilities…they do today. They are perfectly poised to be a giant participant in our clean-energy future."
> Saul Griffith, *Electrify*, 2021

3. Provide support for energy workers and utility companies. Because the renewable revolution is occurring so rapidly, most utility operators don't know about the current technology and economics of renewables[65,210,225]. Outreach to providers and distributors could help utilities implement best practices and prepare for the expected doubling of electricity production[5,19]. Training and logistical support for smaller energy providers and distributors could protect or grow local jobs while maintaining reliability and low cost during the transition[226]. Utah has cultivated a strong entrepreneurial environment for innovation in both hardware and software. State support to encourage collaboration between businesses and communities (rural and urban) could create innovation incubators for the development of smart grid systems, energy storage, and advanced efficiency[173,215,227]. State and county governments should also collaborate with transitioning energy and mineral extraction companies to provide worker re-training and placement programs. This decreases opposition to renewables[210,228], but more importantly takes care of our people—our most important asset[19,51,227].

4. Cut red tape. There are multiple policy obstacles that slow renewable energy development and increase costs. **First**, rooftop solar in the U.S. costs twice what it does in Germany and three times what it does in Australia and Mexico[19,164,167]. Streamlining the design and permitting of residential solar and storage could reduce cost per watt by 70% (Fig. 16)[167,168]. Local and state governments should align their distributed energy regulations with new national best practices[167]. **Second**, state and federal laws should be updated to put transmission lines on the same legal footing as fossil fuel pipelines[50,57]. **Third**, the *Energy Policy Act of 2005* should be updated to give geothermal drilling the same expedited permitting currently afforded to oil and gas exploration[229,230]. **Fourth**, local, state, and federal governments should provide low-cost financing, tax incentives, feed-in tariffs, and direct subsidies for electrification (EVs, heat pumps, etc.), and renewable power generation and storage—similar to what has been done for fossil fuel energy for decades[26,49,110]. **Fifth**, establish grid neutrality, which allows market forces to optimize energy production, transmission, and storage costs (details in section 8)[19,135]. **Sixth**, building codes should be updated to require all-electric or at least electric-ready homes and businesses[231–237]. Utah's residential energy code hasn't been updated for two cycles, leaving us with outdated requirements that increase pollution and cost Utah families more for energy. Provisions for EV charging and heat pumps cost thousands less during new construction than as a retrofit.

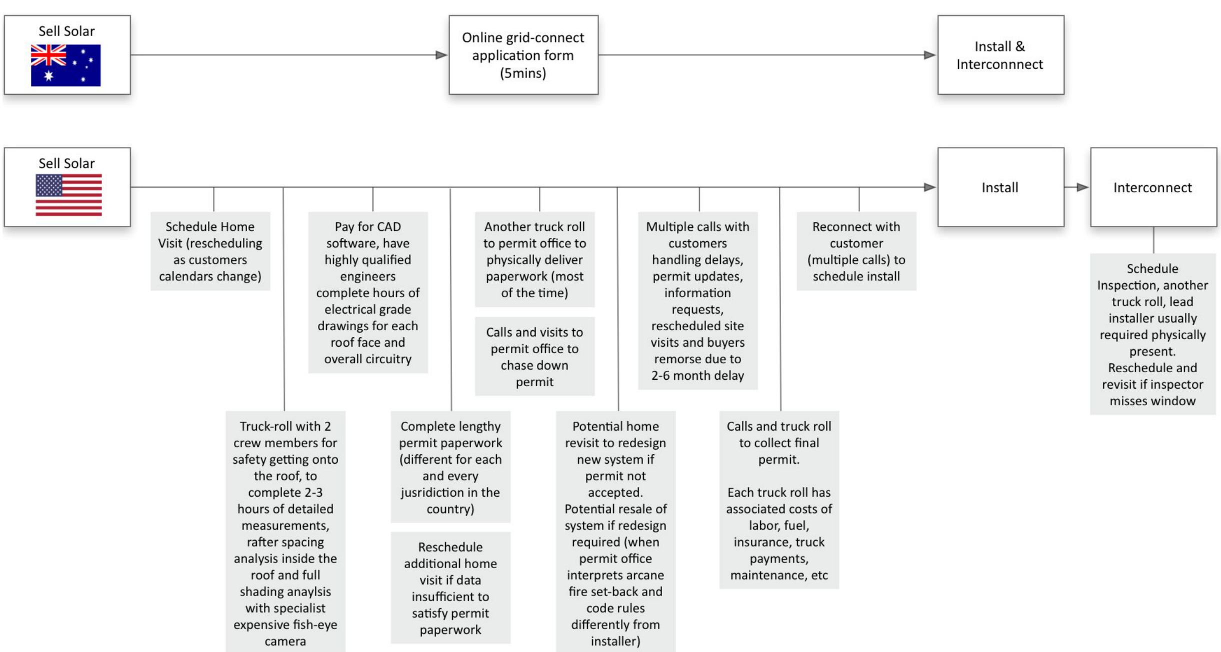

Figure 16*. Rooftop solar permitting and installation in Australia vs. the U.S. Though solar installers make more in Australia (~$40/hour), soft costs from outdated regulation make rooftop solar 3-times more expensive in the U.S. (Birch 2018)*

***5. Retire dirty assets early*.** Energy producers are announcing early retirements of fossil fuel plants (especially coal) on a weekly basis[238–240]. For 56% of coal plants globally, it is already cheaper to build new renewable capacity than to continue operating, and this is expected to be true for 78% of coal plants by 2025[226]. However, 93% of coal plants are currently shielded from competition by contracts and noncompetitive tariffs, meaning that communities and states could be locked into expensive and dirty coal power for decades[226,238]. Many states and communities are negotiating early retirement of noncompetitive coal and gas plants through refinancing and reinvestment options for shareholders[226]. These phaseout deals have demonstrated that early retirement can be a win-win-win that reduces energy costs, restores profitability, and generates low-cost capital for supporting transitioning workers and communities[226,238].

***6. Invest in research and manufacturing*.** Public-private partnerships at multiple universities in Utah have been highly successful at prototyping EV infrastructure and developing enhanced geothermal methods[241,242]. Additional innovation centers and initiatives around clean electrification could create major economic opportunity for Utah nationally and internationally[243]. Lake Bonneville—which used to cover much of Utah—created some of the world's highest quality lithium brine deposits[47,48]. This salty groundwater can be safely extracted and reinjected after lithium harvesting with minimal environmental disturbance. Specific areas of needed R&D include smart grid technologies, battery and solar manufacturing, off-river pumped hydro, advanced lithium extraction methods, improved power-to-x techniques (e.g., hydrogen, ammonia, etc.), advanced batteries, and innovation in carbon capture and sequestration[75,121,148,149,200]. Between its human and natural resources, Utah is the perfect place for renewable research, manufacturing, and deployment.

5. Making renewables cleaner

One of the official laws in ecology is "There ain't no such thing as a free lunch"[244]. Renewable energy technologies must be manufactured, installed, and dealt with at the end of their useable life, all of which has an environmental impact. We need to consider this entire *life cycle* to fairly compare renewables with other energy sources and figure out how to shrink their environmental footprint further[245,246]. As mentioned earlier, renewables already use much less land and water than fossil fuels and typically produce less than 1% of the waste and pollution[5,19,84,86–90]. However, <1% of a large number can still be important, and we should take advantage of the current upheavals in energy to create a more circular economy that requires less raw material and produces less waste[247].

Thankfully, researchers, manufacturers, and installers around the world are working on innovative ways to make renewables cleaner[86,248–251].

Lithium-ion battery chemistries have vastly improved to enhance performance while reducing environmental and societal impact. Nickel and cobalt have been reduced in mobile battery applications such as EVs[18,252] and removed altogether in stationary batteries, which use lithium-iron-phosphate (LFP) chemistry. These ingredients are nontoxic and easy to source and recycle[18,252]. Battery reusing—transferring mobile batteries from old EVs to stationary uses—is widespread in countries that were early adopters of EVs (Fig. 17), and lithium-ion recycling has quickly become profitable and available worldwide[54,252]. As the global supply chain of batteries has grown, dozens of large-scale lithium-ion refurbishing and recycling companies have sprung up, creating economic opportunity

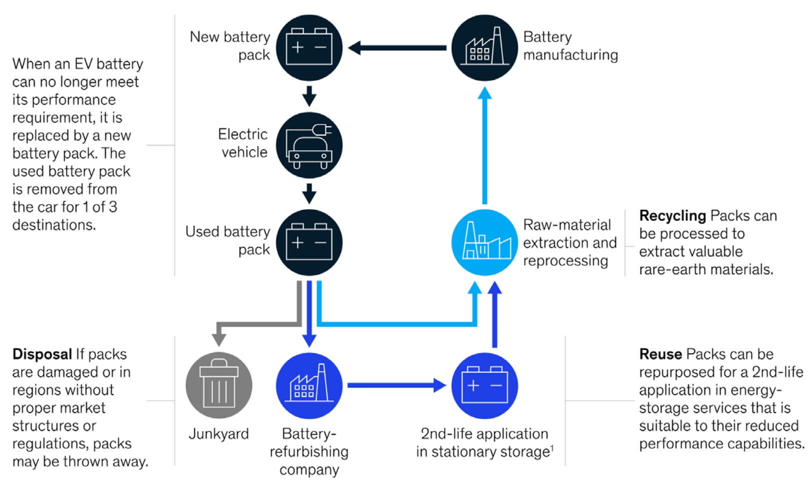

Figure 17. *Life cycle diagram for an EV battery. (McKinsey 2019)*

in rural and urban regions[253–255]. Automakers are recycling or reusing batteries and other materials from their EVs, creating a cleaner and more circular life cycle[253].

Pumped hydro systems used to be "on-river", moving water from below a dam back into the reservoir. This creates large fluctuations in water flow that can degrade aquatic habitat[256]. New "off-river" pumped hydro systems (Fig. 7) reduce water use and eliminate disturbance to aquatic ecosystems. Some installations even take advantage of abandoned mines and buildings, solving two environmental issues with one tool[18,257].

Figure 18*. An agrivoltaic system in France produces power and creates a high level of control over insolation, humidity, and protection from wind and pests. (Sun'Agri 2020)*

Solar panels are already the most recyclable energy source because of their standardized design, solid state operation, and limited number of materials[248,258]. Advances in manufacturing, deployment, and reuse are extending panel life and allowing direct refurbishment—the gold standard in circular economics (reduce > reuse > recycle)[259–261]. To decrease land requirements, panels are being installed on nearly every surface imaginable, including rooftops, canals, reservoirs, landfills, parking lots, and even in agricultural fields[80,169,200,262,263]. These *agrivoltaic* deployments are particularly promising because partial coverage can enhance the growth of some crops by modifying the local microclimate (Fig. 18)[264]. Agrivoltaics can increase yields while reducing water use by 20% or more, expanding the potential range of some crops and providing greater food security in the face of extreme weather events and climate change[265–268].

For onshore and offshore wind, techniques have been developed to *repower* turbines—modifying blade profiles and refurbishing equipment to enhance production[269–271]. Greater turbine height has increased production per unit of material and land while also decreasing bird and bat impacts. We point out that the effect of wind turbines on bird and bat populations have been completely misunderstood. A head to head comparison among energy sources reveals that wind turbines cause an average of 0.3 bird fatalities per GWh of electricity produced compared to 0.4 for nuclear and 5.2 for fossil fuels[272–274]. This means that replacing fossil fuel plants with wind turbines would prevent more than 12 million bird fatalities every year in the U.S. alone[273]. Painting one blade black has been found to further reduce bird impacts by 73%[272]. Between repowering and increased height, individual turbines are now achieving huge outputs of 14 MW or more[275], allowing wind farms of a few turbines to produce what previously required dozens or hundreds of units.

Heat pumps—the critical technology needed for electrifying heating of air and water—now use compressed CO_2, propane, or organic refrigerants in closed loops. This replaces fluorinated gases, which improves efficiency and reduces potential climate and ozone layer disruption from gas release during disposal[19,185].

6. Your personal clean energy infrastructure

While most of this report is focused on system-level energy transitions, we wanted to highlight some of the personal energy options that are now available. The renewable revolution has created unparalleled personal choice in energy, giving individuals and families the power to build and operate their own clean energy infrastructure at the scale of an individual house or apartment building (Fig. 19)[19]. While these personal electrification options aren't financially accessible to all, early adopters have ended up playing important roles in accelerating rollout and decreasing costs[58,158].

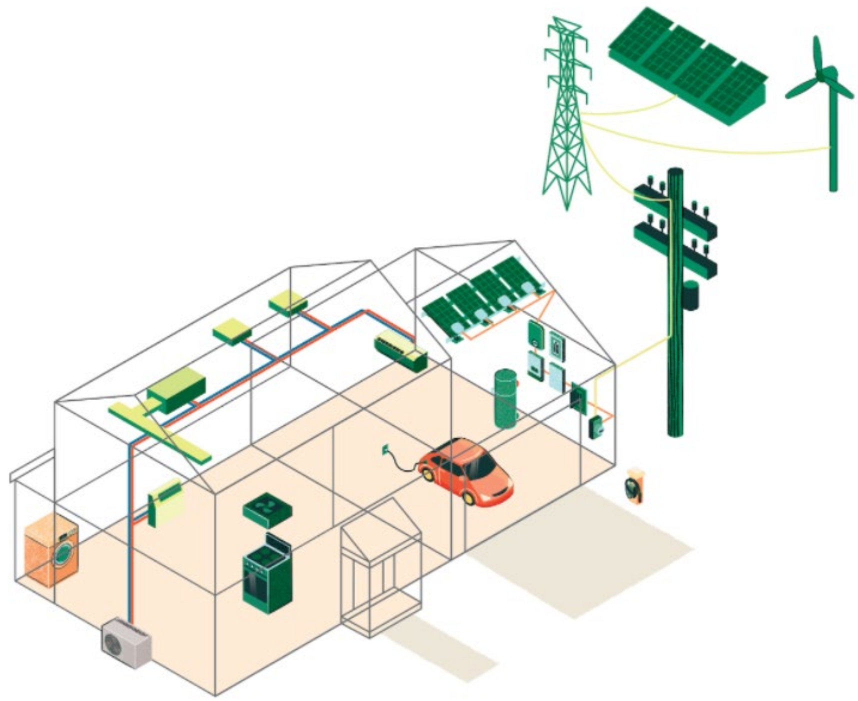

Figure 19*. Currently available equipment allows full electrification of a household. (*[Rosenberg](#) *2021)*

While these technologies cost less than their fossil fuel counterparts over the course of their lifetime, the upfront costs of purchase and installation can put them out of reach for some households[19,171,197]. Thankfully, many cities, counties, and states have grants or financing to help offset purchase and installation because these technologies increase efficiency and decrease pollution[179,216]. Whether or not you are in a position to invest in this infrastructure, educating those around you about their benefits, especially elected officials and utility operators can help build support for the clean electrification we need for healthy communities and a stable climate[210,276,277].

Here are the main components of your personal clean energy infrastructure:

1. Electric vehicle (low maintenance and affordable transportation without local outdoor pollution)
2. Heat pump (high efficiency electric heating and cooling without indoor and outdoor air pollution)
3. Induction stove/oven (high performance cooking with less indoor air pollution and safety hazards)
4. Rooftop solar panels or community renewables (clean production displaces coal and natural gas)
5. Residential battery storage (grid independence and maximized benefit from solar panels)

Items 1-3 are particularly important because they eliminate the indoor and outdoor pollution that harms our health and wellbeing (see section 3). For details and recommendations, here are four awesome resources:

1. Electrify Everything in Your Home (Joel Rosenberg)
2. All I Want for the Holidays Is an All-Electric Home (Sara Baldwin)
3. Electrify Now! (Rewiring America)
4. Net-Zero Electric Home in Utah (Tom Moyer)

7. Why not stick with fossil fuels?

Fossil fuels have significantly reduced global poverty and improved human quality of life since 1850. Fossil fuels have served the U.S. well, and we should thank the dedicated men and women who built and operate our energy system[19]. However, in a world of nearly 8 billion people with rapidly growing per-capita consumption, fossil fuels are causing four major problems: air pollution, climate change, consumption of land and water, national insecurity, and scarcity.

First, as discussed in section 3, the biggest problem with fossil fuels is the immense damage to human health. With one-in-five deaths each year attributable to fossil fuel pollution[3,63], our energy choices are about much more than economics; they reveal our moral values. Leaving all environmental concerns aside, we must transition to clean energy as rapidly as possible for the health and wellbeing of the human family.

Second, the extraction and burning of fossil fuels produce the greenhouse gases that are destabilizing global climate (Fig. 20)[278–280]. We have known about the greenhouse effect since 1856[281], and every president since Lindon B. Johnson has been briefed about the national security, environmental, and economic dangers of altering our climate[282]. The consequences of climate change have been described in detail elsewhere (this leaked report by J.P. Morgan and Chase is direct and readable), but in brief, climate change threatens nearly every aspect of our lives. From the global food supply to the global economy, human flourishing depends on stable seasons, reliable precipitation, and healthy oceans.

You may have heard friends and family ask how human activity could be affecting something as large as the Earth's climate. It is difficult to grasp the current scale of human activity[283–285], and it's worth exploring this question. Our fossil fuel use produces around 35 billion tons of CO_2 every year[279]. That is more mass than all the other products of humanity combined[27]. Take a minute to soak that in. If you add up all the buildings, concrete, asphalt, vehicles, foods, electronics, and Black Friday specials that we make every year, they still wouldn't add up to the amount of CO_2 that we create each year by burning fossil fuels. CO_2 is our number one product as a species. The cumulative burning of fossil fuels since the Industrial Revolution has increased CO_2 in the atmosphere by 50%[279]. CO_2 is the Earth's thermostat, controlling the partial pressure of water vapor and hence global temperatures of both atmosphere and ocean[286].

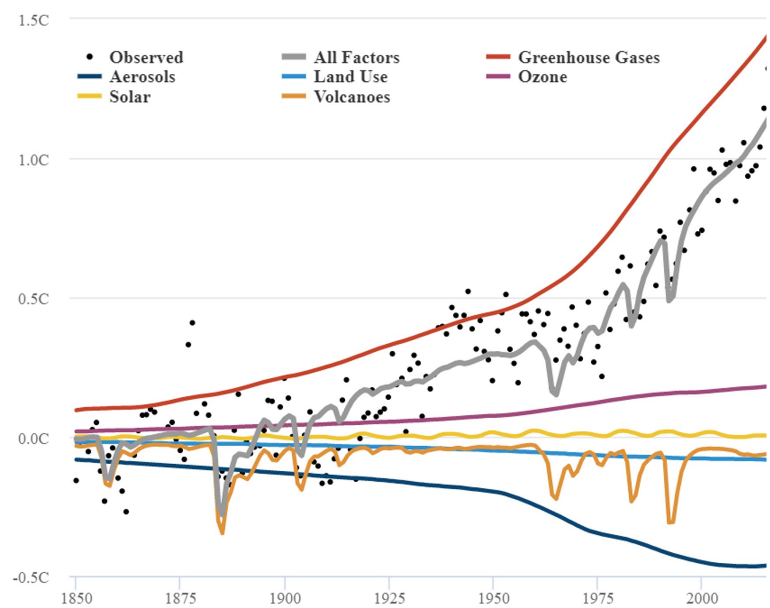

Figure 20. *Observed mean annual air temperature compared to natural and human sources of climatic variability. (Carbon Brief)*

While natural climate change has always been a part of the Earth system, the current unnatural warming is more abrupt than any known period in the Earth's history[285]. Human production of greenhouse gases and aerosols accounts for 100% of the observed deviation in climate since 1850 (Fig. 20)[279]. This is no longer just a problem for endangered species and future generations living on island nations. Our disruption of the Earth's climate threatens humanity and the ecosystems that support us[287–289]. Here in the western U.S., human-caused climate change is already exacerbating droughts, decreasing snowpack, supercharging wildfires, and creating unreliable weather patterns[290–292]. For more detail on climate change, check out the resources and readings in BYU's open course: Climate Change Science & Solutions.

Third, extracting, refining, and using fossil fuels causes widespread environmental destruction and immense water consumption[293]. Because the modern economy consumes so much coal, oil, and natural gas, we have to disturb huge amounts of land to extract and transport the fuels—between three and ten-times more land than would be required to produce the same amount of energy with wind and solar[5,27,81]. From mountaintop removal in Appalachia, to the expansive oil fields of Alaska, to the checkerboarded high plateaus of eastern Utah (Fig. 21), the damage to our landscapes is enormous. Some of these disturbed areas can regain some of their ecological function with decades of costly ecological restoration[82], but most of this damage is effectively permanent[83]. The extraction, refining, and combustion of material also is the single largest category of water consumption in the U.S.[293], causing local water shortages and severe water pollution, including radionuclides, heavy metals, and organic pollutants[19,294]. The extraction and use of fissile materials for nuclear power generation cause less damage because nuclear requires less fuel than coal and gas, but it still creates substantial soil and water pollution in vulnerable regions[295].

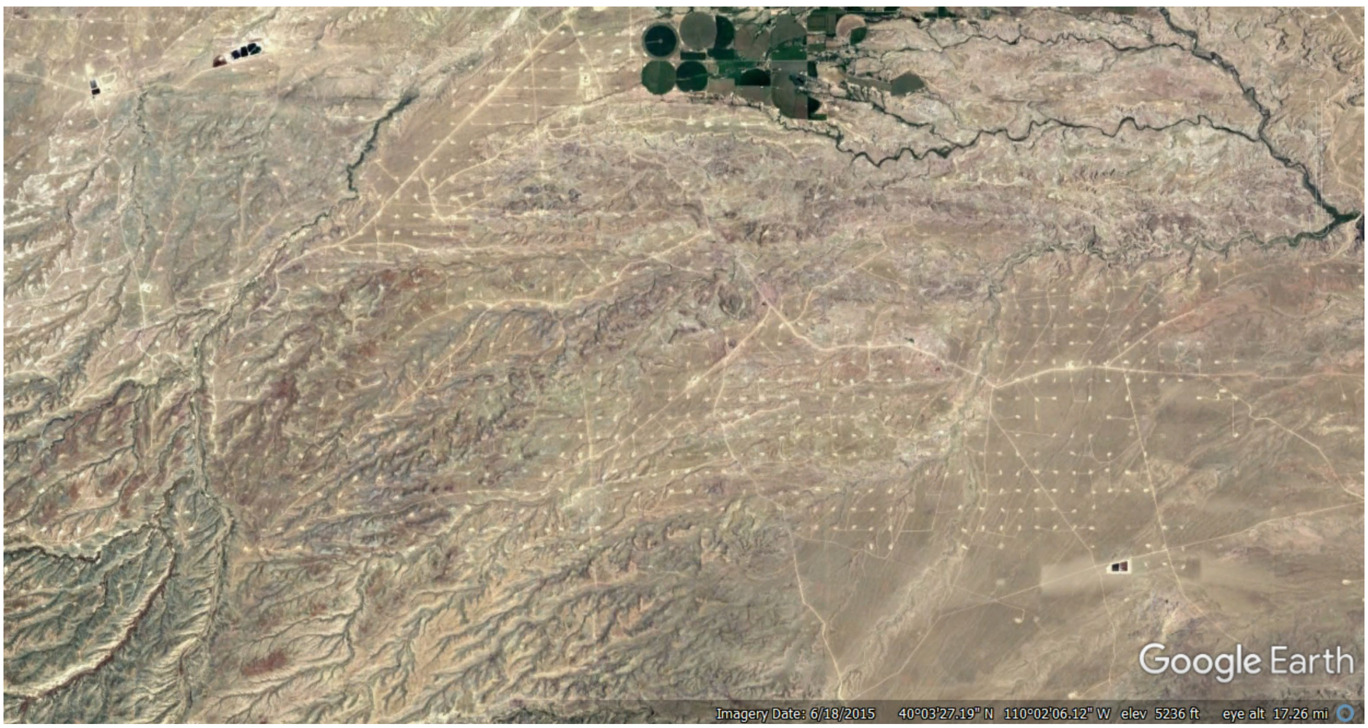

Figure 21. *Abandoned gas wells near the Uinta and Ouray Reservation in northeast Utah. These gas fields have some of the highest leakage rates in the world, losing 7% of the gas during transmission into the pipeline (Lin et al. 2021). Because natural gas is composed of methane and volatile organic compounds, this leakage creates a huge amount of local pollution and causes as much global warming as all the vehicles in Utah combined.*

Fourth, even when we produce our own fossil fuels, interconnections with international supply and demand create fluctuations in gasoline and natural gas prices that negatively affect American families[10,35,199,296,297]. A fully renewable economy will be more secure, healthier, and better protected against foreign energy suppliers and consumers who often do not share American values.

Fifth, fossil fuels are inherently limited and inefficient. Because they are nonrenewable, fossil fuels constrain us to a world of energy scarcity[19]. Indeed, the amount of usable solar energy in a single year is 20-times greater than the energy content in all known and estimated fossil fuel deposits within the Earth (Fig. 22). We currently use 12.4% of total energy just extracting and transporting fossil fuels[5,19], and thermodynamic constraints result in further losses during combustion. This means that of the 100.2 Quads of energy used by the U.S., 68 are lost as waste heat[19]. Contrast these limitations with renewable energy sources, which offer a future of energy abundance and efficiency[5,6]. Wind and solar convert natural energy to electricity directly, bypassing combustion entirely. Electricity is a universal form of energy that can create light, heat, motion, and chemical energy[121]. Together, these advantages allow an electric economy to provide the same services with only 43% as much primary energy[5,19,121]. Additionally, electric infrastructure is quieter, more efficient, and higher performance, offering improved quality of life and a cleaner environment[19].

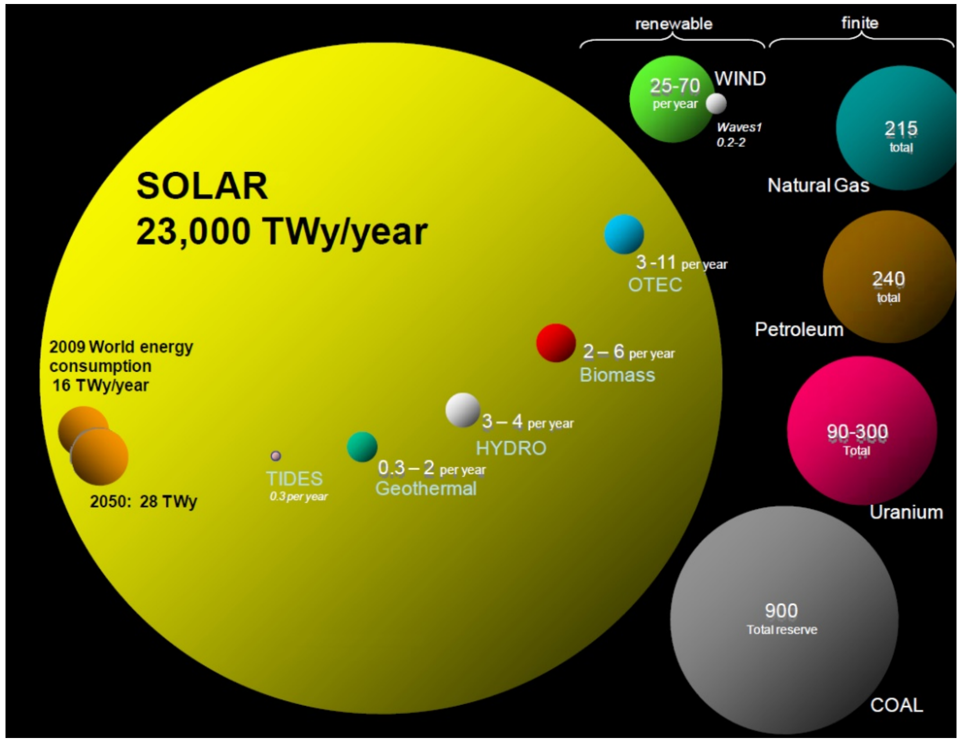

Figure 22. *Comparison of global energy sources. The size of the circle shows the relative abundance of the energy source. Renewable sources are shown in terawatt-years per year, while nonrenewable energy sources are shown in total terawatt-years stored in the Earth. For example, all the coal deposits on Earth only contain 1/26th of the exploitable solar energy that reaches the Earth's surface in a single year. (Perez and Perez 2015)*

In conclusion, while the economic and environmental advantages of clean electrification are compelling, we are most motivated by the moral implications of our energy choices[2,63,298]. We believe it is our duty to leave a clean, healthy, and abundant world for future generations. We invite people of conscience from all backgrounds to work together to create a healthier and freer world through clean electrification.

8. Additional details

The general principles of how to achieve grid stability with renewables are quite simple, but the details are extremely technical. For utility operators and advanced readers, here are some technical resources:

1. The publication database of the National Renewable Energy Laboratory. NREL is run by the U.S. Department of Energy and has technical papers, case studies, and energy transition scenarios for every region of the U.S. They are also collaborate and fund public and private energy projects ranging from individual buildings to state-wide transition plans (partnership opportunities here).
2. The Rocky Mountain Institute (RMI) provides another comprehensive resource spanning the technical, policy and market dimensions of the renewable revolution.
3. GridLab has a deep resource library of renewable case studies from across the country[299]. Their reports cover both project planning and retrospective analysis from municipal to national levels.
4. For a more colorful but still rigorous analysis, Saul Griffith's Rewiring America handbook lays out a technical and economic plan for clean electrification of the entire economy from an engineering perspective. Griffith's new book *Electrify*, by MIT press is even better, but it isn't freely available yet.
5. The 2035 report and supporting resources lay out a granular, nationwide pathway to clean electricity and transportation. They include policy and economic considerations that can be helpful for decisionmakers.

Finally, here are some miscellaneous details that didn't fit neatly in other sections of this report:

Types of energy production. Energy production methods fall into three general categories based on their ability to be ramped up or down: 1. High flexibility energy sources are capacitors, batteries, and hydropower, which can be throttled in seconds to quickly match demand; 2. Medium flexibility energy sources are natural gas peaker plants, solar thermal plants, and potentially enhanced geothermal, which can be ramped up and down in a matter of minutes to meet daily swings in consumption; and 3. Low flexibility energy sources are combined-cycle gas, coal, nuclear, traditional geothermal, and biomass plants, which take hours to throttle and are typically only suitable for baseload applications. Fossil fuel energy systems must maintain high energy inertia because they depend mainly on baseload power that can't be throttled, while renewable energy systems with their flexible backup can function reliably with extremely low inertia, providing resilience and lower costs[49,130,162].

Energy Storage. Storage solutions range from minutes to months, with the cost per unit energy generally increasing with the length of time stored[102,144]. Pumped hydro makes up 95% of global energy storage capacity currently (181 GW of power and 1.6 TWh of capacity), with lithium-ion batteries accounting for the remainder[18,71,140]. Though these two technologies are very different, both can deliver bulk electricity storage economically ($50 to $200/MWh depending on the configuration) with round-trip efficiencies of around 80% for both[18,75,127].

For truly long-term energy storage (seasonal or even multi-annual), high-energy-density fuels can be produced through two complementary methods. The most efficient and already widespread approach is to capture biogas (methane) produced by the decomposition of organic material. Methane is produced during the anaerobic breakdown of crop residues, livestock manure, and sewage sludge (Fig. 23)[77,78,300]. Capturing methane reduces pollution from landfills, feed lots, and wastewater treatments plants, and the gaseous fuel can be easily stored, transported, and used in existing fossil fuel infrastructure.

***Figure 23.** A biogas digestor produces methane at a hog farm in Milford, Utah. (Trent Nelson of the Salt Lake Tribune)*

The second method for long-term storage uses electricity to create energy-dense fuels through "power-to-x" processes. These methods typically start with hydrogen, which can be created through electrohydrolysis (splitting water with electricity) during periods of excess solar and wind production[121,301]. The free hydrogen can then be combined with nitrogen or carbon to create e-ammonia, e-methanol, and more complex fuels for long-distance marine and aviation uses and heavy industry[15,121,301]. Power-to-x applications are quite inefficient, with 75% or more of the input energy lost in conversion compared to only 5 to 20% loss in battery and pumped hydro storage. Later in the renewable transition, this inefficiency isn't a problem because renewable electricity is so cheap and abundant[121,127]. However, even when produced with clean electricity, the combustion of these biofuels and artificial fuels still creates local air pollution and should only be used when other clean energy sources aren't practical[150].

Lowest-cost grids make use of multiple energy transmission and storage solutions, typically depending on transmission and batteries for daily fluctuations, pumped hydro for daily to weekly variability, and biogas and power-to-x methods only when essential[5,6,121,144,154].

> "The internet wouldn't have emerged as it did, for instance, if the FCC hadn't mandated open access for network equipment in the late 1960s. Before then, AT&T prohibited anyone from attaching non-AT&T equipment to the network. The modems that enabled the internet were usable only because the FCC required the network to be open."
>
> *FCC chairman, Tom Wheeler, 2021*

Grid neutrality. The wholesale energy markets that utility companies buy and sell power on generally use dynamic pricing that reflects the cost of production. However, retail markets for consumers often do not. Retail markets charge the same price per kWh regardless of production cost. This is called "static pricing"[79], which can create conflict between rooftop solar producers and utilities, who may pay above-market rates during times of peak production[19,26,65]. This isn't an issue if the government ensures a set purchase price for renewables (a feed-in-tariff), but without government support, static pricing leaves the utility footing the bill for above market prices during part of the day or year. As more distributed energy resources such as rooftop solar and household batteries become available, we need *grid neutrality* to optimize costs and synchronize supply with demand without sacrificing reliability[134,135,302,303]. Analogous to net neutrality, grid neutrality ensures direct and equal participation in wholesale markets, creating a level playing field for all producers and consumers[19,117,134,135,158,303]. Like the open access required of telecommunication companies in the 1960s[304], grid neutrality would change current energy business models and represent a major opportunity for growth. Rather than utilities and power providers acting act as sole producers or "natural monopolies"[134], they would act as brokers of a dynamic network of devices that are producing, distributing, and consuming electricity[65,79,135,305].

Figure 24. An air source heat pump provides heating and cooling more efficiently than a furnace and air conditioner. (Brecha 2021)

Next generation heating and cooling. Heat pumps resemble an air conditioner unit in appearance and operation (Fig. 24). They use compressors to move heat between your house and the air or ground, providing cooling in the summer and heating in the winter at 2- to 6-times the efficiency of a natural gas furnace (efficiencies higher than 100% are possible because electricity is used to move thermal energy rather than create it)[181]. Previous generation heat pumps only operate down to 40°F (4°C)[306], limiting them to the Southeast U.S., where they already account for the most popular heating equipment[307]. However, new, cold-climate heat pumps operate to -13°F (-25°C), and they are rapidly expanding in cold and very-cold regions[179–181,185,307]. In addition to their efficiency, heat pumps create more constant and comfortable conditions compared to natural gas heating, without producing indoor or outdoor air pollution.

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> "Of course, I don't like dictators much myself, but I think the whole country ought to be run by electricity."
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> Woody Guthrie, *Talking Columbia Blues*, 1947