Renewable Energy Analysis
in the Lower 48 States
November 18, 2022

This analysis reviews what it will take to move to a "carbon free" electric grid in the continental 48 states of the United States. It is based on research from generally available sources and does not reach any conclusions regarding the ability to make such a transition, the timeframe that would be required, or the cost do so, including the cost to consumers.

1) Non-coincident peak electric demand – Source Energy Information Administration

   According to the EIA peak demand has reached 790 GW in the lower 48 states. In recent years it has dropped to 704 GW. This represents the peak instantaneous electric demand. To serve all this load, that means we will need renewables and storage to serve this amount of peak demand plus any projected increase in electric demand because of a conversion of transportation and potentially other industries to electric.

   This will require that we build new renewables plus storage in this amount plus a margin to account for unavailability. To do so will require vast amounts of open land.

   Acreage in the United States

   Renewable resources require land for solar and wind resources as well as for storage. The United States has more than 2.4 billion acres of total area (land and water). Alaska accounts for more than 17% of the total acres in the United States. Alaska has more acres than Texas, California & Montana combined. There are only three states with more than 100 million acres of total area in the United States: Alaska, Texas & California.

   Focusing on the lower 48 that means there are 1,996,726,285 acres in the lower 48 states.

   A good percentage of the total land in the United States is already developed and would not be available to be developed for wind, solar, storage. Cities and towns cannot generally be developed for utility scale renewable resources other than installations on parking structures, warehousing, and possible storage. Other developed urban areas can accommodate limited solar on roofs, parking garages, and warehouse facilities. Currently, 66 million acres are considered developed lands in the United States. The total acreage for rural residential is 73 million acres and may support some small solar installations.

   Of the available land, about 349 million acres in the U.S. are planted for crops. This is the equivalent of about four states the size of Montana. This land would not be available for solar since food production is critical for human and animal consumption.

Forest lands comprise 747 million acres. Of these lands, some 501 million acres are primarily forest (minus lands used for grazed forest and other special categories). This land would also be presumed to not be available to be cleared for wind, solar, and storage projects as maintaining forests for photosynthesis and our environment is necessary.

Some 788 million acres, or 41.4 percent of the U. S. excluding Alaska, are grazed by livestock. This is an area the size of 8.3 states the size of Montana. It is presumed a percentage of this land would be available for wind but not for solar as it would most likely remove the land from grazing by larger animals such as cattle herds or horses unless solar is spaced to allow for sunlight to reach the ground to grow the grazing grasses.

This leaves about 900,000,000 acres available for solar development less the area in non-urban areas that already have utility scale solar installations.

For wind, the total number is about 1,111,000,000 acres available for wind farm development less that acreage that has already been used for wind development.

Of course, the numbers for land use by wind and solar are not mutually excusive in that if the land is used by one resource, it will limit the amount of the other resource that can be installed on the same land.

2) Average acreage required by wind and solar resources

Solar

Recently, a city near my house added a 20-acre solar array. It produces 2 Megawatts. Florida Municipal Power Agency just completed a large scale (greater than 100 MW solar installation) and it required 10 acres per Megawatt as well. Another planned installation in Illinois will require 900 acres and produce 100 MW at peak output. Unfortunately, this site is planned on some of the best cropland in Illinois and, in this case, will remove the cropland from production.

According to the Solar Energy Industries Association, depending on the specific technology, a utility-scale solar power plant may require between 7 and 10 acres per megawatt (MW) of generating capacity. A conservative estimate for the footprint of solar development is that it takes **10 acres** to produce one megawatt (MW) of electricity. This estimate accounts for site development around the solar arrays, including for maintenance and site access. Like fossil fuel power plants, solar plant development requires some grading of land and clearing of vegetation. The land required for utility scale solar farms have little useful purpose once the solar is installed beyond grazing by small livestock or very limited crop growth.

Wind

Wind turbines need to be spaced hundreds of yards apart so that the turbulent wake of one does not interfere with another. As a result, just a few wind turbines can cover a very large area. The total area of a single wind project is typically defined as the area within a perimeter surrounding all the turbines within that project. This amount is highly variable depending on the wind farm configuration 87 acres (± 60 percent) per megawatt. However, the land may be used for farming or grazing. Typically, the land cannot be occupied for residential or many other uses due to the possibility of wind turbine blade failures, ice on the blades, noise, etc.

Storage

Battery storage acreage requirements depend on the capacity of the batteries and how long those batteries are expected to supply energy. A good rule of thumb is 1,000 square feet per MWh of battery storage. To date, the largest utility scale battery systems installed are capable of providing the rated MW output for four hours. Storage will need to be designed and added to cover the demand for the expected time that renewable resources are not available.

3) Can we rely solely on solar, wind, storage, and microgrids?

Given that solar takes less space than wind, we can calculate how much land it would require to meet the peak demand assuming the sun is shining everywhere at the time of the peak. Assuming some level of efficiency and using the average of 7.5 acres per megawatt, that means there would theoretically be 833,000,000 acres/7.5 acres per megawatt resulting in a total possible megawatt production of 111,066,667 megawatts if the sun is shining fully across the United States. This would represent 0.6% of the total land mass required for solar to meet the current electric peak demand of 704,000 megawatts given the assumptions above (5,280,000 acres/833,000,000 acres).

For wind, the calculation is 1,111,000,000 acres/60 acres per megawatt resulting in a total possible megawatt production of 18,516,667 megawatts. This would represent 3.8% of the total land mass required for wind to meet the current electric peak demand of 704,000 megawatts given the assumptions above (42,240,000 acres/1,111,000,000 acres).

Wind generating resources have also been installed offshore, so additional wind resources could be built offshore.

Even with this amount of wind and solar, all loads could not be served by these resources without much more wind and solar resources to create energy for the time periods when the wind is not blowing or the sun is not shining or sunlight is not reaching the solar panel (snow or sand covering the panels, for example). This will be significant and will likely require two to three time the amount of wind and solar discussed above with storage or other generating resources.

Solar availability is roughly 25% due to the angle of the sun, cloud cover, and darkness. Wind availability is now reaching 40% on land and better offshore. To serve all the loads all of the time will require the installation of additional wind, solar, and storage resources. This will be discussed further in the section on reliability.

As mentioned earlier, a good percentage of the total land in the United States is already developed and would not be available to be developed for wind and solar.

4) Hydro power and pumped storage

The United States has a total hydropower installed capacity of almost 103,000 MW (103 GW). This comprises about 80 GW of conventional hydropower and almost 23 GW of pumped storage hydropower.

Hydro power is considered as renewable resource; this will reduce the amount of wind and solar required to meet demand.

Storage will become significant with wind and solar. Since these resources are less than 50% available, there will be a need to have significantly more installed wind and solar (intermittent resources) along with sufficient storage to cover any extend periods of low wind or solar production.

5) Nuclear power

Nuclear power in the United States is provided by 92 (originally 94) commercial reactors with a net capacity of 96.6 gigawatts (GW). Nuclear units are available over 93% of the time. Nuclear does not produce carbon dioxide. Nuclear combined with hydro, wind, and solar will further reduce the amount of land required for wind and solar production facilities.

Nuclear power plants historically are fission (splitting atoms to release energy) have been considered as "base load" resources. These resources serve the load that is not peaking in nature and represents the minimum loads that are on the system 24 hours a day. Further, nuclear plants are not generally "cycled" up and down in output as the reactor may not reach the same output level once it's output is reduced.

Two new reactors are under construction and will be on-line in 2023 in Votgle, Georgia. No other reactors are under construction in the United States. Russia is continuing to build reactors and exporting them to other countries. Much of Europe still utilizes nuclear power and have recently announced that new units are being planned.

Interestingly, recycling reactors are commercially viable and could use the waste product from the uranium enrichment facilities. With this fuel, there is currently hundreds of years of fuel stored at these facilities that would meet the entire electric demand of the United States.

Fusion reactors are in the news. However, the plasma in the reactor is contained in a magnetic field and while they are theoretically possible, no commercial scale fusion has been achieved.

Small, self-protecting, reactors are now used elsewhere in the world and some utilities are looking to add them in the United States. These are generally known as Small Modular Reactors (SMRs). They are factory built and have a capability of up to 300 MW. Unlike the historical nuclear reactors, each one is the same design. Historically nuclear reactors were each a unique design and constructed on the utility site. Wolf Creek nuclear was designed to be a repeatable design, but no further such plants were ever built.

Presently, the SMR manufactures are all start-up organizations, and one has a licensed reactor design in the US. These will likely be installed in other countries, especially in countries with little infrastructure like in Africa.

Nuclear generating units will and would provide inertia for grid stability, motor starting, and cold load pickup that will be difficult with inverter-based resources.

6) Reliability

Adequacy of supply

The adequacy of supply is the ability to supply the expected electric demand with the resources provided. Wind and solar have a much lower availability than hydro power or traditional resources due to periods with calm wind conditions limiting wind generation and darkness, sun angle, cloud cover, snow, dust, etc. limiting solar resources. In February of 2021, the Midcontinent Independent System Operator experienced a 72 hour "wind drought" when there was practically no wind generation across all the Midcontinent System Operator's footprint. Of course, Texas was experiencing rolling blackouts over a 10-day period during a week in February of 2021. While traditional generation unavailability played a large role in the event, the grid operator, ERCOT, did not expect for there to be much wind or solar available when the event started due to icing on wind turbine blades and ice/snow covering solar arrays.

To ensure the adequacy of supply, large scale interconnection wide studies will be required to determine how to maintain the current level of reliability if all other carbon dioxide producing fossil resources are retired (coal, natural gas, biomass, etc.). These studies, typically Loss of Load Expectation studies, require defining a typical level of reliability. Historically this has been defined as a one day in ten-year loss of load expectation meaning that all firm loads could not be served on one day once in a ten-year period. With traditional generating resources (fossil fueled, nuclear, hydro) providing high levels of availability and low forced outage rates, reliability in the United States has been excellent. Given that the traditional resources have a high level of availability, or in the converse low unavailability, typical reserve margin requirement have been between 15 and 20 percent. Reserve requirements for a system driven primarily by intermittent resources will need to be determined and include storage availability.

Recent examples of supply shortages in California and Texas during summer and winter conditions highlight the need to perform these reliability studies to determine the amount of reserve that will be required for a system where the demand and energy needs are primarily met by intermittent renewable resources. To maintain a reliable system, it will be necessary to fully understand the supply resource mix including availability during all weather conditions, forced outage rates, partial outage rates, and how non-traditional resources perform during system disturbances, ride through capability, black start capability, etc. including how storage performs and its long-term availability to withstand long periods of wind, solar, and hydro unavailability.

Given that wind and solar are available less than 50% of the time, to provide sufficient system adequacy during a long term periods of wind and solar unavailability, it is likely that multiple times the amount of peak electric demand in terms of wind and solar capacity will need to be installed in order to provide energy for storage systems (pumped storage, battery storage, etc.). This will result in more land usage required for these resources and the storage to provide energy when they are not available.

System stability

Today, the bulk power system is always operating in a stable state, although it can rapidly become unstable. Much of this system stability is produced by the inertia (kinetic energy) of the large rotating generating machines currently installed at fossil generating stations. This kinetic energy is delivered instantaneously to the system during faults (shorts) on the electric grid. This is accomplished through the inertial response when the energy is delivered, and the machine instantly begins to slow down. The traditional resources then can supply additional output from governor response (control action) and Automatic Generator Control response (central control action). Stabilizing torque is critically important and must also be understood.

Solar produces no system inertia and wind has very limited inertia production based on control settings. These resources are supplying the grid through inverters and frequency converters since they are either generating direct current energy or variable frequency energy. Protective relaying designed to clear shorts on the system will not operate properly as presently designed.

As with adequacy of supply, detailed system stability studies, including small signal stability, must be completed to ensure a stable power system during system faults, stuck breakers, and extreme disturbances. Wind, solar, and storage are supplied through inverters. These inverters are computers that operate independently of each other. With traditional resources, harmonics and system oscillations occur but are studied and operating guides put in place to prevent such oscillations. The oscillations can result in blackouts and must be prevented with renewable resources and their inverters as well.

Starting the system from a blackout must also be considered. To do so, batteries may be used. However, those batteries will need to be fully charged at all times to ensure there is sufficient resources to start a system. For example, the 2003 blackout in the Northeastern United States and parts of Canada required a full 30 hours to restore the system. Further, often during black start, the system can collapse again attempting to add loads, large industrial motors, etc. and the process would need to start over.

The impacts of wind, solar, and storage systems must be accounted for and properly modeled, potentially including distribution system resources such as distributed energy resources, microgrids, and localized energy storage. These may be able to supply energy locally, but it is unclear if the larger grid and be started from these distributed resources.

Further, the ability to restart the grid from these resources, including storage, should be evaluated. Typically, wind and solar resources are considered as “grid following” and not as “grid forming” resources. While there is work underway to consider how these resources can become more grid forming, it has yet to be a proven technology in utility scale operations. Batteries may be used to start the system however; those batteries will need to be fully charged at all times to ensure there is sufficient resources to start a system. For example, the 2003 blackout in the Northeastern United States and parts of Canada required a full 30 hours to restore the system. Further, often during black start, the system can collapse again attempting to add loads, large industrial motors, etc. and the process would need to start over.

Work is underway with inverter controls (including battery storage) that will allow the renewable and storage resources to provide some level of stability and possibly blackstart capability. Many inverters are designed to carry rated load current and are not designed to supply fault level currents required to restore systems. Inverter systems designed to be "grid forming" need to be applied, proven, and fully modeled in future systems stability analysis.

Energy Storage

It is clear that energy storage will play a big part in adding more intermittent resources to the grid. How much storage will be the key challenge. Today, even the largest battery systems (185 MW) will supply the grid for only 4 hours. With the examples in Texas and elsewhere, how much storage is necessary will be the key question.

7) Transmission and distribution

The transmission system today was built to deliver capacity and energy from central station fossil, hydro, and nuclear generation to loads primarily in urban centers. These units are large (up to 1300 Megawatts each) often with multiple units at a single site.

Quality wind and solar emissivity are located in limited areas and generally not where the transmission system hubs exist today to move the existing generation. Transmission will need to be developed based on a change in supply resources and their location to reliably deliver capacity and energy from new renewable resources and storage to load centers. Distribution systems, with distributed energy resources and microgrid development will also need to be updated and automated with Advanced Meter Infrastructure. Distribution System Operators and their control centers will need to also be retrained and updated to handle the changes and operate the system reliably.

Given the need for the resources in urban areas to serve the loads, the limited ability to place those resources in urban areas, it is likely more rural areas will push back on having their landscape covered with large wind farms, utility scale solar farms, the transmission to deliver this energy, and possibly large scale storage for the benefit of urban centers. Large amounts of additional transmission will need to be constructed to move this power from these new, very diverse locations.

System shorts are cleared by protective relaying that sense fault currents and opens the appropriate circuit breakers. Traditional generating resources provide inertia and high levels of fault currents; often orders of magnitude greater than load current. Unfortunately, inverter-based resources provide very limited amounts of fault current and stabilizing torque to the overall power system. This will also be challenging when restoring the system or portions of the system following a large-scale blackout. Black start of the system must be considered and plans developed to restart during a blackout including using storage.

Off site power for nuclear plants is also critical as demonstrated at Fukushima in Japan. Plans will need to be developed to serve the nuclear plant safety systems during a blackout to prevent nuclear accidents.

8) Electric Vehicles

Conversion from fossil fueled modes of transportation to electric vehicle transportation will require a massive system upgrade to the Bulk Electric System and to the electric distribution system.

First, a conversion from fossil fuels to electric vehicles, if fully implemented, will likely double the electric energy usage in the Unites States. That would greatly expand the need for renewable resources. Since renewable resources will need to be added in multiple amounts of current electric demand, the same is true if the electric demand is doubled. However, in this case of EVs, they contain storage that could be used as part of the grid solution with sufficient intelligence and communication between the grid operators, both transmission and distribution, and consumers with EVs who are willing to allow their EV batteries to be part of the grid.

The use of electricity to charge vehicles, including tractor trailer trucks, buses, recreational vehicles, and cars and light trucks will require massive upgrades to the system. Simply charging tractor trailers overnight at a truck stop will likely require a supply at truck stops from a higher voltage source than the current distribution to supply the capacity necessary. Charging at hotels and RV campgrounds will also require significant upgrades. For a typical EV with a 300 - 500-mile range, a “fast charger” will be required to fully charge the vehicle in a single overnight.

Residential distribution systems may also need to be upgraded to support a large penetration of EVs charging at home overnight, particularly if consumers move to faster levels of charging. Indeed, most homes may need an upgrade to their electric system as many do not have 120 V dedicated circuits for level 1 charging or 240 V dedicated circuits for level 2 charging capability in their garages. Fast chargers will not be available in residential settings since they require 480 V to charge.

9) Other Options

One option that may not produce as much carbon, would utilize the electric grid as currently constructed with fewer additions, and provide stabilizing torque (kinetic energy/inertia) is the use of hydrogen as a generating fuel. This would require repowering numerous central generating stations, where feasible, along with new renewable resources, is an option that is currently being researched and demonstrated.

Carbon capture would allow some existing plants to continue to operate. Capturing carbon dioxide is technically feasible and stabilizing the carbon and storing back where it came from in an area mined for coal may be possible.

Small scale modularized nuclear is another option that has been researched and should be considered.

Storage options include hydro generation (to offset renewable unavailability), batteries, flywheels, pumped hydro storage, ice, lifting weights, compressed air energy storage, as well as other new emerging technology. All of these will likely be needed to ensure the level of reliability and adequacy that we have become accustomed to and expect for our modern society.

10) Threats

As the system changes, there will be many hurdles to overcome and threats to address. As we rely on more computer-based controls for inverters, residential usage, EV charging and possibly discharging, cyber and supply chain cyber threats must be addressed. Having even one vendor of this equipment with a vulnerability exploited that would shut down these remotely distributed systems would be catastrophic.

Protection from a Geomagnetic Disturbance or an Electromagnetic Pulse will also be critical. Such an event could shut down these systems and render the United States, cities, or even large area without power.

Conclusion

While it is possible to power the United States today with renewable resources based on the amount of land that would be required however, there will be many technical and physical challenges. Conversion of transportation and other petroleum-based systems to electric will require between two and three times the amount of electricity being used today. Many new transmission lines will also be required and will become a land use challenge.

Planning and analysis will be the key and must be completed prior to full implementation. RTO/ISOs today tend to plan based on the interconnection requests (queue) they receive and will need to change that paradigm to forward looking to ensure a reliable and resilient electric supply system. Regulators will need to take action to allow for proper planning, analysis, and return on these investments.