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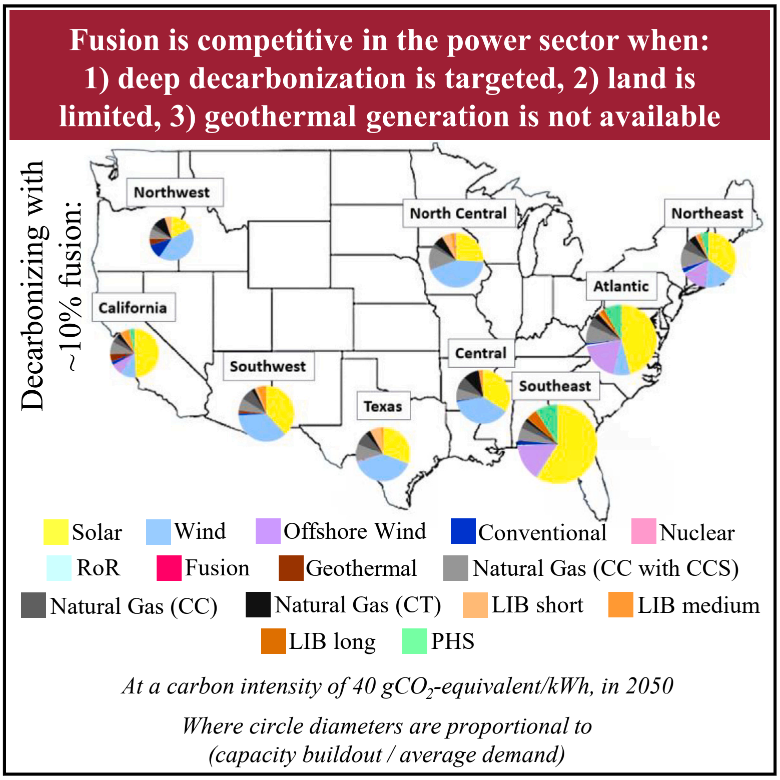
Article

In what regions can fusion help decarbonize the US power sector

Graphical abstract



Highlights

- A capacity expansion model (with TEA and LCA) is used to evaluate fusion
- Regional capacity limits most strongly dictate fusion adoption
- Integrating fusion allows regions to reach deeper decarbonization levels in the US
- Without decarbonization targets, fusion is not economically viable

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In brief

This study uses a capacity expansion model to evaluate the potential role of fusion in a decarbonized future of the USA. At an emissions intensity of 20 gCO_2-equiv/kWh, all modeled regions rely on fusion. In fact, without fusion, the lowest emissions intensity that most regions can reach is 25 gCO_2-equiv/kWh. But without a carbon cap, no fusion is installed in any region, even at capital expenditure costs as low as $3,000/kW.

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In what regions can fusion help decarbonize the US power sector

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SCIENCE FOR SOCIETY The USA is beginning the challenging but imperative decarbonization of its energy economy. Decreasing emissions from the power sector is crucial as the other sectors (transportation, commercial, residential, and industrial) electrify. The power sector is difficult to decarbonize. Most low-carbon generation technologies are either intermittent (solar and wind), limited based on location (geothermal and hydro), or considered dangerous by the public (nuclear). Fusion is a developing technology that has the potential to safely provide dispatchable power. Because of the complexity of this technology, it is estimated to be more expensive than nuclear. This paper explores the potential role of fusion in the different regions of the USA. Without decarbonization targets, fusion is not commercially viable because of its high price tag. But, at deep decarbonization levels, fusion has a role to play in all regions. Fusion is especially important in regions with limited geothermal and weak wind.

SUMMARY

This paper evaluates the potential role of fusion in decarbonizing the US power sector in the year 2050. This is done by breaking the US electricity system into regions to understand factors that favor or disadvantage fusion. Fusion is economically competitive in all regions at a grid emissions intensity cap of 20 gCO_2-equiv/kWh and lower. As the emissions ceiling lowers, fusion penetration quickly increases, reaching 15%–35% of regional system capacity at 15 gCO_2-equiv/kWh. The dispatchability of fusion is valuable as it operates seasonally, with its highest monthly output occurring in the summer and lowest occurring in the spring. Because of this, fusion competes most directly with low-carbon dispatchable options (geothermal and natural gas with carbon capture) and long-term energy storage technologies (pumped hydro storage). Fusion is economically competitive when deep decarbonization is targeted and when land availability is limited.

INTRODUCTION

Current grid and upcoming targets

The power sector is a central element of global energy system decarbonization. This requires that we reduce the emissions from electricity generation while also electrifying the other sectors (e.g., electric vehicles for transportation and electric heating for residential and commercial sectors). As the second-highest emitting country, the US has an opportunity to significantly reduce global emissions and therefore mitigate the impact of climate change. The US has set important and challenging targets. For example, the US Nationally Determined Contribution provides sector-level decarbonization pathways to reach the national goal of 50% emissions reduction by 2030.[1] Also by 2030, President Biden's goal for the power sector is 100% generation from low-carbon generation sources (i.e., solar, wind, nuclear, etc.).[2] Finally, the US has pledged overall net-zero emissions for the entire national economy by 2050.[3] These goals show that the US is serious about quickly and effectively decarbonizing the power sector and its overall energy economy.

Achieving these national targets is essential to limiting the impacts of climate change, but current projections and analyses of policies show that we are not on track to reach these goals. A 2020 compilation of subnational climate policies shows that current commitments only reduce emissions levels by 25% in 2030.[4] Kerry and McCarthy highlight the difficulty of decarbonizing the transportation sector, showing that stringent policies and standards that improve efficiency and reduce vehicle usage and ownership are needed to complement electrification to successfully limit transportation emissions to 2050 targets.[5] Even the most optimistic global decarbonization scenarios fall short of the international 1.5°C Paris Agreement goal.[6] A global

Table 1. Comparison between nuclear and fusion technologies

	Nuclear value	Nuclear source	Fusion value	Fusion explanation
CAPEX ($/kW)	6,668	NREL ATB	8,500	roughly 25% increase from nuclear CAPEX
FOM ($/kW/year)	152	NREL ATB	188	calculated from Sheffield paper
VOM ($/MWh)	2	NREL ATB	18.4	calculated from Sheffield paper
Fuel costs ($/MWh)	6.9	NREL ATB	0	deuterium is naturally abundant, and tritium will be bred via a reaction with lithium
Lifetime (year)	60	NREL ATB	40	common assumption
Capacity emissions (gCO_2-equiv/kW/year)	4,104	SESAME	32,116	calculated based on materials required for a commercial project with similar dimensions, parameters, and technologies as employed by ITER; details available in the supplemental information
Operational emissions (gCO_2-equiv/kWh)	7.9	SESAME	0.26	calculated based on blanket and diverter replacements based on Sheffield paper; details available in the supplemental information
CF limit (%)	93	NREL ATB	85	almost 10% reduction from nuclear availability; more importantly, all maintenance must occur in a 3-month period
Operational limits	baseload	current nuclear operation patterns in US	unlimited ramping	based on published tokamak physics advancements

assessment shows that the emissions intensity of the grid must decrease at a rate 3.2 times faster than it has since 2010 to reach 2030 targets.[7]

To encourage this transition, there is a collection of national subsidies that have been enacted—most notably is the Inflation Reduction Act (IRA).[8] The IRA is recognized as the most significant climate legislation ever passed. Bistline et al.'s review of the IRA's impact using a variety of US energy sector models shows that the IRA is projected to motivate 38%–80% reduction in emissions compared with 2005 levels by 2030 and stimulate 66%–87% reductions by 2035.[9] This brings the US closer to its target range in the Paris Agreement. But, even with this promising enactment, there remains a serious need to further decarbonize the power sector to halt the damage of climate change.

Current electricity decarbonization technology options are progressing in promising directions but still leave important gaps to fill. Solar and wind generation technologies are economically competitive on a levelized cost of electricity basis, but their intrinsic intermittency means that they must be augmented to continuously match supply and demand in the electricity system. This can be accomplished in many ways, including storage, transmission, or firm-generation resources such as nuclear and hydropower. These add additional costs to the system and can come with siting and permitting issues. Currently, nuclear has a negative public perception as being disproportionally dangerous in comparison with other generator options. In fact, even though nuclear provides ∼20% of national demand, there has been only 1 new plant since 2016.[10] By 2050, nuclear capacity is projected to decline by 20% from 2022 levels.[10] Hydropower is dispatchable but is limited based on geography.[11] Carbon capture technologies have the potential to greatly reduce emissions of natural gas-powered generators, but costs rise with the percentage of carbon captured, and complete capture is not feasible. Even with all these technological options, there remains a need for a firm, low-carbon electricity source.[12]

Fusion

Fusion is a promising, rapidly developing technology that has the potential to fill this firm, low-carbon generation need. Many approaches being pursued today use magnetic or inertial forces to compress or maintain fuels in plasma. In the plasma, two light atomic nuclei react to form a heavier one and release energy. This analysis considers the fusing of deuterium and tritium to helium via magnetic confinement because this is the most common fuel-confinement combination. Neutrons are created in this reaction. The energy of these neutrons can be converted to heat, which can in turn be converted to electricity via standard thermal power conversion cycles. This power generation technology is low-carbon with readily available fuel sources. Fusion is also a naturally self-quenching reaction, meaning that there is no risk of uncontrolled reactions.[13] Having said that, there is still potential for the production of radiological hazards, which will require specific considerations. While fusion generator technologies remain under development, there is a significant push toward commercialization within the next 5–10 years. In fact, $4.8 billion in funding was raised in 2022 by fusion startups.[14] This combination of promising potential and momentum prompts the following investigation of the potential impact of fusion in the power sector in the year 2050.

Fusion and nuclear are distinctly different technologies. Their representations in the model are contrasted in the below Table 1. A more detailed description of fusion-related assumptions with relevant sources is presented in the supplemental information. In general, fusion is estimated to be more expensive than nuclear but has fewer operational emissions and greater operational flexibility. Note that this paper assumes no construction of new

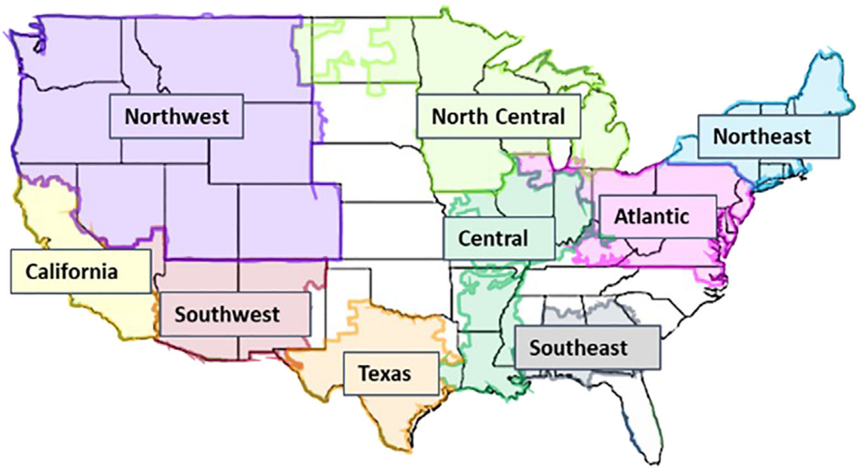

Figure 1. Map of the nine selected regions of analysis

nuclear power plants, so fusion is not competing with nuclear. But this comparison helps the reader understand how this publication is distinctly different from manuscripts on the role of nuclear in decarbonization. Having said that, nuclear is the most similar technology to fusion, and so allowing for new installations would compete with fusion penetration.

Since fusion technology is still developing, there have been a limited number of studies investigating fusion's potential for impact on the power sector. Most similar to this study is Schwartz et al.'s article on the value of fusion in the US power sector at net-zero emissions intensity, without considering embodied emissions.[15] A 2020 paper shows that fusion is most competitive in countries that do not have alternative renewable energy options, such as Japan, Korea, or Turkey.[16] Nicholas et al. provide a high-level discussion on how fusion fundamentally complements renewables because it provides firm potential.[17] An investigation by the International Atomic Energy Agency shows that fusion will contribute significantly to the world energy market if successfully introduced.[18] Lastly, Sepulveda et al.'s paper highlights the importance of firm, low-carbon power sources in decreasing electricity prices at deep decarbonization levels.[19] Although this analysis is based on nuclear fission, geothermal, and biofuels, the conclusions can also be related to fusion, as it is expected to have similar benefits to the electricity system if successfully commercialized.

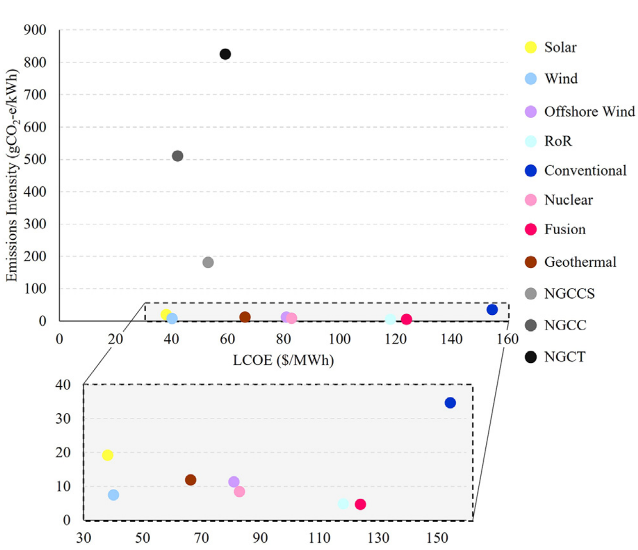

Figure 2. 2050 Projected levelized cost of electricity and emissions intensity for each generator type

Fusion's cost is important to its potential for widespread integration into the power sector. Bustreo et al. analyze fusion's potential in decarbonizing the European power sector, with a focus on identifying capital cost ceilings that fusion must stay below to remain commercially viable in each region.[20] Also, it is shown that fusion can play a big role in the energy transition, but that capital cost and date of commercialization can play a big role in penetration levels.[21] Other research suggests that fusion developers should target markets with high-priced electricity to better compete against renewables.[22]

Transmission expansion

Although not explored in this study, it is important to talk about the potential role that transmission expansion can play in decarbonization. First, it is important to mention the three interconnection regions within the US: Western Interconnection, Electricity Reliability Council of Texas (ERCOT) Interconnection, and Eastern Interconnection. There is limited interconnection between these three regions for a variety of reasons, most namely frequency discrepancies, regulatory conflict, and political barriers. The Northwest, California, and Southwest referred to as ideal grid (IG) regions are in the Western Interconnection, Texas is in the ERCOT Interconnection, and North Central, Central, Southeast, Atlantic, and Northeast are in the Eastern Interconnection. In considering inter-regional transmission, it is important to remember that there is a significantly higher barrier when building lines between regions located in different interconnections.

Having said that, a variety of studies have explored the value of transmission buildout. Brown and Botterud's article showed that the optimal way (when minimizing system cost) to reach zero-carbon electricity (without considering embodied emissions) is to expand current transmission infrastructure by 90% by 2040.[23] This transmission expansion reduces system costs by $18/MWh when compared with the scenario when transmission infrastructure is not expanded.[23] An AGU Advances article calculates that lowest-system cost decarbonization involves expanding current transmission infrastructure by 168% by 2050.[24] Most new transmission is between wind-rich and wind-poor regions because there is more diversity in wind resources than there is in solar resources.[24] For solar, it

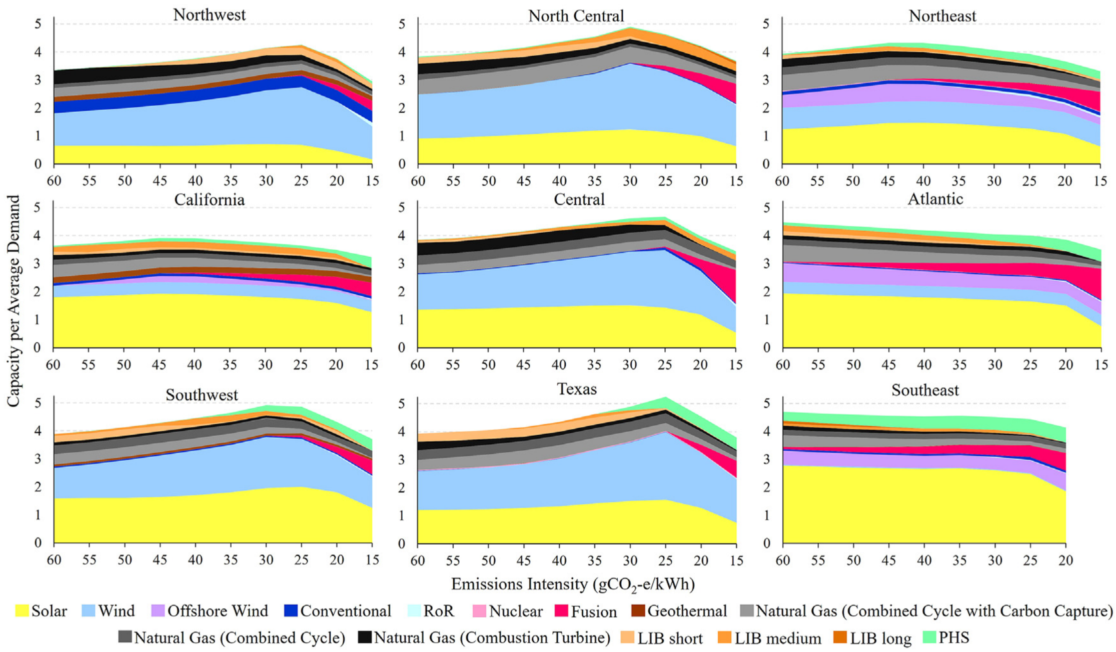

Figure 3. Regional power system compositions at varying emissions intensity ceilings

is almost always cheaper to install capacity closer to demand.[24] A third study computes that the lowest-cost way to reach 100% clean electricity by 2035 is to increase transmission by 124%.[25] Transmission allows for the installation of higher-quality renewables and smooths out demand and generation variability.[25]

Having stated the potential values of transmission, it is important to examine the feasibility of the extensive transmission buildout described in these papers. A 124% increase in transmission would require the installation of anywhere from 60,060 to 121,940 miles of new transmission capacity (depending on rating of installed infrastructure) by 2035.[25] Assuming buildout begins in 2025, this would mean ~91,000 miles total (averaging 60,060 and 121,940), or ~9,100 miles annually. Between 2009 and 2020, an average of only 1,257 miles of transmission were installed annually, with the highest annual installation of 4,098 miles in 2013.[26] Another data point to consider is that some projection transmission capacity will increase by only ~10% by 2035, compared with current levels.[25]

This study is novel and impactful for three main reasons. First, we are investigating fusion's impact on system investment and operation in the year 2050. We are using a capacity expansion model with an hourly timestep to model economic dispatch decisions to see how fusion would affect the system. Second, we compare fusion integration in 9 regions within the US to illustrate the impacts of installation location. This is done at a variety of decarbonization levels to track when fusion becomes economically competitive. Lastly, emissions from all stages of the life cycle are accounted for to provide a more accurate decarbonization assessment. More information on emissions assumptions is available in the supplemental information.

RESULTS

Relevant regions and technologies

The basis of this analysis is the cost-minimization of the future power system for each region shown in Figure 1. Existing assets that will last until 2050 are considered, but all other installations

Table 2. Buildout constraints that are active when fusion is integrated at most lenient carbon cap

	Atlantic	California	Central	North Central	Northeast	Northwest	Southeast	Southwest	Texas
Solar	–	–	–	–	–	–	–	–	–
Wind	at max	at max	–	–	at max	at max	at max	–	–
Offshore wind	–	–	–	–	–	–	–	at max[a]	–
RoR	–	–	–	–	–	–	–	–	–
Conventional	–	–	at max	at max	at max	–	–	–	–
Geothermal	at max[a]	at max	at max[a]	at max[a]	at max[a]	at max	at max[a]	at max	at max[a]
PHS	–	–	at max	at max[a]	–	–	–	–	–

[a]Regional limit = 0.

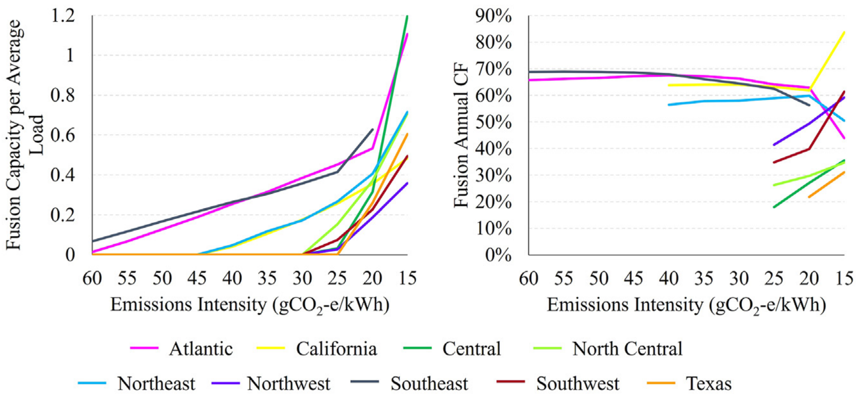

Figure 4. Fusion in the different US regions
(A) Fusion installed capacity and (B) annual capacity factor at varying carbon emissions intensity ceilings.

are determined by the model to best design an optimized grid. This brownfield, linear capacity expansion model is part of MIT's Sustainable Energy System Analysis Modeling Environment (SESAME) and is IG.[27] IG optimization accounts for capital costs and operating costs while satisfying demand and emissions constraints.

IG incorporates fifteen technologies in this analysis. Generator types include land-based wind, fixed-bottom offshore wind, solar, run-of-river (RoR) hydro, conventional hydro (conventional), natural gas-fueled combustion turbine (NG CT), natural gas-fueled combined cycle (NG CC), natural gas-fueled combined cycle with 90% carbon capture (NG CCS), nuclear, geothermal, and fusion. Included energy storage technologies are lithium-ion batteries (LIBs) with 4-h duration, 2-h duration, or 8-h duration and pumped hydro storage (PHS) with 10-h duration. Construction of new nuclear fission (nuclear) is not included in this analysis. Based on current legislation and public opinion, there is little to no momentum toward building new fission power plants. As the aging nuclear fleet reaches retirement, there is a possibility that this technology will no longer be included in the US's power sector. More information on IG's structure and functionality can be found in its initial publication.[28]

Life cycle assessment and technoeconomic analysis are combined to track emissions and costs from all stages of the life cycle. Figure 2 maps the relevant cost-emissions space for technologies considered here. Emissions from generators are normalized by average generation but vary significantly based on actual infrastructure operation and output. Cost values are 2050 projections sourced from NREL's 2022 Annual Technology Baseline, with forecasted values from the moderate scenario.[29] Emissions values are computed in MIT's SESAME, which uses life cycle assessment to track emissions from all stages of the life cycle.[27] Note that all emissions values are CO_2-equivalents but are referred to as CO_2-equiv, for brevity. No technologies are considered to be carbon-neutral because there are difficult to abate embodied emissions associated with manufacturing materials for all generator technologies. Manufacturing grid emissions intensity is assumed to be 223 gCO_2-equiv/kWh.[30] This value was calculated by dividing projected national power demand in 2050 by projected national power-system emissions in 2050. Exact cost and emissions values are included in the supplemental information for all technologies.

Fusion is assumed to have infinite ramping capabilities across hourly timesteps, so resources can transition from production at 0%–100% power output within an hour. Annual fusion capacity factor (CF) is limited to 85% to allow for periods of maintenance. Also, it should be noted that although the reactor will operate in short pulses, the power output will be steady.[31] These short pulses allow for high ramping abilities. Molten salt will be used as a thermal regulator.[32] It should be noted that there may be some engineering limits that constrain ramping, but this is a good first-order approximation of expected capabilities. Because cost and emissions values are uncertain, a sensitivity analysis is conducted on system cost.

Other modeling details, including regional capacity limits, variable renewable energy (VRE) CFs, and temporal dimensions are included in the experimental procedures section and in the supplemental information.

Fleet buildout at a variety of carbon caps

Various emissions caps are applied to evaluate how each system responds to stricter constraints, as shown in Figure 3. The emissions caps range from 60 gCO_2-equiv/kWh at the most lenient to 15 gCO_2-equiv/kWh at the most stringent, at 5 gCO_2-equiv/kWh increments. 60 gCO_2-equiv/kWh is roughly an 80% reduction in emissions intensity from the 2021 US grid average.[33] Emissions reduction stops at 15 gCO_2-equiv/kWh because lower emissions intensities are unattainable when embodied carbon is accounted for. This makes sense when referencing Figure 2, which shows that emissions intensities of all technologies are nonzero. It should be noted that all scenarios have "capacity per average demand" values greater than 1. This is because renewable technologies are curtailed, and dispatchable technologies are not

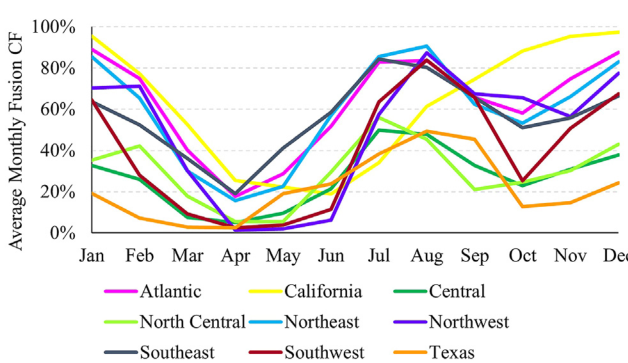

Figure 5. Monthly fusion CFs at 20 gCO_2-equiv/kWh carbon limit

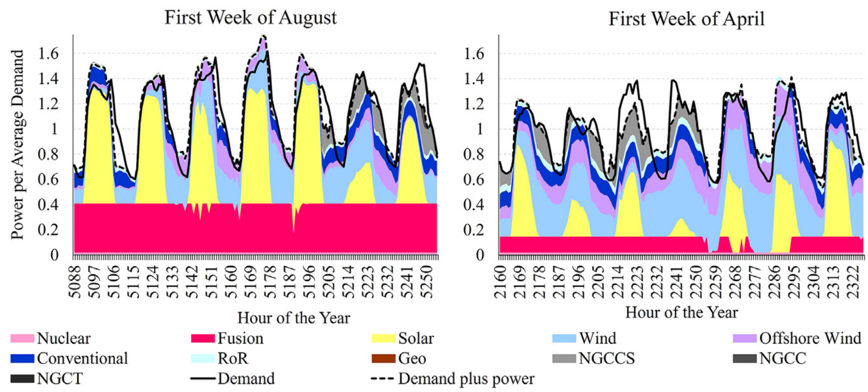

Figure 6. Hourly system operations for the Northeast at 20 gCO_2-equiv/kWh

operating at 100% CF annually. Lastly, no data are provided for an optimization of the Southeast grid, given a 10 gCO_2-equiv/kWh carbon cap. This is because there is no buildout combination that meets all demand but stays below the given carbon constraint.

In all regions, fusion becomes economically viable at lower emissions caps. As fusion reliance increases, overall system size decreases significantly. At the lowest emissions intensity (15 gCO_2-equiv/kWh), fusion ranges from 0.48 capacity per average demand, totaling 15% of system capacity in California, to 1.20 capacity per average demand, totaling 35% of total capacity in the Central region. It should be noted that the combination of wind and solar resources shifts, depending on region, but with increasing reliance on wind at lower emissions caps. At the lowest emissions intensity (15 gCO_2-equiv/kWh), the nation favors wind (onshore and offshore capacity) over solar resources, at a 1.4 ratio.

PHS replaces LIB in more stringent scenarios due to its lower emissions intensity but higher power-density cost. Energy-density cost is almost identical for LIB and PHS. In the Atlantic, Central, North Central, Northeast, and Southeast regions, PHS deployment is limited by available capacity. Conventional hydro capacity is limited in the Atlantic, Central, North Central, Northeast, Southeast, Southwest, and Texas regions. The national total of conventional hydro capacity lowers as emissions intensity allowances decrease below 30 gCO_2-equiv/kWh due to its relatively high emissions intensity of ∼30 gCO_2-equiv/kWh. RoR capacity limits are hit in all regions except the Northwest. Because RoR buildout potential is so low, it stays below 5% of regional capacity, even at maximum buildout. Land-based wind capacity limits are encountered in the Atlantic, California, Northeast, and Southeast. Geothermal limits are active in all regions. Lastly, offshore wind capacities never approach imposed limits, staying below 70% of allowed capacity in all regions. Regions that install nonnegligible amounts of offshore wind are those that have maximized land-based wind resources. Land-based wind is favored over offshore wind because it is less emissions intensive and less expensive. Table 2 shows which buildout constraints are active when fusion is first integrated. A similar table is available in the supplemental information where percentage values are shown.

Capacity limits are the regional characteristic that most strongly dictates fusion adoption. Geothermal capacity is always maxed out before fusion is integrated. This is because these two resources are both dispatchable low-carbon energy technologies and so directly compete, and geothermal is less expensive. The four regions that see the earliest and largest fusion integration (Atlantic, California, Northeast, and Southeast) have the most stringent wind constraints. In all these regions, if wind buildout is maximized, wind still cannot produce enough electricity to satisfy one-quarter of demand. Not surprisingly, these regions with severely limited wind buildout require fusion at even lenient decarbonization targets.

Fusion installations and operations

Figure 4A shows the fusion capacity results from Figure 3 but without all the other generator types to display the fusion trends more clearly and to allow comparisons across regions. The Atlantic and Southeast are the only regions to adopt fusion at 60 gCO_2-equiv/kWh. California and the Northeast adopt fusion at 40 gCO_2-equiv/kWh. Note that these four regions have the most stringent land-based wind restrictions, showing the importance of siting availability. Central, North Central, Northwest, and Southwest install fusion at 25 gCO_2-equiv/kWh. Texas installs fusion at 20 gCO_2-equiv/kWh. At 15 gCO_2-equiv/kWh, two out of the nine regions have fusion capacity that exceeds average load.

IG solves economic dispatch decisions at each hour and uses these results to calculate hourly fusion power output and the annual fusion CF values for each case. These values are shown above in Figure 4B. There is large variance in fusion power output depending on region and emissions intensity constraint, with CFs ranging from 18% to 84%. The large range shows how operation varies greatly from region to region. When choosing investment locations, CF trends are important as they can correlate with revenue.

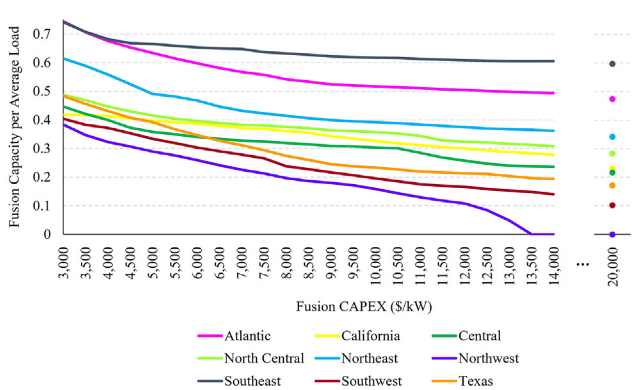

Figure 7. Regional fusion penetration as a function of fusion CAPEX

Table 3. Decrease in fusion capacity (per demand) when comparing installations at $3,000/kW–$14,000/kW CAPEX

	Atlantic	California	Central	North Central	Northeast	Northwest	Southeast	Southwest	Texas
Decrease (capacity per demand)	0.25	0.14	0.21	0.18	0.25	0.38	0.14	0.26	0.29

To clarify the range of annual CFs, monthly CFs are investigated. The CF trends shown in Figure 5 assume a 20 gCO_2-equiv/kWh carbon emissions intensity ceiling. For most regions, fusion has its highest CF in summer and winter months. The magnitude of this "high operation" in the summer varies greatly. The Northeast sees the highest CF in the summer, with multiple months above 85% CF, contrasted with the Central and Texas regions, where monthly CFs peak at ~50%. Spring sees the lowest operation, with most of the CFs in the 0%–25% range. This is caused by the imposed low availability of the system due to shutdowns for blanket and diverter replacement and general maintenance. Figure 6 shows hourly system operations for the Northeast at 20 gCO_2-equiv/kWh. Note the lower power output from fusion because of the imposed maintenance scheduling. Note that the "demand plus power" trend indicates when energy storage is charging or discharging. When it is above demand, energy storage is charging, and vice versa when below.

The reason for summer and winter peaking in most regions is a combination of multiple factors. First, seasonal demand peaks in the summer and winter for all regions. Secondly, monthly wind CFs are lowest in the summer months. Also, monthly solar CFs are lowest in the winter months. A combination of these factors explains the fusion seasonal trends. Lastly, California's anomalous behavior should be noted. California's fusion CF has only one annual peak, the winter months. This is due to California's relatively high reliance on solar. More analysis is needed to better parse out the relative impact of each of these contributing factors for all regions. For example, one could explore the impact of the seasonal demand shape by flattening the annual demand and observing its effect on fusion's operation.

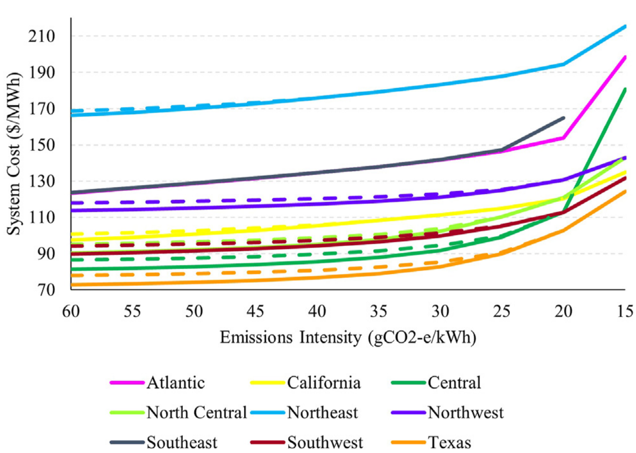

Figure 8. System cost of energy (SCOE) without forced fusion (solid line) vs. with at least 0.1 fusion capacity per average demand (10%) (dashed line)

Lastly, it should be noted that this sinusoidal annual CF trend is present at all carbon ceilings where fusion is included. For example, with a 20 gCO_2-equiv/kWh carbon ceiling, the national CF low occurs in April, which sees a 9% average, and the national CF high occurs in August, at 71%, resulting in a very wide range of operation. By contrast, at a 15 gCO_2-equiv/kWh carbon ceiling, the low occurs in April at 17% and the high occurs in July at 70%, resulting in only a slightly narrower range of operation.

CAPEX sensitivity analysis

Most results in this report assume an $8,500/kW CAPEX for fusion. This is a ~25% increase from NREL's ATB-reported current nuclear costs due to the increased complexity of the technology. Since there is large uncertainty regarding the future cost of fusion power plants, we have examined the impacts of overnight capital costs ranging from $3,000/kW to $14,000/kW in $500/kW increments. This was done for all regions, with an emissions cap of 20 gCO_2-equiv/kWh. Figure 7 shows the resulting fusion capacity installations to demonstrate fusion penetration's sensitivity to CAPEX.

Also, the difference in fusion installations is compared when fusion CAPEX is $3,000/kW vs. $14,000/kW (Table 3). Regions are impacted by fusion CAPEX differently. From least to most sensitive, the regions are Southeast, California, North Central, Central, Atlantic, Northeast, Southwest, Texas, and Northwest.

Lastly, and most importantly, Figure 7 shows that fusion plays at least some role in the US power sector, even at a wide range of cost assumptions. In fact, even at a CAPEX of $20,000/kW, all regions except the Northwest install some amount of fusion, given a 20 gCO_2-equiv/kWh carbon cap. Without a carbon cap, fusion is not competitive, even with installation costs as low as $3,000/kW.

Forcing fusion installations

The above sections discuss that fusion is not present in all least-cost fleet buildout. Fusion becomes less relevant at more lenient carbon ceilings. Having said that, it is informative to examine how forced deployment of fusion can impact the system. In this analysis, sufficient fusion is required to be installed to meet ~10% of demand. Since fusion is a dispatchable, low-carbon generation source, it has the added value of being able to meet demand when other generation assets cannot. As stated earlier, our IG model is based on perfect foresight regarding renewables and demand. The reality is that we cannot know the weather or the demand in the future. Therefore, fusion's reliability is valuable.[34]

When 10% fusion is forced into the system at an emissions cap of 60 gCO_2-equiv/kWh, total system generation capacity shrinks by 1%–2% depending on region. This forced inclusion of fusion impacts low-carbon technologies, namely NGCCS, wind, solar, and offshore wind. When fusion is forced, natural gas combined cycle with carbon capture decreases in national capacity by 18%. Offshore wind decreases by 21% because it

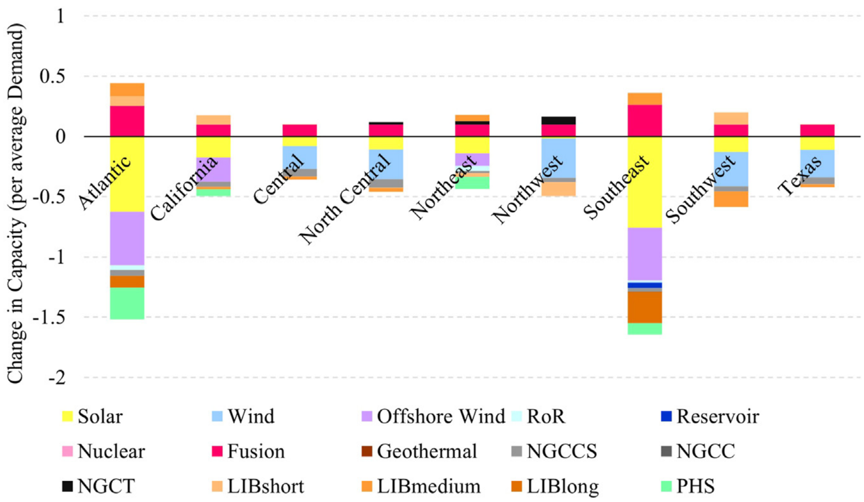

Figure 9. Fusion's impact on the capacity of other generation resources for an emissions cap of 40 gCO_2-equiv/kWh

The bars above the horizontal line denote increases in capacity when at least 10% fusion is required, and bars below the horizontal axis indicate decreases in capacity.

is the most expensive VRE, so it is phased down first. Wind and solar see 9% and 7% reductions, respectively. Natural gas without carbon capture and short-duration LIB are the only technologies to see an increase.

This 13% natural gas combined cycle increase is a counterintuitive modeling result that does not reflect reality well. This occurs because fusion has very low emissions, so when it is forced into the system, it creates space in the carbon budget for higher-carbon technologies to also exist. When fusion is not included, all other components are increased in size, so the excess room in the carbon budget shrinks, forcing the system to rely on lower carbon dispatchable options that are more expensive. LIB replaces PHS when fusion is increased because fusion operates seasonally, therefore lowering the need for long-duration storage. As the emissions cap is tightened, the overall impact of forcing 10% penetration of fusion decreases and ultimately disappears. At these low emissions limits, fusion is organically economically competitive.

Figure 8 shows the impact on cost when fusion is forced into the system. At 60 gCO_2-equiv/kWh, systems with forced fusion are \$0–5/MWh more expensive than their non-forced regional counterpart, which corresponds to a 0%–7% price increase. This is an important finding because fusion provides dispatchability that variable renewable resources do not,[12] but this flexibility comes at a price. The added cost of imposed fusion decreases as the carbon ceiling lowers. This is because lower emissions intensities drive the system to higher-cost, low-carbon technologies. Hence, adding fusion results in a smaller price hike.

Decarbonizing the power sector with vs. without fusion

This section focuses on a direct comparison of decarbonization of electricity systems with vs. without fusion. Figure 9 shows the change in capacities for each region when fusion is forced to be at least 10% of average demand, compared with when it is not allowed, at an emissions intensity cap of 40 gCO_2-equiv/kWh. Bars above the horizontal axis indicate an increase in capacity when fusion is forced, and bars below the horizontal axis indicate a decrease in capacity when fusion is forced. The forced ~10% inclusion of fusion is clearly apparent because fusion is always above the horizontal axis, at a height of at least 0.1 capacity per average demand. Cheap, dispatchable technologies (combustion turbine or combined cycle natural gas) also increase with fusion because the system has more room in its carbon budget to rely on higher emissions technologies when it is balanced by fusion, which is the cleanest generation option. There is also a decrease in VREs and energy storage because fusion provides dispatchability.

Other important considerations when comparing decarbonization with vs. without fusion are land-use and materials requirements. A more fusion-reliant system will require less land and materials because fusion is projected to be more energy dense than most of the technologies it displaces, as can be seen in Table S15. Sufficient materials are available to meet a variety of projected decarbonization futures.[35]

Lastly, it should be noted that without fusion, the minimum emissions intensity that can be reached is significantly limited, with most regions reaching a minimum of 25 gCO_2-equiv/kWh. The Southeast is the most constrained region in this regard, as it is unable to reach even 35 gCO_2-equiv/kWh, which is why all analysis in this section is done for 40 gCO_2-equiv/kWh. This conclusion may change as major technological breakthroughs are made in the decarbonization space. Table 4 shows the minimum emissions intensity that can be reached in each region without fusion.

Sensitivity of other fusion assumptions

This section explores the impact of fusion assumptions that are not addressed in their own dedicated section. Note that different magnitudes of uncertainty are tested for different assumptions. Table 5 displays the range explored for each assumption. Note

Table 4. Minimum emissions intensity that can be reached without fusion

	Atlantic	California	Central	North Central	Northeast	Northwest	Southeast	Southwest	Texas
Emissions intensity (gCO_2-equiv/kWh)	35	25	25	25	30	20	40	25	25

Table 5. Range of sensitivities explored

	Base case	Low estimate	High estimate	Justification
FOM ($/kW/year)	188	94	282	50% decrease and 50% increase
VOM ($/MWh)	18.4	14.8	33.3	calculation provided in supplemental information
LIB costs (install and operational costs)	see supplemental information	basic calculations	basic calculations	50% decrease and 50% increase
Embodied emissions (gCO_2-equiv/kW/year)	32,116	16,058	48,174	50% decrease and 50% increase
Operational emissions (gCO_2-equiv/kWh)	0.258	0.100	1.774	calculation provided in supplemental information

that whenever a comprehensive sensitivity range was not calculated, the range explored is 50%–150% of the base case assumption.

The first four sensitivities shown in Figure 10 are the most intuitive to understand. As fusion costs decrease (VOM or FOM), fusion installations increase. In fact, reducing FOM by 50% can encourage up to 20% more fusion installed in the more price-sensitive regions (Texas, Southwest, and Northwest). A high VOM has the potential to reduce fusion installations by 3%–14%, depending on the region.

The impact of LIB costs is less intuitive. Decreasing LIB costs decreases fusion installations in the Central, North Central, Northwest, and Southeast regions. In all three of these regions, medium- and long-duration LIB and wind capacities are increased, and natural gas and short-duration LIB installations are decreased. Less expensive energy storage allows for a transition to longer-duration energy storage, with a greater reliance on variable generation sources, namely wind. In all other regions, decreasing LIB costs causes a shift in the technology of energy storage deployed. PHS and short-duration LIB installations are reduced, and medium-duration LIB installations are increased. The replacement of long- and short-duration energy storage technologies with medium-duration LIBs allows for less reliance on variable technologies and requires firm-generation fusion.

Reducing fusion-embodied emissions decreases fusion penetration because more space is allowed in the carbon budget to rely on solar supplemented with natural gas with carbon capture, which are both significantly cheaper than fusion. Given base-case assumptions, fusion is responsible for anywhere from 4% to 12% of total system emissions, as can be seen in Figure 11. Since most fusion-related emissions are embodied, adjusting this value has significant impact on the optimization. Operational emissions are responsible for a smaller fraction of total fusion emissions, so adjustments of this value have a smaller impact on the optimization. When increasing fusion's operational emissions, there is a mixed impact on fusion penetration but a consistent reduction in fusion annual CF in each region. Lastly, it should be noted that with 50% increased embodied emissions, the Southeast cannot reach 20 gCO_2-equiv/kWh emissions intensity.

DISCUSSION

The above sections provide a comparison of fusion integration into nine regions of the US. Fusion is a firm, low-carbon technology, and to provide a conservative analysis of this future power generator technology, we have assumed that it will be the most expensive option. Without any emissions constraints imposed on the electricity system in 2050, no fusion will be installed unless the CAPEX drops significantly (below $3,000/kW).

Next, a variety of emissions caps are applied, ranging from 60 to 15 gCO_2-equiv/kWh. At lower emissions ceiling, fusion

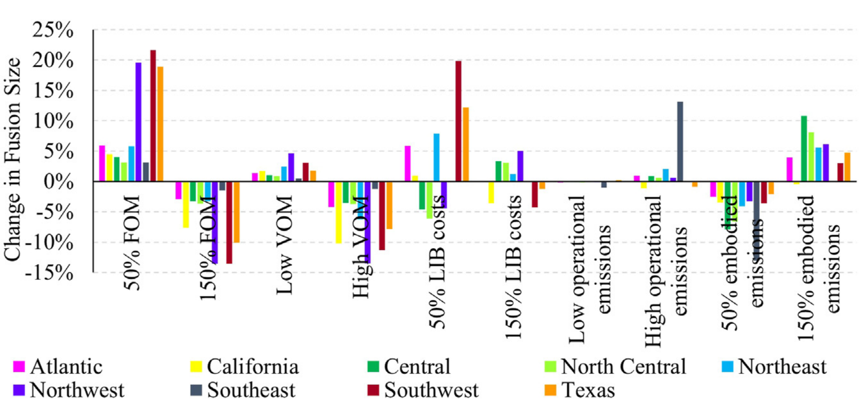

Figure 10. Sensitivity of assumptions on fusion installations

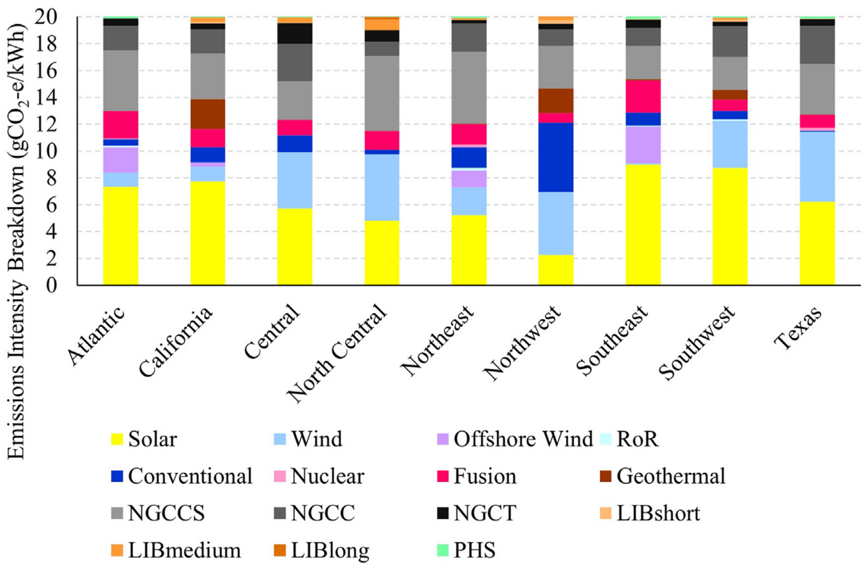

Figure 11. Base case emissions intensity breakdown by technology for each region

A CAPEX sensitivity analysis was performed because of the large uncertainty in commercialized capital cost. It is shown that cost sensitivity is region dependent. The Southeast and California regions are least sensitive to cost, in contrast with Texas and the Northwest, which are most sensitive to cost. In general, the above analysis shows that fusion is the most competitive in regions that do not have alternative options available (such as conventional hydro, RoR hydro, or PHS) and/or are space limited. It is important to keep this cost sensitivity in mind when interpreting the results of this analysis.

Finally, a more comprehensive sensitivity is conducted on assumptions around fusion assumptions. Changing VOM or FOM assumptions has similar impact on fusion adoption. Decreasing FOM by 50% causes an increase in fusion penetration of up to 20%. Operational emissions are so small that they have almost a negligible impact on fusion adoption.

becomes economically competitive. At tighter emissions caps, fusion capacity is monotonically increased, and system size monotonically decreases. Technology siting limitations significantly impact fusion adoption. The four regions with the most significant fusion adoption (Atlantic, California, Northeast, and Southeast) also have the most stringent wind restrictions. In another set of scenarios, fusion was forced into the system at 60 gCO_2-equiv/kWh, even if it was not economically competitive. This caused the system cost of energy to increase by \$0–5/MWh, corresponding to a 0%–7% cost increase. This is a relatively small increase considering that fusion is both firm and dispatchable.

Analysis of the optimized economic dispatch schemes showed that fusion operates seasonally. Fusion operates at the highest CF in the summer and winter months and at the lowest CF in the spring. At a carbon ceiling of 20 gCO_2-equiv/kWh, fusion exhibits a national average summer peak CF of 77% in August and monthly CF low of 27% in April. Note that required maintenance was restricted to occurring in only the spring because it is the period of lowest operation.

EXPERIMENTAL PROCEDURES

Hourly CF profiles for VRE sources

Wind and solar availabilities are compiled from data pulled from the zero-emissions electricity system planning with hourly operational resolution (ZEPHYR).[23] For each region, hourly CF vectors are sourced for 169 equidistant sites within the boundary, each 30 miles apart. These 169 CF curves are then aggregated to create a profile that is representative of the region. Wind CF values are calculated based on NREL's Wind Integration National Dataset (WIND) Toolkit, assuming a 100 m hub height.[36] Solar CF values are calculated based on NREL's National Solar Radiation Database (NSRDB), assuming single-crystalline modules with single-axis tracking systems and 1.3 DC-to-AC inverter ratios.[37]

RoR availabilities are calculated based on the United States Geological Survey (USGS) daily flowrate data. This source provides flowrate data on over 1.9 million water resources within the US. River resources were sorted into their

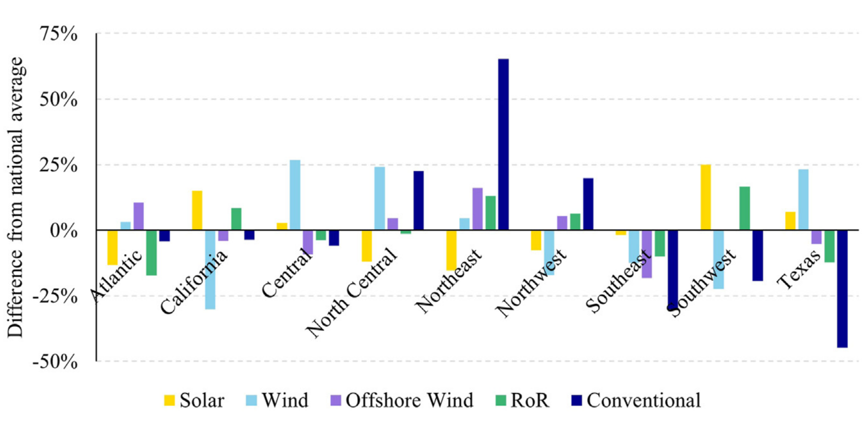

Figure 12. Regional CF's difference from technology's national CF average

Table 6. Regional demand values

	Atlantic	California	Central	North Central	Northeast	Northwest	Southeast	Southwest	Texas
Annual demand (TW)	1,415	721	602	593	513	681	552	353	727
Peak demand/average demand	1.71	1.79	1.69	1.79	1.70	1.61	1.80	1.79	1.74

appropriate regions based on latitude and longitude coordinates. Daily flowrates were summed together and then used to calculate power output. These data are only available at a daily timestep, so the corresponding CF values are assumed for all 24 h of the day. Also, conventional hydropower CFs are constrained at monthly checkpoints to account for reservoir volume limitations. Within each month, the hourly CF is allowed to ramp without restriction.

For all resources that have externally impacted power output, CF curves are generated for the years 2007–2013 because these are the years with the most complete datasets. Figure 12 shows the average relative strength of each technology in a region, where the CF national average is 25% for solar, 36% for wind, 40% for offshore wind, 63% for RoR, and 36% for conventional. In general, the Southeast can be highlighted as a region with weak renewable resources. CF curves for all technologies are available upon request.

Regional demand data

645731553784500Demand profiles were sourced from NREL's *2022 Cambium* dataset.[38] NREL provides hourly demand data within NERC boundaries. Some of the smaller NERC regions are aggregated to represent the regions shown in Figure 1. It should be noted that results are shown in a relative format to allow for inter-regional comparisons. Demand is scaled down by a different factor in each region so that the average hourly demand is 1 kW. This format measures installations in "capacity over average demand" units because 1 kW of generator installations implies that all resources were operating at 100% CF. Table 6 can be used to convert to real values.

Regional installation limitations

All three types of hydro resources (conventional, RoR, and PHS), land-based wind, offshore wind, geothermal, and solar have capacity limits in each region. Conventional hydro is limited based on estimates from *Electric Power Annual*, *Hydropower Vision*, and *An Assessment of Energy Potential at Non-Powered Dams in the US*.[39–41] RoR capacity limits are sourced from the *New Stream Reach Development*.[42] PHS capacity limits are obtained from NREL's *Closed-Loop Pumped Storage Hydropower Resource Assessment for the US*.[43] More details around these limitations can be found in *Accurately Modeling Hydropower in the US*.[11] NREL's *Assessment of Offshore Wind Energy Resources for the United States* provides estimates for offshore wind capacity limits.[44] Land-based wind, solar, and geothermal restrictions were obtained from NREL's *US Renewable Energy Technical Potentials*.[45] Figure 13 shows the regionally imposed limits. Normalized solar limits are not included in Figure 13 because they are above 2 times average demand in all regions.

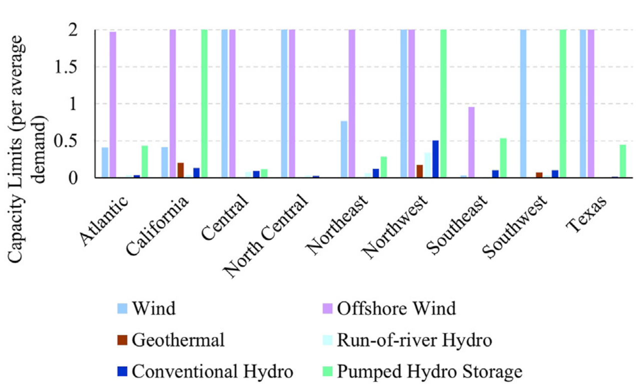

Figure 13. Normalized regional capacity limits

Temporal dimensions

IG calculates economic dispatch decisions at an hourly timestep. The optimization is conducted for 7 consecutive years. This 7-year timeline is chosen because weather data vary from year to year, and it is important to design a robust system that will satisfy demand for a variety of scenarios. The optimized fleet must satisfy demand during all 7 years.

Fusion maintenance

Fusion is assumed to have an 85% annual availability factor. Fusion is expected to perform periodic replacement of key elements, such as blankets and diverters, which will require extended periods of maintenance.[46] To capture the impact of this need, the 1,314 h of annually required maintenance were constricted to occur only within the 3 months where fusion sees the lowest operation. Below, Table 7 shows maximum hourly CFs for the maintenance season selected for each region. Maintenance scheduling was distributed monthly based on runs conducted without maintenance represented.

Transmission and distribution costs

Transmission costs and distribution costs are both regionally and technology-specific. Distribution costs are estimated and projected out in Tables 54.1–54.25 of the EIA's *Annual Energy Outlook 2023*.[30] Distribution costs are provided for regions separated along the NERC boundaries, which coincide conveniently with IG's nine regions of analysis, allowing for easy aggregation of the 2050 projected values. Resultant values are shown in Figure 14. Note that distribution costs in the Northeast are over double the cost of any other region. Having said that, these values have no impact on optimized buildout and only impact estimated electricity cost.

Transmission costs are calculated based on a series of publications from Berkeley Labs. A series of analyses have been conducted to gain clarity on the interconnection costs of different technologies in different regions. A study was done in the following territories: New England's ISO,[47] the Southwest Power Pool,[48] New York,[49] Pennsylvania-New Jersey-Maryland,[50] and the Mid-continent Independent System Operator.[51] These reports show that there is significant regional and technological variability in interconnection costs. Since this analysis was only conducted for a collection of regions, the other areas are assumed to have costs equal to the national average. Also, no data were available on the cost of offshore wind installations in the Central and North Central regions, so again, the national average is assumed. The resultant values are shown in Figure 15.

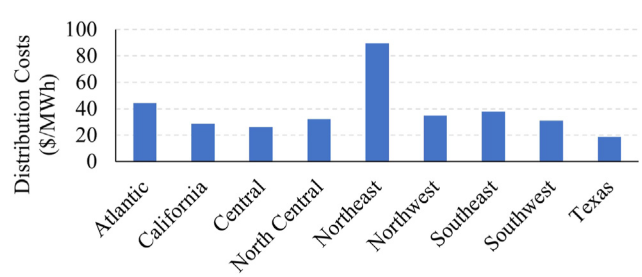

Figure 14. Regional distribution cost projections for 2050

Table 7. Regional hourly CF limits for maintenance seasons

	Atlantic	California	Central	North Central	Northeast	Northwest	Southeast	Southwest	Texas
Jan	–	–	–	–	–	–	–	–	–
Feb	–	–	–	–	–	–	–	–	43%
Mar	54%	–	41%	50%	50%	–	48%	45%	37%
Apr	26%	42%	38%	35%	33%	38%	24%	37%	36%
May	41%	40%	43%	36%	39%	39%	50%	40%	–
Jun	–	37%	–	–	–	43%	–	–	–
Jul	–	–	–	–	–	–	–	–	–
Aug	–	–	–	–	–	–	–	–	–
Sep	–	–	–	–	–	–	–	–	–
Oct	–	–	–	–	–	–	–	–	–
Nov	–	–	–	–	–	–	–	–	–
Dec	–	–	–	–	–	–	–	–	–

Figure 15 shows current interconnection values, but these values are expected to increase. The EIA's *Annual Energy Outlook 2023* contains regional estimates for transmission cost increases. These values are collected and aggregated in the same way that distribution costs were. Note that projected % increases are applied equally to all technologies. Table 8 shows the % price increase of each region by 2050, reaching up to 100% in some regions.

Brownfield installations

Based on the respective installation date and lifetime of current infrastructure, current units that will not have retired in 2050 can be incorporated into the model. Both emissions (embodied and operational) and costs are considered from current infrastructure. The values are calculated from data sourced from the EPA's eGRID.[52] Resultant active infrastructure for the year 2050 is shown in Figure 16. Note that IG allows for early retirement of only fossil-fuel power plants.

Other model assumptions

There are a few other basic model assumptions to note. There is an assumed transmission and distribution (TD) loss of 4.7% and tax of 6.35%. IG is deterministic, meaning that it has perfect foresight of demand and VRE CF profiles.

Framework and runtime

IG is run in Python, using Pyomo. It is solved using Gurobi version 9 in about 25 min on a 64-bit operating system.

RESOURCE AVAILABILITY

Lead contact

Information and requests will be fulfilled by the lead contact, Amanda Farnsworth (amfarnsw@mit.edu).

Materials availability

No new materials were generated by this study.

Data and code availability

All data used in this study are publicly available, with sources included in supplemental information and the below sections. Code for this study will be made available upon request.

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AUTHOR CONTRIBUTIONS

Conceptualization, A.F. and E.G.; methodology, A.F.; software, A.F.; validation, A.F.; formal analysis, A.F.; investigation, A.F.; data curation, A.F.; writing –

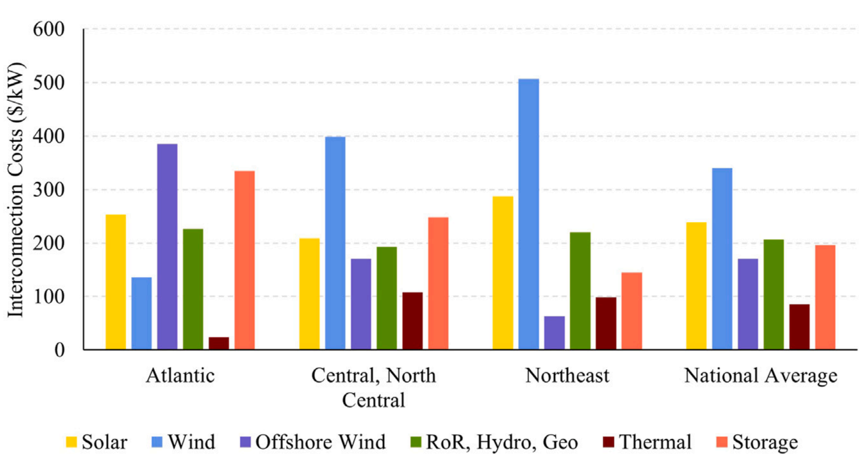

Figure 15. Regionally and technologically specific interconnection current costs

Table 8. Projected change in interconnection costs, by region

	Atlantic	California	Central	North Central	Northeast	Northwest	Southeast	Southwest	Texas
2050 interconnection cost increases	30%	103%	52%	50%	75%	105%	64%	27%	93%

original draft, A.F.; writing – review and editing, A.F. and E.G.; visualization, A.F.; supervision, E.G.; project administration, E.G.; funding acquisition, E.G.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.crsus.2024.100238.

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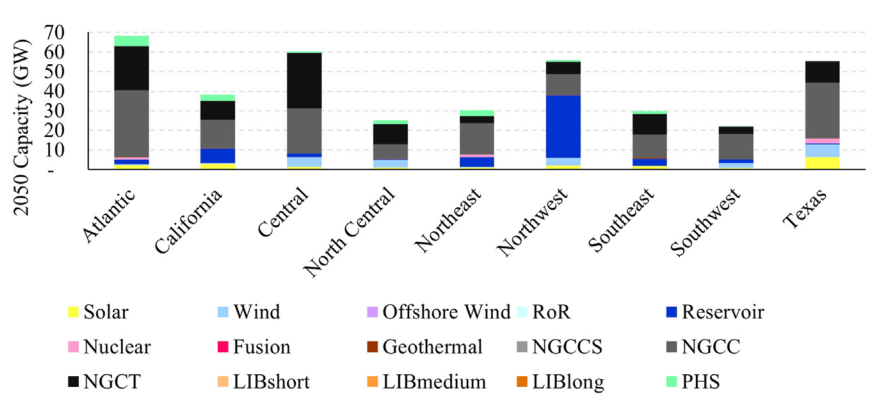

Figure 16. Current infrastructure expected to be active in 2050, based on estimated technology lifetimes

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