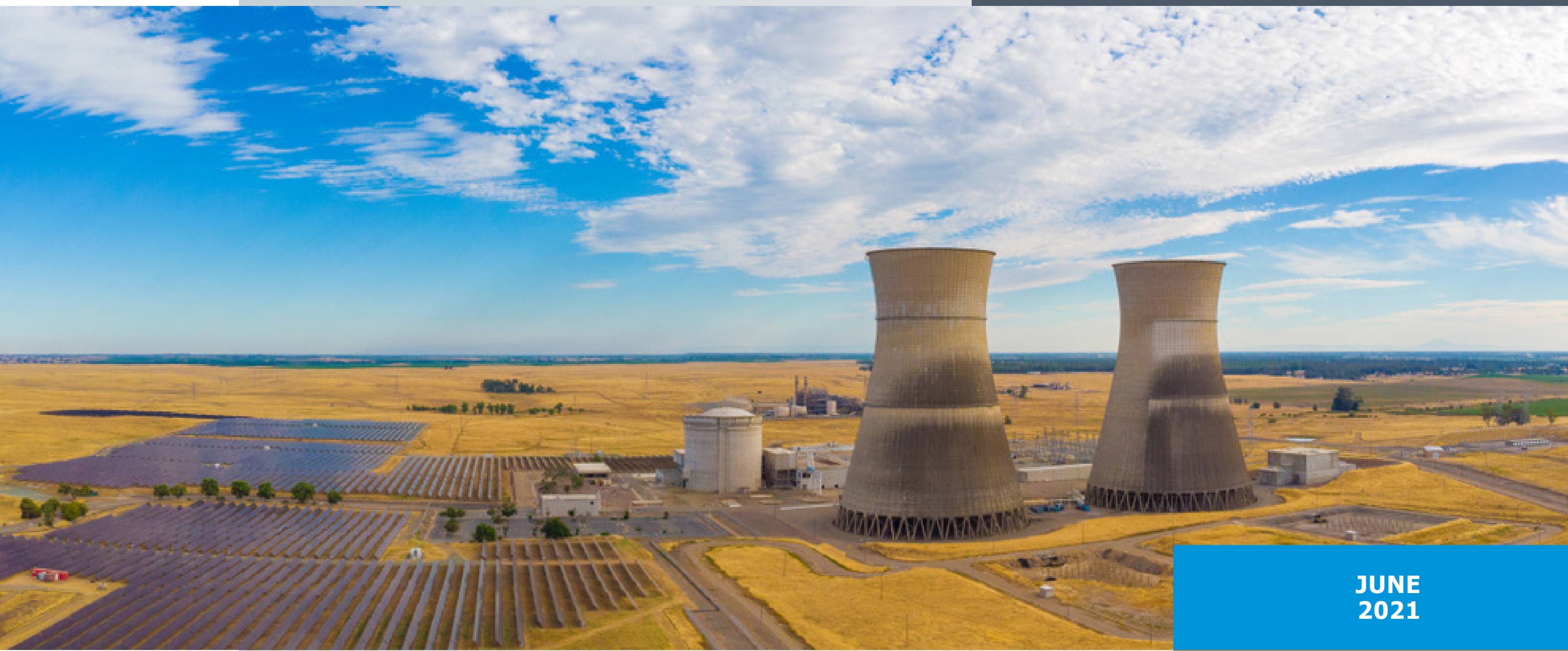
NOTES
DE L'IFRI



JUNE
2021

ifri
since
1979

The Herculean Task of Decarbonizing the American Power System by 2035

Center for Energy
& Climate

Charles MERLIN

The French Institute of International Relations (Ifri) is a research center and a forum for debate on major international political and economic issues. Headed by Thierry de Montbrial since its founding in 1979, Ifri is a non-governmental, non-profit organization.

As an independent think tank, Ifri sets its own research agenda, publishing its findings regularly for a global audience. Taking an interdisciplinary approach, Ifri brings together political and economic decision-makers, researchers and internationally renowned experts to animate its debate and research activities.

ISBN: 979-10-373-0372-1

How to quote this publication:
Charles Merlin, "The Herculean Task of Decarbonizing the American Power System by 2035", *Notes de l'Ifri*, Ifri, June 2021.

Ifri

27 rue de la Procession 75740 Paris Cedex 15 – FRANCE

Tel.: +33 (0)1 40 61 60 00 – Fax: +33 (0)1 40 61 60 60

Email: accueil@ifri.org

Website: Ifri.org

Author

Charles Merlin was for two years the Deputy Counselor for Nuclear Energy at the Embassy of France in Washington for the French Alternative Energies and Atomic Energy Commission (CEA). As such, he realized multiple economic intelligence studies about clean energy (nuclear and renewable) in North America.

He holds a Master's degree in International Energy from Sciences Po Paris and a Master's degree in Plasma Physics from the Université Pierre et Marie Curie (Paris VI).

Abstract

The Biden Administration has so far taken the focus of the Biden candidate on climate issues seriously, especially the commitment made during the campaign of a net zero power system by 2035.

This engagement, reiterated at the April Climate Leaders' Summit, is particularly ambitious. Indeed, even if power related carbon dioxide emissions are decreasing since 2008 in the United States (US), this has been mainly achieved thanks to the still ongoing coal to gas transition enabled by the shale revolution.

Even if wind and solar power have been contributing to last decade's drop in emissions, deep decarbonization of power generation by 2035 will be extremely challenging, if not impossible. Indeed, renewable energy sources face physical limitations, carbon capture and storage (CCS) for power plants is far from mature and the grid itself is not ready and will need massive investments.

Even assuming a flat electricity demand, the task would be particularly difficult. Yet the rush to a net-zero economy by 2050 will push electricity demand as electrification is almost the only tool to reduce directly or indirectly emissions in most sectors like transportation, industry, or heating, no matter the gains in energy efficiency. The spread of digital technologies could also push up demand further.

Decarbonizing the grid will be a Herculean task. Heavy investment in available low carbon technologies such as onshore wind turbines and solar photovoltaics will be needed, but far from enough. A strategy based only on renewables will hit a wall as intermittency, land and material requirements and even public acceptance will probably not allow wind and solar power to satisfy more than 50% of electricity demand. This limit has already been confirmed by the National Renewable Energy Laboratory (NREL) of the Department of Energy (DOE). Moreover, experts and most stakeholders already know that storage will solve these problems only marginally. Indeed, pumped hydro and its huge direct environmental impact face low public acceptance, when batteries and hydrogen are expected to be suitable only as ultra-peakers.

The Biden Administration knows that heavy public support will be needed to trigger investments in new power generation and plans to extend tax deductions for renewable energy sources. Yet it also knows that wind and solar will not be enough and that it could face

strong bipartisan opposition from the many States which would not profit from these energy sources or suffer from fossil fuels phase-out.

This is why President Biden and Energy Secretary Grandholm announced they will multiply private-public partnerships to demonstrate new technologies, especially CCS and advanced nuclear.

As every CCS power plants on the continent have been utter failures so far, nuclear has become attractive as the only firm dispatchable and clean power source that can be expected to be available and reliable.

Utilities already include advanced nuclear in the form of SMR in their resource planification. They know new nuclear will be needed to replace unabated gas power generation in the next decades. Even more, nuclear will probably be needed to phase-out coal nationally as stakeholders are looking for solutions to avoid building new gas power plants after 2025/2030 which could become stranded assets between 2040 and 2050 in a net-zero rush.

Even if the American nuclear industry is just blooming again and if most of its potential will not be available before 2030, it appears that the Federal and local governments want to accelerate the deployment of new reactors, as nuclear can be expected to become a strategical cornerstone for emissions reduction.

These initiatives will not be enough to successfully decarbonize the electricity system by 2035, which looks impossible to achieve within 14 years, but they will drive the American technological leadership on clean energy with an important export potential. This could lead the US not only to net-zero power production in the longer term but also to a net-zero economy by 2050.

Table of contents

Introduction

The CO_2 intensity of power generation in the US has been in decline since 2008, from around 520 grams of CO_2 equivalent per kilowatt hour (gCO_2eq/kWh) to around 390 gCO_2eq/kWh in 2019, a 25% decrease.

Most of this performance has been achieved by the ongoing replacement of coal generation by gas fired power plants, enabled by the American shale boom and large volumes of cheap natural gas.

Over the same period, wind power generation kicked-off, helped by subsidies put in place by the Obama administration and has also slightly contributed to the decrease of coal power generation, with solar having a noticeable impact as well.

More precisely, with total power production staying constant, coal generation has been halved from 2,133 to 1,059 TWh/year, and replaced at 67% by gas, 23% by wind, and 9% by solar. At the same time, the share of hydro and nuclear power remained constant.

Table 1: US Power Generation Indicators, 2002, 2008, 2019

Generation/Year (TWh)	2002	2008	2019
GHG Emissions (gCO_2eq/kWh)[1]	524	517	391
Coal	1,933	1,986	965
Oil	95	46	18
Gas	702	895	1,598
Nuclear	780	806	809
Hydro	264	255	288
Wind	10	55	295
Solar	1	1	107
Biomass	54	55	57
Geothermal	15	15	15
Total Generation (TWh/an)	**3,854**	**4,114**	**4,152**

Source: Energy Information Administration.

In the case of nuclear, operational improvements and the commissioning of Watts Bar 2 (1,165 MWe) in 2016 compensated the closure of eight reactors accounting for 6 electric gigawatt (GWe)

1. Every emission calculation in this paper is based on Intergovernmental Panel on Climate Change (IPCC) average values: 820 gco_2eq/kwh for coal, 650 for oil, 490 for gas, 12 for nuclear, 24 for hydro, 11 for wind, 45 for solar, 230 for biomass and 38 for geothermal.

between 2009 and 2019. The US nuclear fleet, which already performed well, is today running with a 93% capacity factor, a worldwide record.[2]

Historically, only a handful of federal States have been preoccupied by the decarbonization of power generation: California, States in New England, and the State of New York. Yet, their policies have been focused on Renewable Portfolio Standards (RPS – which impose by law that a specific share of the electricity used must come from renewables) and demonstrated relatively poor results in terms of emission decreases because of the simultaneous loss of nuclear capacity due to political bargaining.

In recent years, more States have started to tackle the issue of reducing greenhouse gas emissions (GHG) from the power sector and started implementing Clean Energy Standards (CES). This policy tool works the same way than RPS but includes every clean energy source, not only renewables, as nuclear or fossil fuel with CCS are eligible. To get a broader support, some states with RPS started to shift to a CES model, like California. Even if more local governments are rallying against climate change, only the District of Columbia, Porto-Rico and 21 States have either RPS or CES with targets beyond 2021.[3]

President Biden has now committed to decarbonize the US electricity system by 2035. This is both aimed at meeting the US revised National Determined Contribution (NDC) and at enshrining US climate and technological leadership. Challenges are manyfold: technological, regulatory, economic, institutional. Massive investments will need to be unlocked, not least through the new infrastructure packages planned as recovery measures. While decarbonization will have to be achieved, security of electricity supplies will also remain paramount, and the US is vulnerable to power outages and cyber incidents.

This note assesses the challenges ahead, and how this ambitious target could be met.

2. "Energy Availability Factor", International Atomic Energy Agency, Power Reactor Information System, available at: https://pris.iaea.org.

3. L. Shields, "State Renewable Portfolio Standards en Goals", National Conference of State Legislature, July 7, 2021, available at: www.ncsl.org.

The low-hanging fruits (2020–2030)

The US is already planning for unprecedented financial support measures to build its leadership in low carbon technologies and solutions.[4]

Table 2: FY2022 DOE Budget Requested by the Biden Administration

DOE Applied Energy Programs	FY2021 Budget Enacted (M$)	FY2022 Budget Requested (M$)	Change
Energy Efficiency and Renewable Energy	2,862	4,732	65%
Cybersecurity, Energy Security, and Emergency Response	156	201	29%
Office of Petroleum Reserves	209	218	5%
Electricity (Grid, Transmission, Storage…)	212	327	54%
Nuclear Energy	1,508	1,858	23%
Fossil Energy Carbon Management	750	890	19%
TOTAL	**5,697**	**8226**	**44%**

Note: M$ (million dollars); FY (Fiscal Year).

Source: DOE.

In order to accelerate the decarbonization of the US electricity system, a number of measures can be taken which could have a quick and effective impact.

Preserving current nuclear capacity

Since 2012, eleven nuclear reactors have ceased operations in the US, and at least seven others could close in the next five years. None of these closures are safety related, as they are fully motivated by political calculations (in New England, New York, and California) or economically forced by low gas prices and subsidized intermittent solar and wind production, even if their LCOE is exceptionally low (30 $/MWh).[5] Yet the situation is a big issue for advancing the decarbonization, as the American grid already lost more than

4. Statement by Energy Secretary Granholm on the President's U.S. Department of Energy Fiscal Year 2022 Budget, May 28, 2021, available at: www.energy.gov.
5. LCOE (levelized cost of energy). See J. Conca, "Communities Surrounding Closed Nuclear Power Plants Face Terrible Challenges Moving Forward", *Forbes*, October 25, 2020, available at: www.forbes.com; H. Desai, *Nuclear by the Numbers*, Nuclear Energy Institute, August 2020, available at: www.nei.org.

70 TWh/year of clean nuclear generation potential, a number which will grow to at least 130 TWh/year in 2025, if nothing is done.[6]

Worse, many of these reactors were critical for the grid stability and reliability as dispatchable generation. California, which already experienced blackouts, and now New York City are rushing to build new gas power plants to compensate for politically motivated closures.[7] These new fossil fuel units will be there for at least 20 years and will make any long term decarbonization targets extremely difficult to attain.

Confronted with this situation, the Biden Administration seems inclined to create federal subsidies called Zero Emission Credits (ZEC) for economically struggling nuclear power plants, to keep as much clean generation as needed.[8] It can capitalize on successful local programs, like the one put in place by New Jersey, which created a 10 $/MWh ZEC for its plants running from 2019 to at least 2025.[9] Federal ZEC have bipartisan support and could be in place by 2022 or 2023. In association with 80 years license renewals, most of the current nuclear capacity will probably be preserved.

Grid modernization

The Biden "Infrastructure" Plan calls for 100 G$ to be invested by the federal state in the grid modernization,[10] mostly to repair out of shape existing lines (California), but also to build at least 20 GW of new ones. They will allow more interstate power exchanges, but also link consumers to distant areas with high solar and wind potential.

This small overhaul of the American power grid will be especially instrumental for the Coastal States to attain their goals. The think-tank "Americans for Clean Electricity Grid" (ACEG) has published a report evaluating which lines projects could profit from this 100 G$ financing.[11]

6. Derived from the last full year production data of closed or closing plants since 2012. See the "Database on Nuclear Power Reactors", International Atomic Energy Agency, Power reactor Information system, available at: www.pris.iaea.org.
7. S. Johnson, "New York's Indian Point nuclear power plant closes after 59 years of operation", US Energy Information Administration, April 30, 2021, available at: www.eia.gov.
8. A. Natter, "White House Backs Nuclear Subsidies That Split Climate Advocates", Bloomberg, May 5, 2021, available at: www.bloomberg.com.
9. S. Dolly, "New Jersey Utility Board Extends ZEC Subsidies for PSEG Nuclear Plants", April 28, 2021, available at: www.spglobal.com.
10. S. Patel, "Heavy Push by Industry, Biden Administration to Jumpstart Transmission Expansion, Grid Modernization", *Power*, April 29, 2021, available at: www.powermag.com.
11. M. Goggin, R. Gramlich, and Michael Skelly, *Transmission Projects Ready to Go: Plugging Into America's Untapped Renewable Resources*, Americans for a Clean Energy Grid, April 2021, available at: www.cleanenergygrid.org.

Table 3: Key Electricity Interstate Interconnection Projects

Project Name	Region 1	Region 2	Length (Miles)	Maximum Power (MW)	Estimated Cost (M$)
New England Clean Energy Connect	Quebec	Maine	145	1,200	950
Champlain Hudson	Quebec	New York	330	1,000	2,200
NE Clean Power Link	Quebec	Vermont	150	1,000	1,600
Lake Erie Connector	Ontario	Pennsylvania	73	1,000	1,000
Southern Cross	Texas	Mississipi (through Louisiana)	400	2,000	1,400
SOO Green	Iowa	Illinois	350	2,000	2,500
Cardinal – Hickory Creek	Iowa	Wisconsin	100	1,300	520
Grain Belt Express	Kansas	Indiana (through Missouri and Illinois)	780	4,000	2,300
Plains and Eastern Oklahoma	Oklahoma (SPP)	Tennessee (through Arkansas)	700	4,000	2,500
Transwest Express	Wyoming	Nevada (through Utah to the Southwest)	730	3,000	3,000
Gateway South	Wyoming	Utah (to the Southwest)	400	1,500	1,900
Gateway West Boardman to Hemingway	Wyoming	Oregon (through Idaho)	1,300	3,000	4,080
Greenlink	Nevada	California	586	1,525	2,410
Ten West	Arizona	California	114	3,500	300
Sunzia	New Mexico	Arizona	515	3,000	1,500
Southline	New Mexico	Arizona	240	1,000	800
Colstrip Upgrades	Montana	Washington	500	200	227
Total			**7,413**	**34,225**	**29,187**

Source: ACEG Report.

In summary, they are motivated by three major dynamics:

- Increasing the connection between Quebec and New England/New York. These last states will need Quebec hydroelectricity and pumped storage to attain their goals as they will massively lack firm and clean capacity.
- Creating a real interconnected grid in the West, from the Rockies to the Pacific, which would allow solar farms in New Mexico & Arizona and wind turbines in Wyoming and Colorado to supply California and Oregon, which already have an electricity deficit.
- Linking the windy Great-Plains with the more populated Great Lakes and Mississippi regions.

These interstates connection would be associated with some big intrastate projects supporting local renewable developments, especially in upstate New York and Colorado.

Table 4: Major Intrastate Connector Projects

Project Name	Length (Miles)	Estimated Cost (M$)
New York State Connectors	365	2,730
Colorado's Power Pathway	560	1,700
Total	**925**	**4,430**

Source: ACEG Report.

In total, the construction of these lines before 2025 would cost around 35 G$ and enable the development of around 60 GW of onshore wind and solar generation in the US.

Hydro Quebec will be a big winner, with an increase of 4.2 GW of its export potential to the North-Eastern US.

Yet, such initiatives will have a marginal impact on the GHG emission of the US electricity system. Even with world class capacity factors for solar and wind farms, these investments will not put more than 200 TWh/year on the grid.[12] US fossil fuels power generation in 2019 was 2,600 TWh.

In the end, these projects cover indeed only 10% of the transmission lines investment needed to decarbonize the US grid.[13]

An indispensable solar and wind boom

Maintaining the subsidies

The Biden Administration will propose to Congress a 10-year extension of the Production Tax Credits (PTC) and Investment Tax Credit (ITC), the indirect federal subsidies needed for solar and wind farms to be competitive, in complement of various local subsidies schemes.

Table 5: Current Wind PTC and ITC

Year of Construction Commencement (Can claim either the PTC or the ITC)	Wind PTC / Apply for the first 10 years of operation	Wind ITC (percentage of eligible cost) if in-service before 12/31/2025
2016 (or earlier)	25 $/MWh	18%
2017	20 $/MWh	18%
2018	15 $/MWh	18%
2019	10 $/MWh	18%
2020	15 $/MWh	18%
2021	15 $/MWh	18%
2022 and onwards	0 $/MWh	0%

Source: DOE

12. In the US, solar has a 25% average capacity factor, and wind has a 40% one. Calculation: 60 GW with an average capacity factor of 33% would produce 200 TWh/year.
13. NREL estimation in the ACEG report.

Table 6: Current Solar ITC

Year of Construction Start	ITC (percentage of eligible cost) if in-service by 12/31/2025
2019 (or earlier)	30%
2020	26%
2021	26%
2022	26%
2023	22%
2024 and onwards or Didn't make the in-service deadline	10%

Source: DOE.

The goal is to push for a boom during the decade, wind and solar lobbying groups targeting around 250 GWe of wind capacity (30 GWe offshore included) and 420 GWe of solar.[14] Yet solar and onshore wind installations may face multiple issues in the coming years:

- A growing part of the new capacity would have to compensate for retiring farms.
- The best areas are already well developed, and the land and transmission requirements could face public acceptance challenge similar to those in European countries.
- Demand for minerals could soar, leading to rising deployment costs.
- The grid costs can increase sharply when too many intermittent sources are online.
- It is highly probable that Local Content Requirements (LCR) will be imposed for solar and wind farms components and transmission. At best, it will make the costs hit a plateau, at worst it could even increase them, as the use of cheap imported components, often from China, may no more be allowed.
- The recognition of the decommissioning and recycling costs could also impact the sector as the end of life for the first solar panels and wind turbines will come in the next ten years.

Without taking into account most of these challenges, the EIA already forecasts that US solar and onshore wind's LCOE in the next five years will decrease to around 32 $/MWh before staying constant around this level.[15] The cost of PV already increased by 18% since the beginning of 2021.[16] In other words, the sharp decline in cost experienced during the last decade is probably coming to an end, and

14. See Table 8 and associated footnotes.
15. U.S. Energy Information Administration, "Levelized Costs of New Generation Resources in the *Annual Energy Outlook 2021*", available at: www.eia.gov.
16. D. Murtaugh and B. Eckhouse, "Solar Power's Decade of Falling Costs Is Thrown into Reverse", *Bloomberg*, May 24, 2021, available at: www.bloomberg.com.

it may be that an average LCOE under 25 or even 30 $/MWh could not be possible with higher penetration rates.

Offshore wind

The Biden Administration has announced big ambitions for offshore wind, with a goal of at least 30 GW in operation by 2035.[17] These objectives are in adequation with local ones. New England, New York and Virginia have been bullish about offshore wind, as they lack consistent solar and onshore wind potential and as spare hydroelectric capacities in Quebec will already be put in use at their fullest in the next years. For the time being, the US is still a very small player in the segment, as it currently accounts for only 42 MW of offshore wind turbines in operation, all of them from pilot projects.

Table 7: Offshore Wind Targets by Federal States

State	Offshore Wind Targets
Massachussets	800 MW by 2023 1,600 MW by 2025 4,000 MW by 2027
Connecticut	2,000 MW by 2030
New York	9,000 MW by 2035
New Jersey	3,500 MW by 2030 7,500 MW by 2035
Maryland	1,200 MW by 2030
Virginia	2,600 MW by 2026
Biden	**30 GW by 2030**

Source: States' RPS and Permitting.

Table 8: Offshore Wind Projects in the US

State	Offshore Capacity (MW) in 2026 from existant projects
Massachussets	1,600
Rhode Island	700
Connecticut	800
New York	3,100
New Jersey	1,100
Maryland	370
Virginia	2,650
North Carolina	800
TOTAL	**11,120**
Transmission Costs (M$) Estimation (762 $/kW)	8,473

Source: States' RPS and Permitting.

17. The White House, "Biden Administration Jumpstarts Offshore Wind Energy Projects to Create Jobs", *Statements and releases*, March 29, 2021, available at: www.whitehouse.gov.

If offshore wind farms have a large potential, they are expensive (the EIA puts their total system LCOE at 115 $ / MWh in 2026)[18] and still come with intermittency challenges, even if they are more reliable than their onshore counterparts (which have much cheaper system LCOE estimated at 31.45$/kW in 2016 by the EIA) and allow for the localization of large parts of the supply chain. The cost of linking the windfarms to the mainland (estimated at 762 $/kW in 2019),[19] which could be financed by the "Infrastructure Plan" for the first commercial scale installations, will probably not decrease in the next years as the best spots and low-hanging fruits cost reduction opportunities (like reusing decommissioned plants grid connection) will already be plucked.[20] Moreover, offshore wind farms already encounter social acceptability issues. As an example, the governor of Maine, a state with a promising seashore, is already siding with fishermen to put in place a 10-year moratorium on any projects.[21]

Finally, offshore wind may increase electricity costs in the regions which already experienced some of the highest tariffs in the country and any increase in federal subsidies could be a major political issue as it concerns only rich and democrat-run coastal states.

Floating offshore is not off the table but would be even more expensive until large projects are rolled out in Europe and Asia. Yet California is thinking about a demonstration on its seashore with heavy federal financial support.[22] What is clear is that the US could benefit from the European experience in offshore wind planning, consultations and development in order to smooth project development and reduce costs. Participation of European offshore wind champions (Orsted, Engie, EDF, Total, Shell, EDP, Iberdrola) in US tenders will certainly help to kick start this new industry efficiently.

18. U.S. Energy Information Administration, "Levelized Costs of New Generation Resources in the *Annual Energy Outlook 2021*", *op. cit.*

19. T. Stehly, P. Beiter, and P. Duffy, *2019 Cost of Wind Energy Review*, NREL, December 2020, available at: www.nrel.gov.

20. The example of a New Jersey offshore wind farm project connected through the closed Oyster Creek nuclear plant : R. Walton, "Offshore Wind Farm Could Connect to Retired Oyster Creek Nuclear Plant", *Power Engineering*, September 19, 2019, available at: www.power-eng.com.

21. E. Penrod, "Maine gov. Proposes Offshore Wind Moratorium Amid Tensions with Fishing Industry", *Utility Dive*, January 27, 2021, available at: www.utilitydive.com.

22. J. Calma, "Joe Biden Opens Up California Coast to Offshore Wind", *The Verge*, May 25, 2021, available at: www.theverge.com.

Other renewables will probably not play a role

There is around 1,550 MWe of geothermal capacity installed for power production in the US. There is only 170 MWe of planned new capacities and the production will not increase noticeably in the next years.[23] California has ongoing debates about a more intensive use of geothermal power, but the environmental and economic costs are an issue to deploy more capacity. At best, 2,000 MWe additional capacity could be put in operation in the Salton Sea, probably just enough to cover the lithium extraction and refining associated to any project.[24]

Hydropower will not grow either in the US in the next few years. In fact, it could even decrease as more and more dams are removed due to environmental concerns.[25] Indeed, hydropower in the country faces a social acceptance problem, especially with the increasing recognition of Native American tribes' land rights. Even with indirect subsidies, there are no proposals for new facilities, which would add clean firm capacity and generation.

The intermittency challenge

The Texas blackouts in February 2021 resulted from extremely harsh weather conditions (snow and freezing temperatures), low availability of non-winterized gas fired plants and wind turbines on a poorly maintained grid. It demonstrated that even in one of the best places in the world for wind turbines, availability factors could drop under 3% during peak load.[26] Indeed, summer and winter peaks are strongly correlated with anti-cyclonic conditions when winds do not blow. Winter peaks are even trickier, as they always come during the night.

System costs increase strongly with a 30% intermittent sources penetration rate, as already seen in New England and California, and become clearly prohibitive at 50% or more. Indeed, intermittent plants tend to cannibalize each other.

The NREL has assessed that when the declining value of variable generation is taken in account, only 1,500 to 2,000 TWh/year of

23. S. Roth, "California Needs Clean Energy After Sundown: Is the Answer Under Our Feet?", *Los Angeles Times*, January 20, 2020, available at: www.latimes.com.

24. S. Roth, "Lithium Start-up Backed by Bill Gates Seeks a Breakthrough at the Salton Sea", *Los Angeles Times*, January 20, 2020, available at: www.latimes.com.

25. J. Thomas-Blate, "69 Dams Removed in 2020: Nothing Restores a River Like Removing a Dam", American Rivers, February 18, 2021, available at: www.americanrivers.org.

26. ERCOT (Texas Grid Operator) data; S. Patel, "ERCOT Lists Generators Forced Offline During Texas Extreme Cold Event", *Power*, March 4, 2021, available at: www.powermag.com.

renewable energy could be competitive in the next decade.[27] That covers only 35% to 50% of the current US power consumption.

Table 9: Wind and Solar Generation (TWh/year)

Year	Wind	Solar[28]
2008	56	1
2019	303	93
2030 (high estimate)	700[29]	585[30]
Maximum Renewable (NREL)	870	890

Source: EIA, wind and solar lobbying groups and NREL (see footnotes).

Solar and wind will not be enough to decarbonize the grid. Even with a 1% consumption growth (4,600 TWh/year in 2030), the 1,760 TWh/year production with economical maximal penetration calculated by the NREL and a 2030 coal phase-out would just halve the US grid emissions intensity from around 391 gCO_2eq/kWh in 2019 to around 194 gCO2eq/kWh. This is a best-case scenario, as rapid electrification of the economy could imply a massive 5,500 TWh/year electricity consumption by 2030.[31]

Table 10: 2030 Grid Emissions Scenario

Year	GHG Emissions (gCO_2eq/kWh)	Wind (TWh/year)	Solar (TWh/year)	Total Generation (TWh/year)
2019	391	295	107	4152
2030 (coal and oil phase-out) High Renewable Reference Scenario (See table 8)	242	700	585	4586
2030 (coal and oil phase-out) Maximum Renewable Penetration (See table 8)	194	870	890	4586

Source: NREL.

Quick deployment of solar and wind can help to phase out coal and cut emissions in a relatively fast but costly way, reinforcing the trend since over the past years, but their inherent limitations make them not enough to enable real decarbonization of the American power grid.

27. A. Brown *et al.*, *Estimating Renewable Energy Economic Potential in the United States: Methodology and Initial Results*, NREL, August 2016, available at: www.nrel.gov.
28. Concentrating Solar Power (CSP) Plants are marginal and will stay marginal. As such "solar" is in fact 99% solar photovoltaics in the US.
29. Estimation from S&P Market Intelligence: 255 GW in 2030 at 40% capacity factor.
30. Estimation from McKenzie/SEIA: 420 GW in 2030 at 25% capacity factor.
31. D. Steinberg *et al.*, *Electrification & Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization*, NREL, July 2017, available at: www.nrel.gov.

The Impossibility of a Zero-Carbon Grid in 2035

Storage

Some solar & wind supporters argue that storage coupled to intermittent sources could "transform" them in firm power capacities. Yet, there are multiple issues for these three major technologies which will be difficult, if not impossible, to overcome.

Pumped hydro storage

The only mature grid-scale electricity storage technology available is pumped hydro storage, which is basically a reversable dam. The US currently harbor 22 GW of pumped hydro storage capacity. These massive installations suffer of the same environmental and social acceptability problems than classical hydropower, discussed above.

The New England and New York Hydro-Quebec scheme is basically the only relevant planned use of the technology. Very profitable for Hydro-Quebec, it consists of low-cost wind and solar generation imports to fill Canadian dams associated with high prices firm hydropower generation exports to the US when the intermittent sources cannot produce.

Yet even this plan is limited by dam and transmission lines construction issues. Hydro-Quebec has only around 2 GW of new hydropower planned,[32] and the new capacity, if allowed, would probably be online after 2035 at best.

Pumped Hydro Storage is by far the most mature storage technology and represents the only long-duration (which can cut a bit of semi-baseload capacity) systems available.

Battery storage

Grid-scale battery storage is a trendy topic, gaining technological maturity. They are not suited to compete with baseload and semi-baseload due to obvious limitations in matter of storage capacity (the best systems can handle an 8 hours full-power discharge at best) and life expectancy issues (the frequency and depth of charge & discharge

32. Two projects: Petit-Mecatina and Magpie.

cycles can burn a battery in either two years or ten years).[33] Yet they offer an interesting value proposition as ultra-peakers.

Indeed, battery storage will probably stay expensive but could be competitive against the older and less economic gas peaker plants in the years to come, especially when combined with solar surpluses.

As such, they will help to cut an extremely small and marginal share of the carbon emissions. Indeed, as gas peaker plants are not functioning 95% of the time, they are not massive emitters.

The NREL evaluates the maximum potential for economic battery storage to be between 28 and 50 GW of ultra-peak demand.[34] Most of it comes from highly urbanized areas where pollution is also an important factor and peak load can be particularly spiked. The current US noncoincident peak load is 770 GW.[35]

Some American States have already put in place targets in the matter and the Biden administration is proposing a 26 to 30% ITC for standalone battery storage installations.[36]

Table 11: Battery Storage Capacity Targets by States

State	Battery Storage Targets
California	1,325 MW by 2024
Nevada	1,000 MW by 2030
Massachusets	1,000 MW by 2025
New Jersey	2,000 MW by 2030
New York	1,500 MW by 2025 3,000 MW by 2030
Virginia	3,100 MW by 2035
Connecticut	300 MW by 2024 650 MW by 2027 1,000 MW by 2030

Source: States' RPS[37].

Hydrogen and power-to-gas-to-power

Hydrogen or synfuel could be used in fuel-cells or retrofitted gas plants. Yet, to be carbon neutral, the fuel has to be synthesized with primary energy from nuclear or renewables. Power-to-Gas-to-Power

33. K. Smith *et al., Life Prediction Model for Grid Connected Li-ion Battery Energy Storage System Preprint,* NREL and SunPower Corp., August 2017, available at: www.nrel.gov.
34. P. Denholm *et al.*, The Potential for Battery Energy Storage to Provide Peaking Capacity in the United States, NREL, June 2019, available at: www.nrel.gov.
35. Source: EIA
36. J. Plautz, "Biden Budget, Infrastructure Plan Would Create Standalone Storage Tax Credit", Utility Dive, April 13, 2021, available at: www.utilitydive.com
37. J. Burwen, "Energy Storage Goals, Targets, Mandates: What's the Difference?", Energy Storage Association, April 24, 2020, available at: www.energystorage.org.

(P2G2P) is a storage solution which will probably compete with battery for peaking purposes, but hit similar issues and is technologically further down the road. Currently, electricity from hydrogen has an estimated LCOE of 140 $/MWh at best in 2030.[38] Just enough to compete with the less economic peaker plants.

Therefore, it appears than apart from pumped hydro, storage solutions will stay in the ultra-peak niche market. Ultra-high temperature electricity storage may nevertheless slightly charge this picture if current projects can be developed at large scale.

Gas, a treacherous bridge in the US energy transition

The new build paradox

If solar and wind will contribute to a significant decrease in GHG, natural gas will still be the major coal replacement and power any reindustrialization or transport electrification.

Often introduced as a "bridge" energy between the current situation and a low carbon one, it is a treacherous one.

First, its costs are volatile. Indeed, before the shale boom, gas prices have heavily swinged. To rely massively on gas for power creates important volatility in power prices, even more when coupled with intermittent sources. The first one creates intra-year volatility, when the latter ones provoke intraday volatility. Even if the shale gas has led to historically low costs for gas fired power generation, it relies on the shale industry regulations and economics of shale oil production. The prospection bans on Federal lands put in place by the Biden administration could increase fuel costs in a decade, alongside greater green finance pressure on banks and industry.[39] Social acceptance of fracking could also drop even more in the next years and regulation could make this industry less and less competitive, which of course, also depends on the future oil production and their economics, since gas is often associated. One key condition for the competitiveness of gas is the further development of the gas grid, which could prove tricky in the future.

Second, emissions from gas fired power generation could be reevaluated, as more and more comprehensive studies indicate that the IPCC 490 gCO_2eq/kWh is underestimated due to methane leaks.

38. S. Patel, "How Much Will Hydrogen-Based Power Cost?", *Power*, February 27, 2020, available at: www.powermag.com.
39. C. Eaton, "Biden's Order to Freeze New Oil Drilling on Federal Land: What You Need to Know", *The Wall Street Journal*, January 27, 2021, available at: www.wsj.com.

The real figure could be around 630 gCO_2eq/kWh with a probable 1.4% methane leak rate,[40] or even worse (930 gCO_2eq with a 3.5% leak).[41] Such figures could make a coal to gas transition much less efficient on the climate front than expected. Just to give an idea of the impact, the American grid emissions in 2019 were around 391 gCO_2eq/kWh. With such a reevaluation, it would in fact be around 445 gCO_2eq/kWh.

Finally, any new gas plants will have a lifetime expectancy of 25 to 30 years. As such, any installation built between 2020 and 2030 lead to an expected closure date between 2045 and 2060. If the goal is to decarbonize the grid in 2045 (the unrealistic target of 2035 would be even worse), then virtually every new gas plant built from now on, which has no optionality to be coupled with CCS, or later turned into burning ammonia or biomethane, must become at some point a costly stranded asset. It creates a paradox: if any decarbonization target would be taken seriously by utilities, then they should not replace any coal plant by gas generation. Yet this is realistically the only available tool to do so and attain a coal phase-out in the next ten years. So, the only serious possibility to be considered is to plan for future abatement of gas fired power plants: either with CCS, or in retrofitting them to absorb ammonia for example (which will work for ultra peaker plants as ammonia is produced with H2). In the meantime, the economic of gas fired power generation could face challenges for lower running hours due to the penetration of renewables and grid scale battery storage.

In some areas, public acceptance is dropping quickly for new gas capacity, and it has become clear that new builds will have to stop in the next years to hit a decarbonized grid in 2045/2050.

Table 12: Coal and Gas Power Generation in 2030 in Different Scenarios

Year	GHG Emissions (gCO_2eq/kWh)	Coal (TWh/year)	Gas (TWh/year)	Total Generation (TWh/year)
2019	391	965	1,598	4,152
2030 (coal and oil phase-out) High Renewable	242	0	2,132	4,586
2030 (no new gas fired generation) High Renewable	280	534	1,598	4,586

Source: NREL.

40. Value estimated by the Environmental Protection Agency (EPA): D. A. Kirchgessner *et al.*, *Estimate of Methane Emissions from the U.S. Natural Gas Industry*, available at: www.epa.gov.

41. As calculated in another study: R. A. Alvarez *et al.*, "Greater Focus Needed on Methane Leakage from Natural Gas Infrastructure", PNAS, April 24, 2012, available at: www.pnas.org.

Carbon capture and storage

CCS is currently a heavy topic in current political discussions in the US. Indeed, it is a major bargaining item for the Biden administration to get bipartisan support for its climate policies as democrat and republican congressmen from coal and gas regions want more financial support for technologies which they believe could allow fossil fuel industries to run longer even with more stringent regulations.

Yet, the technology is far from maturity and filled with uncertainties. There are currently only 26 infrastructures with CCS around the world and 88% of the CO_2 "used or sequestered" is used for oil and gas enhanced recovery (EO&GR),[42] an obviously unsustainable scheme in a net zero economy. Only two commercial power plants in the western world (in Canada and US) have been equipped with CCS systems. Both are coal plants and have been loss-making. The first one, Boundary Dam in Saskatchewan created a 1 G$ loss for SaskPower.[43] The second one, Petra Nova in Texas, has been mothballed in February 2021 after missing every technical and cost target during its first three years of operation and being idled during 2020.[44] Even worst, the Kemper project in Louisiana, originally a 582 MW coal syngas power plant equipped with CCS, has been converted to a classical gas plant named Ratcliffe after 7.5 G$ have been spent on it, which make it the most expensive power plant ever on a $/MW basis.[45]

A fossil fuel plant equipped with CCS could see its fuel cost increase up to 136% to produce the same electricity for the grid, as the process needs heavy amount of power.[46] Such loss in total efficiency makes the system uneconomical, especially if fuel cost increase in the future. The capital and maintenance costs are also problematic. A high carbon price, or subsidies, will be needed to operate this technology at large scale, although deployment costs are also expected to decrease once scaling up happens. Moreover, there are currently uncertainties about how long the CO_2 will stay in the ground without leaking in the atmosphere and how much of it can really be captured.

42. D. Roberts, "Could Squeezing More Oil Out of the Ground Help Fight Climate Change?", Vox, December 6, 2019, available at: www.vox.com.

43. B. Burton, "The fallout from SaskPower's Boundary Dam CCS debacle", *Renew Economy*, November 12, 2015, available at: www.reneweconomy.com.au.

44. N. Groom, "NRG to Mothball Gas Plant that Powered Petra Nova Carbon Capture Project", Institute for Energy Economics and Financial Analysis, February 1, 2021, available at: www.ieefa.org.

45. K. E. Swartz and C. Anchondo, "Another Kemper? Utilities Struggle with Next Phase of CCS", *E&E News*, June 25, 2020, available at: www.eenews.net.

46. S. D. Supekar and S. J. Skerlos, "Reassessing the Efficiency Penalty from Carbon Capture in Coal-Fired Power Plants", *Environmental Science and Technology*, Vol. 49, Issue 20, September 30, 2015, available at: www.pubs.acs.org.

As such, CCS for power plants is currently technologically unproven and economically unattractive.

The need for nuclear and the rise of Small and Modular Reactors (SMR)

Without large scale CCS deployment at power plants, or massive build of new dams and geothermal plants, there is only one clean energy source which is dispatchable and can replace baseload fossil fuel generation: nuclear power.

Yet, as the rest of the Western world, the US are confronted to the same issues: the loss of know-how has been critical and led to construction failures. The two Vogtle's AP1000 in Georgia (2.3 GWe) went over budget and will start operation in 2022, more than ten years after the construction started.[47] At best, only four other large American reactors (4.7 GWe),[48] mothballed, could start before 2030. This would be just enough to compensate the last plant closures.

Facing this situation, the industry is operating a paradigm shift and going all-in on Small & Modular Reactors (SMR). These units would be able to generate between 50 and 350 MWe and could be factory produced and assembled. It will make their financing easier.[49] Moreover, they could be deployed very quickly and installed on decommissioned fossil fuel power plants.[50] They are technologically proven, as pretty much every concept family has been built as research reactors or even commercial ones.[51] Many of them could even be competitive as peaker plants thanks to molten salt thermal storage.[52]

These characteristics make them well-suited to replace baseload coal generation, and major utilities such as Energy Northwest, Pacificorp, TVA, Duke, Exelon, Xcel, or Dominion are already planning to use them to phase-out coal by 2035 and minimalizing the number of new gas power plants which would become fatally stranded assets.[53] It will be essential that there is continued and robust

47. Total cost estimated at 25 G$ in 2021 against 14 G$ in 2012.
48. V.C. Summer 2 & 3 and Bellefonte 1 & 2.
49. "Benefits of Small Modular Reactors (SMRs), Office of Nuclear Energy", available at: www.energy.gov.
50. T. Gardner, "Shut U.S. Coal Plants Seen as Potential Sites for Small Reactors", Reuters, April 28, 2021, available at: www.reuters.com.
51. P. Samanta, D. Diamond, and W. Horak, "Regulatory History of Non-light-water Reactors in the U.S.", Nuclear Newswire, August 14, 2020, available at: www.ans.org.
52. Terra Power, "Exploring the Natrium™ Technology's Energy Storage System", November 4, 2020, available at: www.terrapower.com.
53. And also smaller ones like Montana's Colstrip Plant stakeholders : K. Petras, "Montana Senate Panel OKs Study to Convert Colstrip Coal Plant to Nuclear", *S&P Global Platts*, February 12, 2021, available at: www.spglobal.com; SMR Start, available at: www.smrstart.org/; S. Patel, "TVA, Eyeing Coal Phaseout by 2035, Will Rely on Nuclear", *Power*, May 5, 2021, available at: www.powermag.com.

bipartisan support (and subsidies) for the development of SMRs if the US is to succeed in fully decarbonizing its power generation system.[54]

The choice to build the first Natrium reactor with federal support on a decommissioned coal plant in Wyoming, in the heart of the windiest area in the US, show that the administration and utilities consider that nuclear will be needed in every part of the country to hit net zero.[55]

Energy Secretary Granholm recently confirmed that "nuclear power is going to play a critical role in America's clean energy future" and that "between DOE's historic budget request and the massive investments in the American Jobs Plan, this Administration is going to be able to launch more nuclear energy projects across the country".[56]

Table 13: Potential SMR Demonstrations in the US Operational by 2030

State	Plant	Operator	Technology Supplier	Reactors	Capacity (MWe)
Idaho	INL	UAMPS Energy Northwest	NuScale	NPM77 x 4 or 6	308 to 462
Wyoming	Retired Coal Plant	Pacificorp	TerraPower GEH	Natrium x 1	345
Washington	WNP	Energy Northwest	X-energy	Xe-100 x 4	320
New Jersey	Oyster Creek	Exelon (Probably)	Holtec	SMR-160 x 1 or 2	160 or 320
Virginia	ND	Dominion	GEH	BWRX-300 x 1 or 2	300 or 600
Tennessee	Clinch River	TVA	ND	ND	Up to 800

Source: Utilities IRP and DOE's Advanced Reactor Demonstration Program.

Yet, even if this revamped nuclear industry will quickly have a role to play to phase-out coal in the next fifteen years, it cannot realistically be ready for a gas phase-out by 2035. As such, the Biden Administration goal of a net zero grid in 2035 is impossible to attain, even more if transport and heating electrification is pushed.

54. B. Meinetz, "Sen. Joe Manchin: Nuclear Gets the Job Done", Energy Central, March 26, 2021, available at: www.energycentral.com.
55. S. Patel, "Wyoming Coal Power Plant May Host Natrium Advanced Nuclear Demonstration", *Power*, June 3, 2021, available at: www.powermag.com.
56. Tweet by Secretary Jennifer Granholm, April 9, 2021, available at: www.twitter.com; Tweet by the Office of Nuclear Energy, June 8, 2021, available at: www.twitter.com.

A Net Zero Economy in 2050: Mapping the Extent of the Challenge for the Grid

Soaring electricity demand

NREL forecast that a net-zero economy by 2050 imply a minimum annual electricity consumption for the US of 8,800 TWh/year, more than doubling the current level. And this figure is an ideal scenario with the best efficiency measures and the maximal use of zero carbon nuclear heat. The reference figure is indeed around 11,300 TWh/year.[57] To provide such amount of clean electricity would be challenging, as highlighted in this table:

Table 14: 2050 Scenarios for the US Power System

	Net Zero Economy Low Estimate for Demand			Net Zero Economy High Estimate for Demand		
Intermittent Share	30%	50%	70%	30%	50%	70%
Non Renewable Baseload (TWh/an)	5,810	4,050	2,290	7,560	5,300	3,040
Wind & solar (TWh/an)	2,640	4,400	6,160	3,390	5,650	7,910
Hydro (TWh/an)	300	300	300	300	300	300
Geothermal (TWh/an)	50	50	50	50	50	50
Total (TWh/an)	8,800	8,800	8,800	11,300	11,300	11,300

Source: NREL.

The implications for solar & wind

Storage technologies would certainly need to improve drastically to enable intermittent sources to cover more than 30% of this load. Yet this is not the only barrier to such a scenario.

Indeed, even considering that the high-capacity factors seen today can be maintained for a much bigger fleet of solar and wind farms and that efficient interconnections could be built to link production and consumption areas, the capacity needed would be unsustainable.

57. D. Steinberg *et al., Electrification & Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization*, *op. cit.*

Table 1: Solar and Wind in 2050

	Net Zero Economy Low Estimate for Demand			Net Zero Economy High Estimate for Demand		
Intermittent Share	30%	50%	70%	30%	50%	70%
Wind & Solar (TWh/an)	2,640	4,400	6,160	3,390	5,650	7,910
Wind & Solar Capacity (GW) in 2050 at 33% Capacity Factor[58]	913	1,522	2,131	1,173	1,955	2,736
Annual average capacity addition (GW) from 2030 to 2050[59]	46	76	107	59	98	137
Land Used (km^2)[60]	168,493	280,822	393,151	216,361	360,601	504,841

Source: See Table 14 and footnotes.

Considering a 50% production share for solar and wind (50-50 proportion) and a 2050 power consumption of 8,800 TWh/year, the US would have to install around 75 GW of new capacity per year from 2030 to 2050. In 2020, 260 GW of new renewable generation (hydropower and geothermal included) have been installed, yet worldwide. It would be difficult to develop the industrial capacity for such endeavors locally, not even accounting for power lines and batteries.

Even more problematic is the land requirement, as around 280,000 km² would have to be dedicated to solar and wind production, an area equal to Nevada, or almost 3.5% of the contiguous US. A 70% production share and a 11,300 TWh/year consumption would imply a dedicated area bigger than California and more than 6% of the contiguous US.

Moreover, if the land requirement is already unsustainable, the raw materials requirements would be probably too huge to satisfy, especially considering batteries and power lines.

As such, if wind and solar can help to decrease the current emissions in power generation, they will fatally be limited to attain a net zero economy.

58. Considering a 50-50 split between wind and solar.
59. Calculation based on a 20-year life expectancy for solar and wind farms.
60. Calculation based on 234 km²/GW for wind and 135 km²/GW for solar. Wind farms could be occupied by some agricultural activities. Source: L. Stevens, *The Footprint of Energy: Land Use of U.S. Electricity Production, Strata Policy*, June 2017, available at: www.strata.org.

The implications for nuclear

As CCS is not yet viable and still unproven, and solar & wind insufficient to decarbonize and ensure security of supplies and competitive power generation, nuclear would probably have to be a particularly important power source for the US in a 2050 net zero economy. Yet, even with the conservation of actual reactors, the deployment needed would be challenging.

Table 16: Nuclear Power in 2050

	Net Zero Economy Low Estimate for Demand			Net Zero Economy High Estimate for Demand		
Intermittent Share	30%	50%	70%	30%	50%	70%
All Nuclear Non Renewable Baseload (TWh/an)	5,810	4,050	2,290	7,560	5,300	3,040
Nuclear Capacity (GW) in 2050 at 95% Capacity Factor	698	487	275	908	637	365
New Nuclear Capacity (GW) to install on the grid from 2030[61]	597	386	174	807	536	264
Annual average capacity addition (GW) from 2030 to 2050	30	19	9	40	27	13
Land Used (km^2)[62]	6,981	4,867	2,752	9,084	6,369	3,653

Source: See Table 14 and footnotes.

As solar and wind will realistically not cover more than 50% of the needs, nuclear capacity will have probably to grow to at least 400 GW in 2050. The land required would probably be a bit more than 5,000 km^2, mines included, a much more sustainable figure close to the surface of Rhode-Island, or 0.06% of the US.

If the deployment of 20 to 40 GW of new capacity every year seems heavy, it is not impossible. France managed a 5 GW/year rhythm for new reactors between 1980 and 1990, with a 700 G$ GDP in 1980. The US GDP in 2019 was more than 30 times this figure, at 21,430 G$. As such, it seems the US economy could attain such cadency and phase-out unabated gas before 2050.

Under such a scenario, the uranium requirements would not be an issue, as breeder reactors and even seawater extraction could allow millions of years of production,[63] not even accounting the eventual rise of nuclear fusion.

61. Calculation based on a 101 GWe capacity in 2030 without retirement between 2030 and 2050.
62. Calculation based on 10 km^2/GW for Nuclear (includes mines and waste storage). Source: *ibid*.
63. World Nuclear Association, "Supply of Uranium", December 2020, available at: www.world-nuclear.org.

Conclusion

Decarbonizing the US power system by 2035 is a much needed, yet highly unrealistic objective. It would be achieved by 2050 perhaps, provided there is a successful and massive roll out of SMRs. In the meantime, the expected boom of solar and wind, and modernization and expansion of electricity infrastructures, can help reduce GHG, provided that the US effectively and rapidly addresses the methane leakage challenge. In any case, nuclear energy will be needed massively to power a net-zero US economy, no matter the scenario taken into. Hence why the US is rightly pushing hard for gaining technological leadership in this segment.

french
institute
of international
relations

since
1979

27 rue de la Procession 75740 Paris Cedex 15 – France

Ifri.org