ERCOT Renewable Grid Analysis

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Executive Summary

Executive Summary

This analysis serves to demonstrate the reliability challenges of operating a grid solely based on solar, wind, storage, and existing nuclear power. The study uses a "copper plate model," which assumes all generation and consumption are interconnected, and it does not consider transmission feasibility. Building the necessary transmission infrastructure to support a grid entirely reliant on renewables and storage is a significant financial and technical challenge beyond the scope of this analysis.

This report analyzes data from 2022 and 2023 drawing conclusions based on those years.

Texas, known for its energy leadership in both production and consumption, has made remarkable strides in adopting renewable energy technologies, even with its roots in oil and gas. Recent years have seen substantial growth in solar and wind installations in Texas. Solar generation increased from 25 billion kWh in 2015 to over 146 billion kWh in 2022, while wind generation grew from 191 billion kWh to 435 billion kWh. This increase in wind generation meets about 25% of ERCOT's demand, reflecting a high integration of intermittent renewables into the grid. Additionally, ERCOT's 9% share of nuclear generation provides firm, clean power.

As Texas transitions away from fossil fuels, this analysis explores the generation and load dynamics under a fully renewable scenario. It aims to determine the renewable installed capacity overbuild and storage requirements necessary to sustain such a grid. The key finding reveals that addressing the intermittency of solar and wind requires substantial overbuilding of capacity and significant energy storage solutions. Due to low capacity factors of intermittent renewable sources, an overbuild, or increasing the installed capacity well beyond the generating capacity, is required coupled with energy storage to "firm" the grid. This report analyzes the annual averages for demand alongside existing solar, wind, nuclear, and battery storage installations to determine what the generating capacity and storage overbuild requirements would be to satisfy average demand with a carbon free grid. The analysis suggests a need for a 3.4x solar and wind overbuild and a 42.4x increase in storage capacity, totaling 203 GW of solar and wind generation and 169 GW of storage, to satisfy the average hourly demand. Noting this is the average demand, there will be periods of higher loads where generation and storage fall short. Despite these high values for renewables and 5 GW of firm nuclear power, the system only meets demand 76% of the time, equivalent to 176 days over the two-year period when generation and storage fall short.

Electricity Generation Mix

Electricity Generation Mix

Comparing ERCOT's Renewable Generation

The United States electricity grid features 21.5% renewable generation, primarily from wind and solar, and nearly 10% from nuclear power, which provides stable, clean, baseload energy. Despite being the second-largest producer of solar and wind generation of all countries, the US would have to grow this capacity substantially to achieve a carbon free, reliable power grid nationwide.

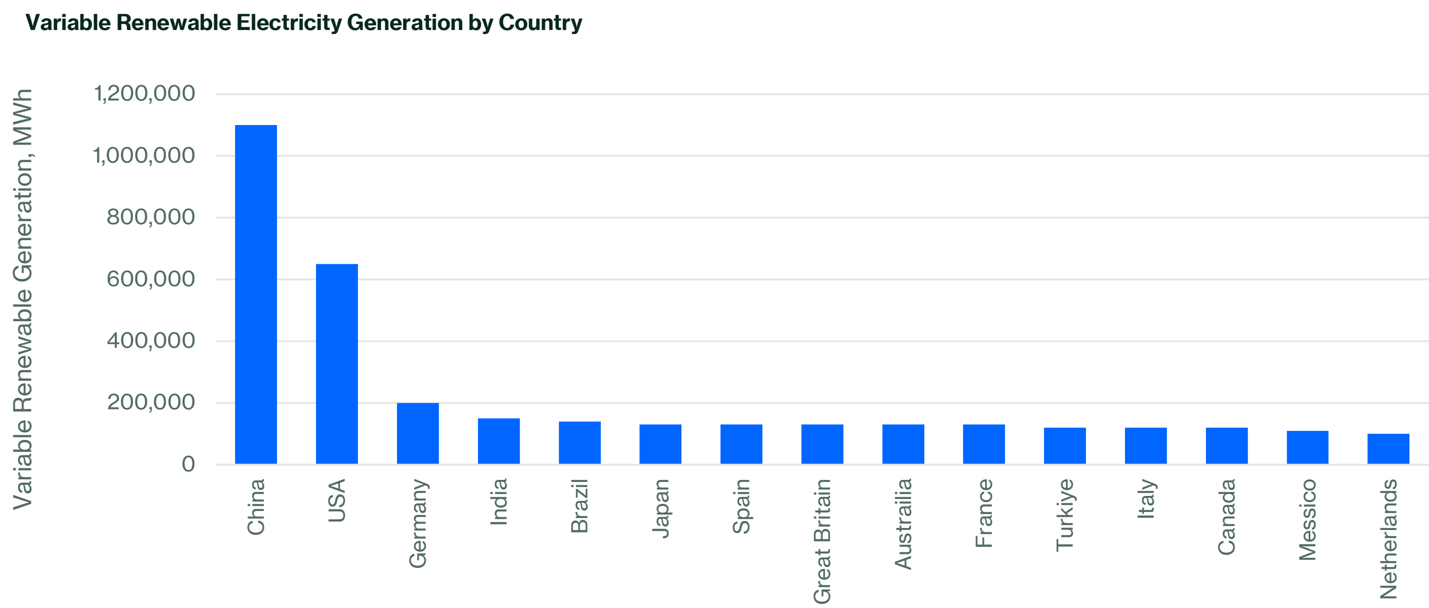
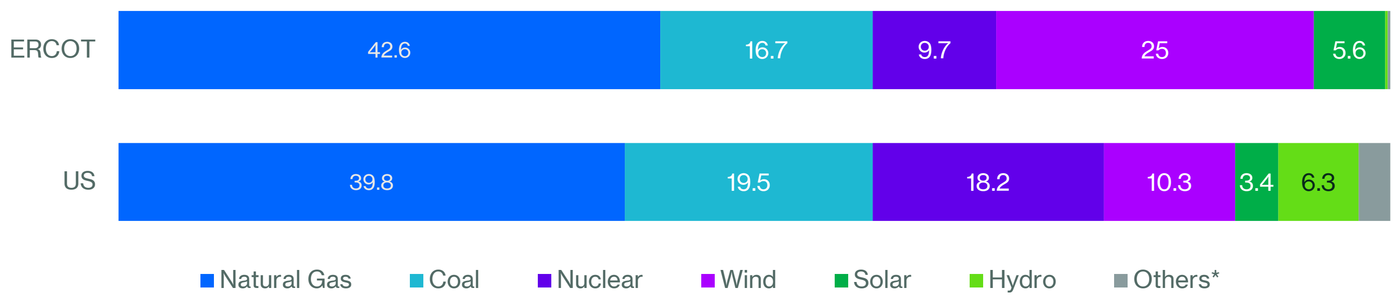


Figure 1. Top 15 variable renewable energy producers

Texas, the largest electricity producer and consumer in the U.S., plays a major role in the country's renewable generation expansion efforts. In 2022, the Electric Reliability Council of Texas (ERCOT), the state's grid operator, generated 30.9% of its electricity from renewable sources. This made Texas the leader in renewable generation, ahead of states like Washington (whose primary renewable is hydropower) and California (whose primary renewable is solar power). Texas's substantial solar and wind capacity is largely due to its favorable geographic conditions, boasting strong solar irradiance and high wind speeds. Even with favorable weather conditions, the load on the grid continues to grow and reach new highs, straining the renewable generation portfolio. Severe weather events, which have recently increased in frequency, further strain the grid and make the need for reliable availability of sun and wind, impossible to schedule commodities, even more important. As this analysis will show, continuing to deploy intermittent renewables in place of baseload assets to support the increasing demand is not without challenges.

ERCOT's grid has over 9% nuclear generation (5 GW) which helps increase reliability by providing a strong percentage of firm power. However, using intermittent renewables and storage to satisfy the rest of the grid does not provide a realistic and feasible pathway to full decarbonization.

Electricity generation mix for the US and ERCOT



*For the US, others include 0.4% geothermal, and 1.3% biomass; for ERCOT, others include 0.1% biomass. ERCOT has no geothermal

Figure 2. Electricity grid composition for the US and ERCOT

By the end of 2023, Texas's intermittent renewable capacity reached nearly 60 GW, out of nearly 155 GW of total installed generation capacity.[1] However, this renewable capacity has not consistently met demand, which peaked at almost 84 GW and averages 50 GW, even when it surpassed the instantaneous load. The highest percentage of the demand met by renewables and nuclear was 83%, a substantial portion, but the lowest percentage of demand met was 11%, remarkably low. This reflects significant variability in the generation of renewable resources. This large variability is due to the weather-dependent nature of solar and wind and the inability to control it. Solar and wind have capacity factors of 25% and 35%, respectively, according to the DOE.[2] Capacity factor refers to the ratio of electrical energy produced for a period of time compared to the amount that could be produced at continuous full power during the same period. The current combined capacity factor for solar, wind, and nuclear on the ERCOT grid averaged 36%, with a high of 67% and a low of just 9%. Solar and wind penetration was 30.9%, and nuclear generation was 18%.

The ERCOT demand less the nuclear generation provides the total solar and wind generation needed at each hour to satisfy demand. Dividing this load value by the percent of demand met by solar and wind for that hour provides the necessary installed capacity:

$$Needed\ Installed\ Hourly\ Capacity = \frac{Total\ load - nuclear\ generation}{Percent\ of\ demand\ met\ by\ wind\ and\ solar}$$

Subsequently dividing by the installed capacity provides the overbuild factor. This was done for each hourly interval and then averaged over months and years to get the most accurate representation for the annual level. For periods when generation does not meet demand, the average shortfall at each hour represents the storage needed for a fully renewable system. This process is then used to determine annual average storage requirements. The data calculated is shown below in Figure 3.

[1] Texas Comptroller
[2] U.S. Energy Information Administration via Energy.Gov

Monthly ERCOT demand and generation data

Month	Average Demand (MW for one hour)	Average Solar, Wind, Nuclear Generation (MW for one hour)	Average Capacity Factor (%)	Average Percent of Demand Satisfied	Average Amount of Storage (MW for one hour)	Average Overbuild
1	44,128	20,073	42%	47%	17,053	3.1
2	45,859	20,971	44%	47%	19,229	3.6
3	41,977	22,245	46%	53%	11,321	2.0
4	42,867	22,745	46%	53%	11,015	1.9
5	50,549	21,499	43%	43%	11,071	2.9
6	59,025	21,548	43%	37%	13,377	4.0
7	62,919	21,452	42%	35%	13,785	4.4
8	62,857	18,690	36%	30%	19,112	5.7
9	56,014	17,951	35%	32%	17,326	4.8
10	45,619	18,644	36%	41%	12,997	2.9
11	43,606	18,722	35%	43%	14,392	2.6
12	45,197	19,453	35%	44%	15,005	2.8
Average	50,052	20,333	43%	42%	14,640	3.4

Figure 3. Monthly and annual averages for key metrics to provide high level view on ERCOT grid performance

Figure 4 below illustrates the demand profile for 2022 and 2023 averaged over 6-hour intervals, the installed capacity of solar and wind, growing from 44 GW at the start of 2022 to just shy of 60 GW at the end of 2023, and the total generation profile for renewable and nuclear generation, also averaged over 6-hour intervals.

ERCOT renewables and nuclear electricity generation and installed renewable capacity
2022–2023

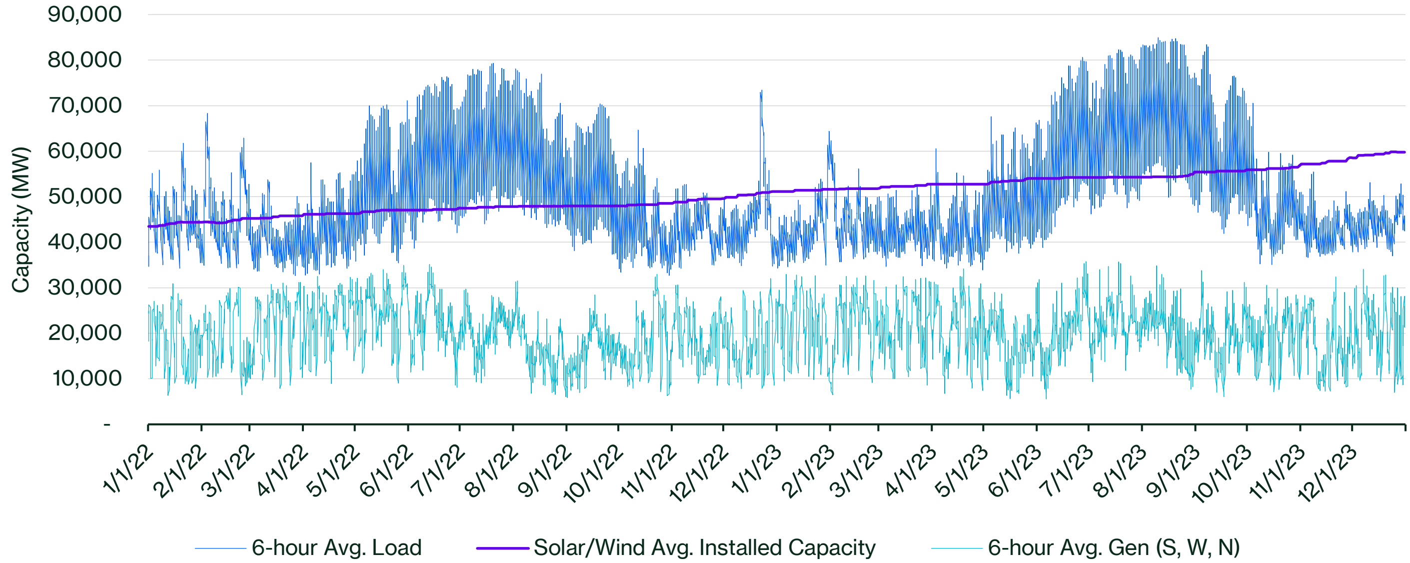


Figure 4. ERCOT load, variable renewable and nuclear generation, and solar and wind installed capacity

Storage and Overbuild Requirements

Storage and Overbuild Requirements

ERCOT publishes hourly data for the grid annually, including metrics on demand, installed solar and wind capacity, solar and wind generation, and capacity factors. Nuclear capacity and generation are detailed in ERCOT's "Report on the Capacity, Demand, and Reserves," which provides a 10-year outlook on the grid. Using this data, we can calculate the overbuild required for an entirely intermittent renewable system on an hourly basis, then average this over several months and a year to model the system.

To determine the overbuild required, we use the following formula:

$$Overbuild = \frac{\left[\frac{(ERCOT\ demand - nuclear\ generation)}{Avg.percent\ of\ demand\ met}\right]}{Total\ Installed\ Renewable\ Capacity}$$

The previous section described how the total required hourly generating capacity was derived. Taking this one step further, the hourly overbuild can be calculated by dividing this number by the current installed capacity to provide the overbuild factor. This was done for each hourly interval and then averaged over months and years to get the most accurate representation for the annual level. For periods when generation does not meet demand, the average shortfall at each hour represents the storage needed for a fully renewable system. This process is then used to determine annual average storage requirements. The data calculated is shown above in Figure 3 in the prior section.

Based on annual averages shown in Figure 3 above, a 3.4x generation overbuild is needed to meet average demand. This calculation is based on 2022 and 2023 data. While this overbuild should theoretically satisfy an average demand of 50,052 MW, the actual load profile varies, resulting in significant times when generation and storage fall short. In designing a proper electricity grid, reliability remains a top priority,[3] and in that case, designing to the minimum would be required. However, this model integrates the storage requirements necessary to fully satisfy the average demand and looks at the combinations in which demand can be fully satisfied.

Increasing solar and wind capacity by 3.4x allows us to recalculate solar and wind generation using ERCOT's hourly capacity factors, while nuclear generation and grid demand remain constant. Despite surpassing 200 GW of installed renewable capacity and over 5 GW of nuclear capacity, generation meets demand only about 60% of the time, leaving 40% of the year unmet. This shortfall occurs over various hourly intervals, with the longest consecutive drought spanning 243 hours, necessitating long-duration storage solutions not yet commercially available. The average shortfall of 12 hours could be addressed by batteries, but longer-duration storage would be more practical. With the generation and demand profile of 2022 and 2023, there are still 7,070 hours over these two years where generation falls short of demand, equivalent to 40% of the time.

[3] Geophysical constraints on the reliability of solar and wind power worldwide

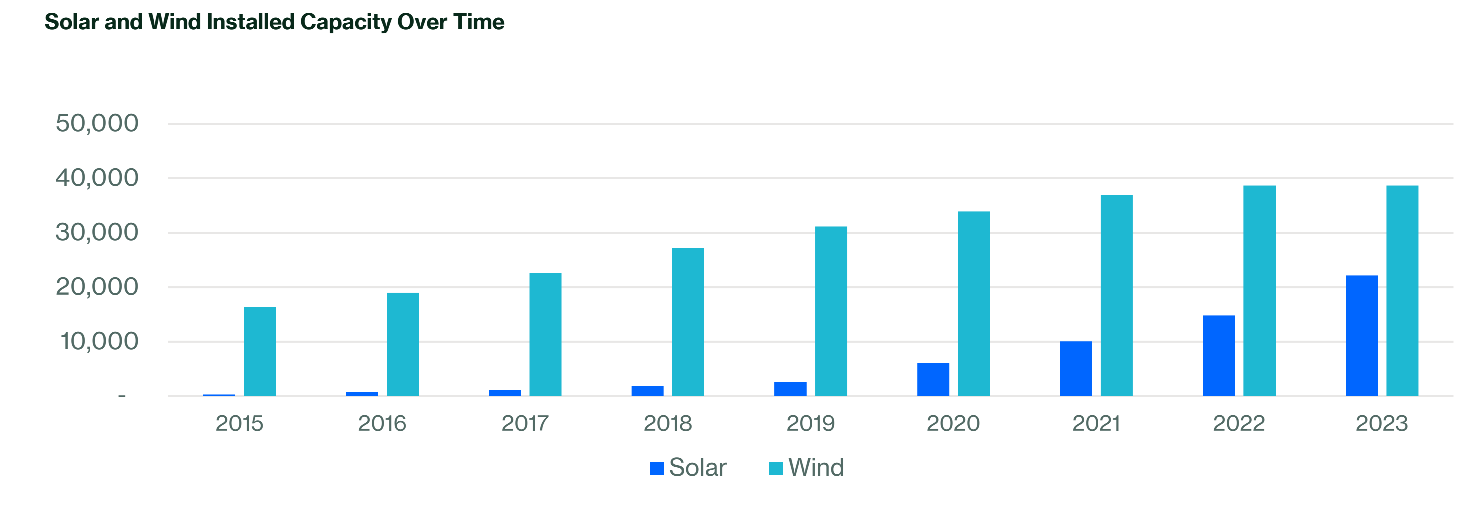


Figure 5. Solar and wind installed capacity over time to show growth in deployments

Multiplying the average drought of 12 hours by the average storage requirement of 14,640 MW per hour, the total required storage capacity for the system to satisfy the average demand is 169,604 MW. Assuming the storage starts empty, excess generation during periods of surplus is used to charge the storage, up to its capacity, then anything above that is curtailed. When demand exceeds generation, the difference is deducted from the storage, until all reserves have been drained. If storage is depleted, generation cannot meet demand. Despite having 169 GW of storage, there remains a 24% shortfall, equivalent to 176 days over two years. Such unreliability, nearly a quarter of the time not meeting demand, would and should be unacceptable to ERCOT residents. Figure 6 illustrates this below.

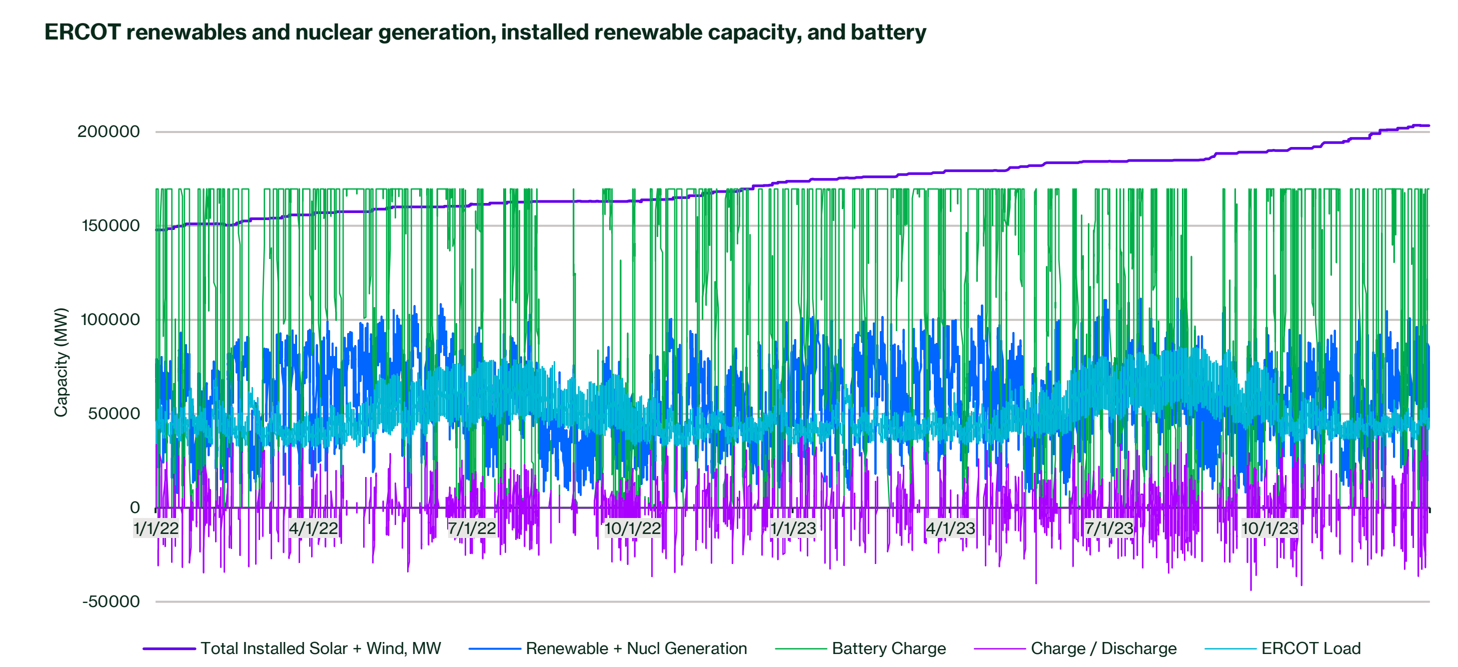


Figure 6. ERCOT grid performance with 169 GW of storage

To reduce the unmet demand, ERCOT must increase the overbuild of solar and wind. However, by doing so, the duration and value of the generation shortfalls decrease, thereby decreasing the amount of storage required. Additionally, the relationship between overbuild and storage capacity shows diminishing returns beyond a 15x overbuild. Figure 7 shows two charts, one representing the overbuild and storage combinations where the percentage of each year that demand is unmet is between 1 and 10.5% of the year. These should be viewed as combinations, not a progressive process.

For example, ERCOT could select a combination of a 5x overbuild and 70,000 MW of storage, but if ERCOT were to decide on a 10x overbuild, they would only install 12,000 MW of storage. In the lower chart, where unmet demand is always less than 1% of the year, storage capacity is held constant at 4.1 GW, representative of ERCOT's current installed value, because no storage would be taken off the grid. Figure 7 below clearly shows the diminishing returns with an ever increasing overbuild. With a 15x overbuild and 4.1 GW of storage, 1.38% of the time is unmet. This reduces to 0.68% with a 20x overbuild and the same amount of storage, and to 0.39% with a 25x overbuild and the same 4.1 GW of storage, so as not to drop below ERCOT's current installations, demonstrating the diminishing returns of excessive overbuilds.

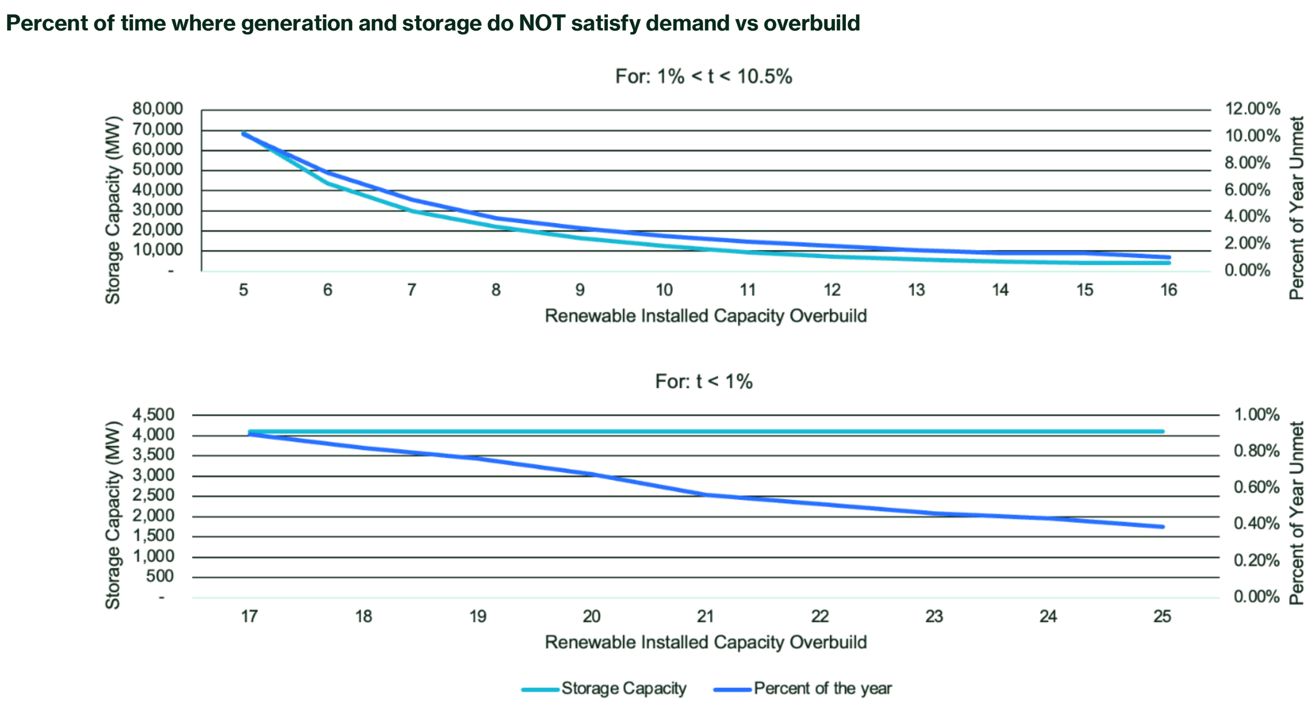


Figure 7. Overbuild and storage capacity relationship

Achieving a reliable grid with a feasible overbuild or storage increase is unlikely. Figure 8 shows that even with a 5x overbuild and corresponding 10x in storage capacity – totaling 299 GW of renewable generation and 40 GW of storage – only 88% of demand can be fully satisfied, not considering transmission challenges.

Percent of demand *fully* satisfied by solar and wind power generation and storage
Based on 2022 – 2023 demand profile

Excessive Overbuild → >5x today's installments (from overbuild 6)

Installed Capacity (GW) and Overbuild

Storage Capacity (GW) and Overbuild	Installed Capacity	59,830	119,660	179,490	239,320	299,150	358,980	418,810	478,640	538,470	598,300	658,130	717,960	777,790	837,620	897,450	957,280	1,017,110	1,076,940	1,136,770	1,196,600
	Overbuild	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
4.1	1.0	0.0%	23.7%	53.0%	72.9%	83.5%	88.8%	92.1%	94.4%	95.8%	96.8%	97.4%	97.9%	98.3%	98.6%	98.9%	99.0%	99.1%	99.2%	99.3%	99.4%
4.8	1.2	0.0%	23.9%	53.3%	73.2%	83.7%	88.9%	92.2%	94.6%	95.8%	96.8%	97.5%	98.0%	98.4%	98.6%	98.9%	99.0%	99.2%	99.2%	99.3%	99.4%
5.6	1.4	0.0%	24.1%	53.7%	73.5%	83.8%	89.1%	92.3%	94.7%	95.9%	96.9%	97.6%	98.0%	98.4%	98.7%	98.9%	99.1%	99.2%	99.2%	99.3%	99.4%
7.0	2	0.0%	24.5%	54.1%	74.0%	84.1%	89.3%	92.6%	94.8%	96.0%	97.0%	97.6%	98.1%	98.5%	98.7%	99.0%	99.1%	99.2%	99.3%	99.4%	99.5%
10.0	2	0.0%	25.0%	54.8%	74.8%	84.8%	89.7%	93.0%	95.1%	96.3%	97.2%	97.8%	98.3%	98.7%	98.8%	99.1%	99.2%	99.2%	99.3%	99.4%	99.5%
13.0	3	0.0%	25.6%	55.5%	75.5%	85.3%	90.2%	93.2%	95.3%	96.6%	97.4%	98.0%	98.4%	98.7%	98.9%	99.1%	99.2%	99.3%	99.4%	99.5%	99.5%
16.0	4	0.0%	25.9%	56.1%	76.1%	85.8%	90.6%	93.5%	95.6%	96.7%	97.6%	98.1%	98.5%	98.8%	99.0%	99.2%	99.3%	99.4%	99.4%	99.5%	99.6%
20.0	5	0.0%	26.3%	56.7%	76.9%	86.3%	91.0%	93.8%	95.9%	97.0%	97.7%	98.3%	98.6%	98.9%	99.1%	99.2%	99.3%	99.4%	99.5%	99.5%	99.6%
25.0	6	0.0%	26.8%	57.4%	77.5%	86.8%	91.4%	94.4%	96.1%	97.2%	97.9%	98.5%	98.8%	99.0%	99.2%	99.3%	99.4%	99.5%	99.5%	99.6%	99.7%
30.0	7	0.0%	27.2%	58.1%	78.2%	87.3%	91.8%	94.7%	96.4%	97.5%	98.1%	98.6%	98.9%	99.1%	99.2%	99.4%	99.5%	99.5%	99.6%	99.6%	99.7%
40.0	10	0.0%	27.7%	59.2%	79.2%	88.2%	92.4%	95.3%	96.8%	97.8%	98.4%	98.8%	99.0%	99.3%	99.4%	99.5%	99.5%	99.6%	99.6%	99.7%	99.8%
50.0	12	0.0%	28.2%	60.0%	80.1%	88.8%	93.0%	95.7%	97.2%	98.2%	98.7%	99.0%	99.2%	99.3%	99.4%	99.5%	99.6%	99.7%	99.7%	99.8%	99.8%
75.0	18	0.0%	29.0%	61.8%	81.8%	90.1%	94.2%	96.6%	98.0%	98.7%	99.0%	99.2%	99.4%	99.5%	99.6%	99.7%	99.7%	99.8%	99.8%	99.8%	99.9%
100.0	24	0.0%	29.7%	63.2%	83.0%	91.0%	95.0%	97.4%	98.5%	99.0%	99.2%	99.4%	99.5%	99.6%	99.7%	99.7%	99.8%	99.8%	99.9%	99.9%	99.9%
125.0	30	0.0%	30.2%	64.2%	83.9%	91.9%	95.7%	97.9%	98.8%	99.2%	99.4%	99.5%	99.6%	99.7%	99.7%	99.8%	99.8%	99.9%	99.9%	99.9%	99.9%
150.0	37	0.0%	30.8%	65.3%	84.8%	92.5%	96.2%	98.2%	99.0%	99.3%	99.5%	99.6%	99.7%	99.8%	99.8%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%
175.0	43	0.0%	31.2%	66.1%	85.6%	93.0%	96.6%	98.5%	99.2%	99.5%	99.6%	99.6%	99.7%	99.8%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	100%
200.0	49	0.0%	31.6%	66.9%	86.2%	93.4%	96.9%	98.7%	99.3%	99.5%	99.6%	99.7%	99.8%	99.8%	99.9%	99.9%	99.9%	99.9%	99.9%	100%	100%
250.0	61	0.0%	32.2%	68.2%	87.2%	94.0%	97.4%	99.0%	99.4%	99.6%	99.7%	99.8%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	100%	100%	100%
500.0	122	0.0%	34.0%	72.5%	90.2%	95.9%	98.6%	99.5%	99.8%	99.9%	99.9%	99.9%	99.9%	100%	100%	100%	100%	100%	100%	100%	100%
1,000.0	244	0.0%	35.0%	75.3%	92.7%	97.8%	99.4%	99.9%	99.9%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
1,500.0	366	0.0%	35.3%	76.8%	94.5%	98.6%	99.9%	99.9%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2,000.0	488	0.0%	35.3%	77.9%	95.6%	99.0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Excessive Storage → >10x today's installments (from 50.0 GW storage)

Figure 8. Percent of demand met based on overbuild and storage combinations

To contextualize these requirements, the current installed solar and wind capacity sits just below 60 GW, and storage capacity reached 4.1 GW by the end of 2023. Satisfying the average demand through renewables and storage would require increasing solar and wind capacity to 203 GW and storage to 169 GW. Figure 9 illustrates these required increases.

Installed capacity gaps between today's installations and target for a 3.4x overbuild and 169 GW of storage

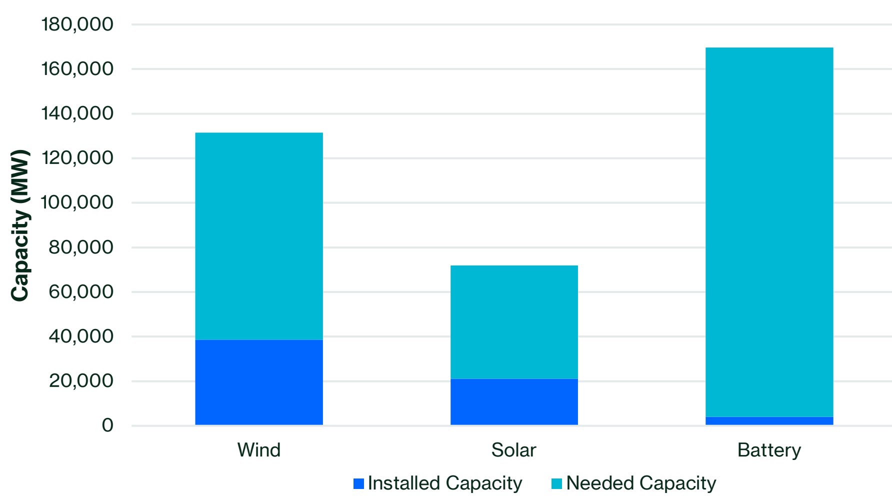


Figure 9. Installed capacity gaps between today's installations and target for a 3.4x overbuild and 169 GW of storage

Solar installations grew from 302 MW in 2015 to over 22,153 MW in 2023. At the current installation rate of 2,731 MW per year, it would take another 10 years to add 50,815 MW more to reach the additional required capacity. Wind installations increased from 16,377 MW to 38,674 MW in the same period. At a similar rate of 2,787 MW per year, it would take over 25 years to add the additional required capacity of 92,814 MW. All this is required just to reach the 3.4x overbuild required for solar and wind installations for average demand, not accounting for supply chain, material, and manufacturing considerations, or growth in demand as this is based on 2022 and 2023 data.

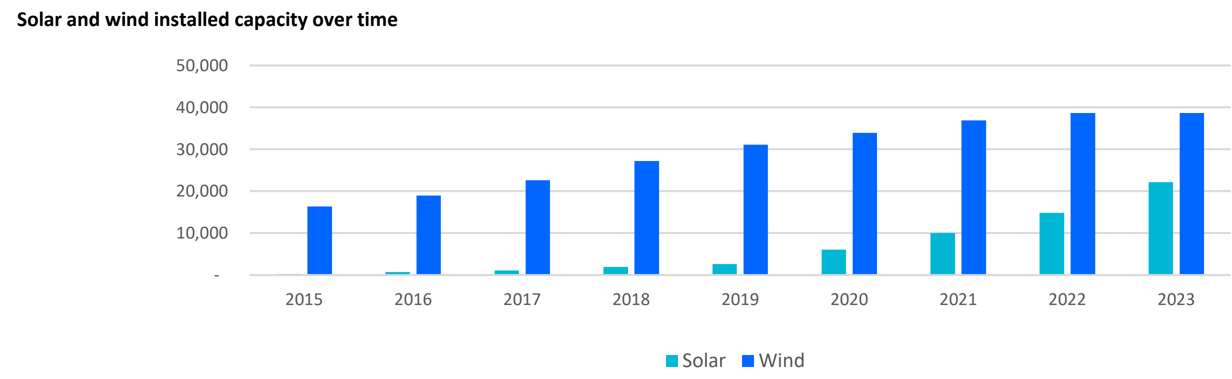


Figure 10. Solar and wind installed capacity over time to show growth in deployments

Land Requirements

Land Requirements

Assuming the availability of all needed solar panels and wind turbines to overbuild to the desired capacity, the next question becomes whether there is enough land available for development. Because solar and wind harness a distributed source of energy, they have very low power densities. Power density measures the amount of power per unit area for a given type of energy. The prevalence and reliance on fossil fuels is largely due to its consolidated surface footprint resulting from its high power density, so it can be co-located with load centers. Solar and wind are on the opposite end of the spectrum.

The National Renewable Energy Laboratory (NREL) published a paper in 2013 on the power density of solar panels in the US, concluding solar has an average power density of 8.6 W/m^2, which includes the land between the solar panels.[4] In 2022, Lawrence Berkeley National Lab (LBNL) published an update for single-axis and fixed-tilt solar panels highlighting a 50% increase in efficiency, reaching 12.9 W/m^2.[5] In 2009, NREL published a report on wind power densities across various geographies in the US, denoting an average of 2.86 W/m^2.[6] Based on these numbers, we can estimate the total current surface footprint of solar and wind capacity in ERCOT and the expected area required for a 3.4x overbuild.

The current installed capacity for solar energy reaches 22,153 MW, resulting in a current footprint of 1,717 km^2. The current installed capacity for wind power exceeds solar and reaches 38,674 MW, but at a much lower power density than solar, requiring 13,618 km^2. Combining the required areas for both solar and wind, this reaches 15,335 km^2.

Holding the ratio of solar and wind generating capacity constant and scaling up the installed capacity to the 3.4x overbuild, the solar installation grows to 75,320 MW and wind to 131,492 MW. These would require 5,838 km^2 and 46,300 km^2, respectively. Combined, this totals 52,139 km^2. For reference, this increase in size is representative of going from an area the size of the state of Connecticut to an area the size of Lake Michigan! This does not include the land required for transmission, storage, or the available land for development in the state.

[4] Land-Use Requirements for Solar Power Plants in the United States
[5] Land Requirements for Utility-Scale PV: An Empirical Update on Power and Energy Density
[6] Land-Use Requirements of Modern Wind Power Plants in the United States

Conclusion

Conclusion

While an energy transition is already underway, fueled largely by the growth in solar and wind, the electric grid cannot operate purely on the renewables available today. Despite progress, this analysis demonstrates that meeting demand solely through renewable sources and existing nuclear power presents substantial challenges. Even with a 3.4x increase in installed solar and wind capacity, amounting to 203 MW, and a 41.4x increase in storage, reaching 169,604 MW, generation fails to meet demand approximately 24% of the time each year. This equates to 176 days over the two-year period considered in this analysis, equivalent to 88 days annually. This 24% occurs in varying durations, ranging from 1 to 243-hour periods and magnitudes over the course of two years, based on 2022 and 2023 demand. This means that the gap between generation and load can range from a few hours a day to multiple days straight, often equivalent to a severe storm hitting the region. This shortfall reflects the inherent intermittency and lack of reliability that renewable sources provide and the limits of energy storage technology. While increasing the overbuild can reduce the frequency, duration, and magnitude of unmet demand, the returns are diminishing and yield limited improvements in reliability. This is evidenced by a 15x overbuild and 4.1 GW of storage (representative of ERCOT's current capacity), leaving the 1.38% of time unmet only being reduced to 0.68% at a 20x overbuild and the same 4.1 GW of storage.

To put these findings into perspective, ERCOT must increase the installed solar and wind capacity to 203 GW and storage capacity to 169 GW to satisfy the average demand. This represents a massive scaling effort from the current 60 GW of solar and wind (to 3.4x) and 4.1 GW (to 41.4x) of storage. The historical installation rates, based on growth from 2015 to 2023, suggest that reaching these levels would take 10 years for solar and over 25 years for wind, not accounting for potential supply chain and manufacturing constraints. The timeline for storage is unclear as it is dependent on the type of storage and its commercial viability to date.

Ultimately, while the shift to renewables is essential for decarbonization, this analysis underscores the complexity and scale of the task. The current infrastructure and technology levels face significant challenges in meeting demand reliably without substantial advancements in storage and generation capacity. While solar and wind ultimately play a prominent role in the energy transition, we must turn our eyes to the next generation of clean, baseload power to revolutionize the energy transition and make it a reality. Moreover, ERCOT's already high solar, wind, and nuclear generation, coupled with Texas's vast amount of land, make it an ideal candidate to model a wholly renewable grid, as it should represent a more feasible challenge. Looking beyond Texas to states or regions where solar and wind have lower capacity factors and less land availability only becomes a more challenging and less economic problem to solve.