

Kazakhstan has the wind to power its demand growth

A hybrid plant combining wind, solar and a small battery can meet 70–90% of a typical demand profile in Kazakhstan at delivered cost below $60 per MWh

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About

This report evaluates the potential and economics of wind power in Kazakhstan. It maps wind resources close to demand centres and existing power lines, then uses hourly simulations to test how much of a typical demand profile a wind plant can meet, and at what cost, when paired with solar and battery. The analysis models 125 wind, solar and battery configurations at each of 15 sites across the country's three power zones, over three weather years and a 30-year project life.

Read the report online at:
https://ember-energy.org/latest-insights/kazakhstan-has-the-wind-to-power-its-demand-growth/

Key highlights

70–90%

Wind, solar and battery hybrids built close to demand can meet 70-90% of it at less than $60/MWh

15–30%

Of annual generation is curtailed by design: the cheap surplus that makes hybrid plants a source of flexibility

66%

of Kazakhstan's territory has mean wind speeds above 7 m/s at 100 m compared to less than a third for a leading wind market like Germany

Executive summary

Kazakhstan can build wind hybrid plants near demand and meet 70-90% of it for less than $60/MWh

Kazakhstan needs new power capacity quickly and its vast wind resources offer a unique opportunity to supply abundant, low-cost electricity at scale. Hourly simulations at 15 sites show that hybrid power plants combining wind, solar and a small battery can supply 70–90% of a typical demand profile, hour by hour, for a delivered cost below $60/MWh. These plants can be built close to demand centres, rather than necessarily at the windiest locations.

Kazakhstan's electricity demand is growing fast, up 16% in the last five years, and the country has been a net importer of electricity since 2022. The government aims to achieve self-sufficiency by 2027 and potentially become a net exporter by 2029. Replacing ageing infrastructure adds to the challenge. Coal power supplied 62% of electricity generation in 2025, but the country's coal units are on average over 50 years old, leading to frequent equipment failures. There were 891 incidents of various severity between January and July 2026.

Wind can help meet this challenge, but not as a standalone source. In a hybrid plant, wind and solar complement each other behind a single grid connection, while a small battery helps manage shortfalls. Deliberately oversizing the capacity means there is enough generation even on less windy and sunny days even with a small battery. The result is a plant with a capacity factor comparable to that of a baseload power station, at a lower cost than new coal. This report tests that proposition with hourly simulations at 15 sites across the country.

01

Wind accounted for just 4.4% of Kazakhstan's power generation in 2025, leaving its vast potential untapped

New onshore wind farms in Kazakhstan achieved a 39% capacity factor in 2025, close to the 41% global average for offshore wind. Average wind speeds exceed 7 m/s across two-thirds of the country, compared with less than a third of Germany's territory. Yet Kazakhstan has only 2.1 GW of installed wind capacity as of mid-2026. Wind supplied 4.4% of generation in 2025, around half the global average of 8.6% and well below wind leaders like Germany (27%). Despite its late start, Kazakhstan could catch up fast: wind's share of generation has quintupled in five years, from less than 1% in 2020.

02

Wind, complemented by solar and a small battery, can meet 70–90% of a typical demand profile, hour by hour, for a delivered cost below $60/MWh

At each site, the best-performing of 125 configurations supplies 70–90% of the electricity in a typical demand profile, hour by hour, over 30 years, at a delivered cost below $60/MWh. This cost represents the plant's lifetime cost per MWh actually delivered, including the cost of curtailed output. The same plants have a generation cost of $41–49/MWh, in line with Kazakhstan's recent wind auctions and well below the $70-170/MWh of new coal.

03

Even in winter, when demand is highest and solar output is weakest, wind remains strong and helps meet over 70% of demand at 13 of 15 sites

Winter (December to February) is the most challenging season at most sites, as solar output is low and demand is at its highest. Even so, the modelled hybrid plants meet

over 70% of demand at 13 of the 15 sites. A single plant has shortfalls, mostly on winter evenings and before dawn, when it delivers less than a fifth of demand. A flexible, interconnected system can fill these gaps far more cheaply than overbuilding each plant.

Wind is already growing fast and leading progress towards Kazakhstan's national target of 15% renewables by 2030, but without an ambitious longer-term target, progress risks stalling beyond that milestone. By 2035, wind and solar could supply 23% of generation, up from 6% in 2025, bringing total renewables to 35% of generation while maintaining reliability and affordability.

Achieving this will depend on greater flexibility and a market that pays for flexibility, not just energy. Hybrid plants are already competitive with new coal on energy revenue alone. Their surplus generation and batteries can also be a source of flexibility. If batteries can earn revenue from balancing, capacity and grid services instead of only shifting their own plant's output, they can deliver their full value to the system and further boost projects' economic competitiveness.

> Kazakhstan has a vast untapped high-quality wind resource that with some solar and a small battery can reach similar reliability to what solar and more batteries can do in sunny places at an affordable cost. And the best part is - wind resources are great across most of its territory, so hybrid projects can be built close to demand, minimising major additional transmission lines.

Kostantsa Rangelova
Senior Battery Analyst, Ember



Chapter 1: Wind potential

Kazakhstan has vast untapped wind resources that can help meet fast-growing demand

Kazakhstan needs to build new power capacity quickly to meet its rising electricity demand and replace aging power infrastructure. Its vast and untapped wind potential offers a unique opportunity.

1.1 Kazakhstan needs new power capacity quickly to meet growing demand and replace its ageing power infrastructure

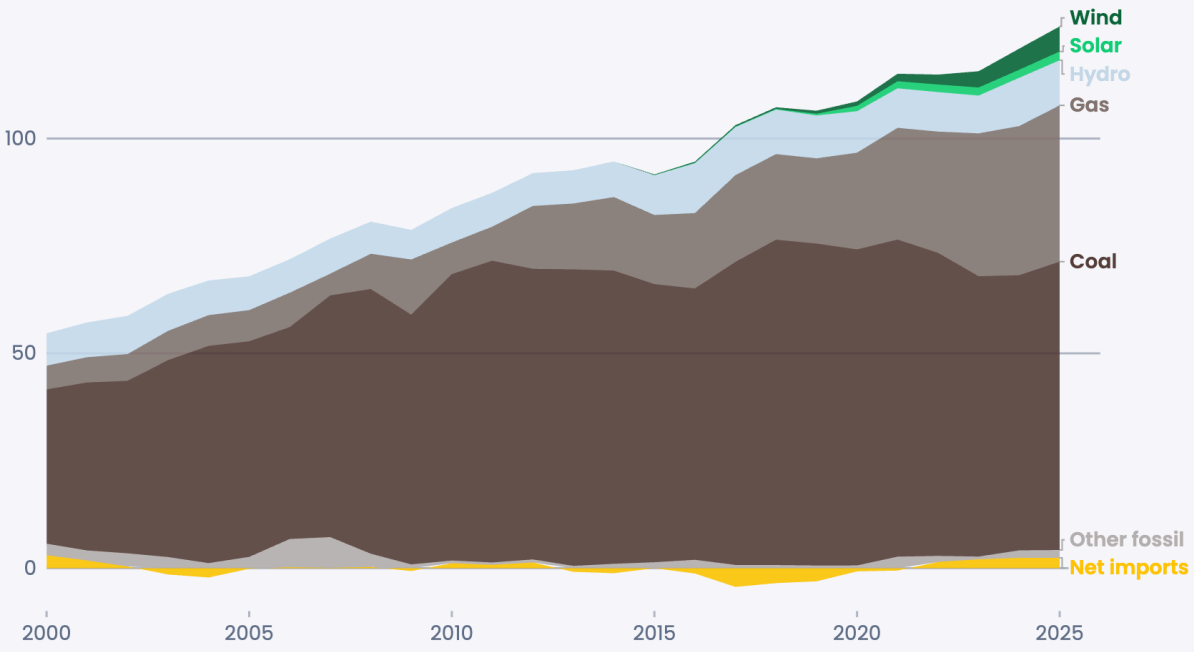
Kazakhstan's electricity demand rose by 16% over the last five years - increasing by 17 TWh from 107.3 TWh in 2020 to 124.6 TWh in 2025. That increase is comparable to Tajikistan's or Kyrgyzstan's total electricity demand in 2025 (19 TWh each). The additional demand was primarily met by increased gas (+11 TWh), wind (+4 TWh) and electricity imports (+2 TWh), according to Ember data, with Kazakhstan becoming a net importer in 2022. Coal generation remained the dominant source of electricity, providing 62% of electricity in 2025. However, the capacity-weighted average age of Kazakhstan's coal fleet is over 50 years, well beyond the standard 40-year lifetime for a coal power plant. This leads to frequent outages and emergency shutdowns. Between January and July 2026, 891 incidents of varying severity were recorded.

The government is aiming to achieve self-sufficiency by 2027 and potentially become a net exporter by 2029. To replace its ageing infrastructure and keep pace with fast-growing demand, Kazakhstan needs to build more capacity quickly and ensure its

availability during peak periods, including winter demand spikes. The capacity also needs to be built close to where demand is to relieve pressure on the transmission network. Kazakhstan already aims to build 6,659 kilometres of new high-voltage lines by 2035 to better interconnect its three largely isolated power zones - North, South and West. This includes connecting the West zone to the rest of the national power system and increasing the limited transmission capacity between the coal-rich North and chronically undersupplied South zone. Building new capacity closer to demand would limit how much more grid needs to be built.

Kazakhstan's electricity demand growth was met primarily by gas, wind and imports

Electricity generation by source and net imports, TWh



Source: Yearly electricity data, Ember

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1.2 Kazakhstan has some of the world's best untapped onshore wind resources, with wind speeds rivalling those offshore

Kazakhstan has some of the world's best wind conditions for power generation, with onshore capacity factors comparable to those of offshore installations elsewhere. Although the windiest parts of the country do not have the world's highest wind speeds , the quality and speed of this resource is exceptionally homogenous across Kazakhstan's vast territory. This means capacity can be spread out and allocated closer to demand centres and existing power lines without sacrificing output. It also makes the country less vulnerable to concurrent weather fluctuations.

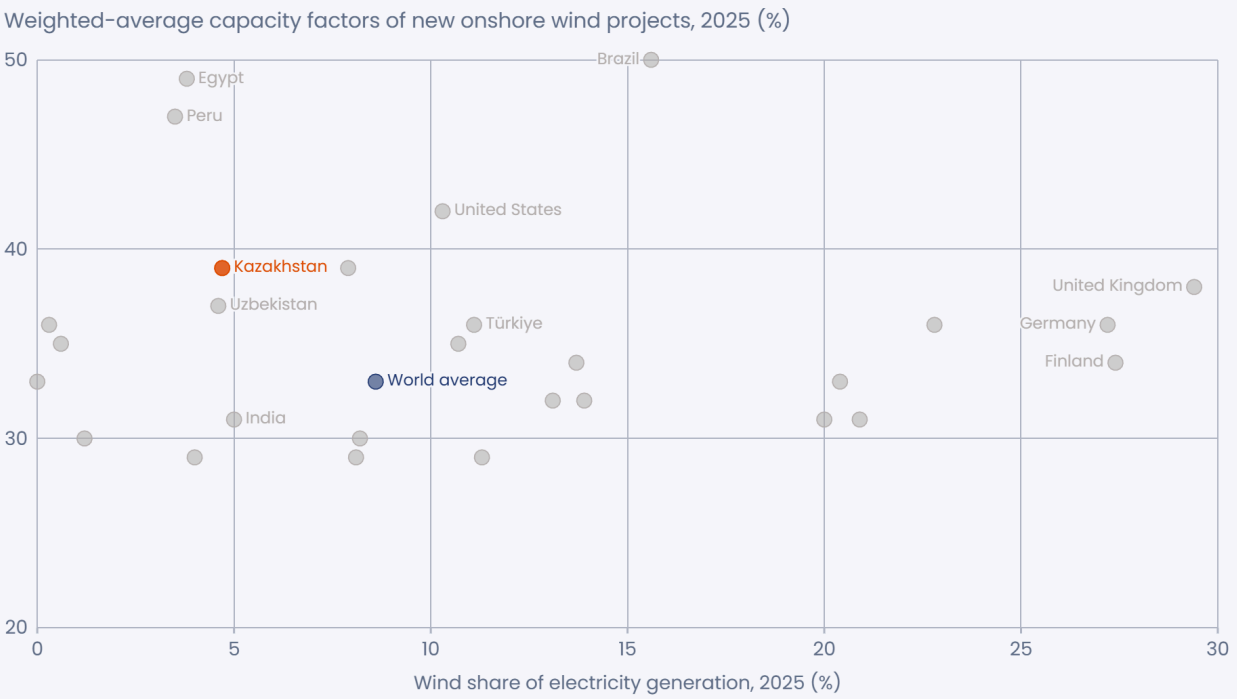
New onshore wind projects have capacity factors comparable to offshore wind, but potential remains untapped

Based on IRENA data for the 30 countries with the largest additions to onshore wind capacity, the weighted-average capacity factor of new onshore wind projects in Kazakhstan was 39% in 2025. This is below the figures for the top three leading countries in the dataset: Brazil (50%), Egypt (49%) and Peru (47%). However, it was almost 20% higher than the world average (33%) for onshore wind and just slightly behind the world average for new offshore wind (41% in 2025).

Despite this strong potential, wind remains underused. Wind accounted for just 4.4% of Kazakhstan's total generation in 2025 - around half the global average (8.6%) and behind leading countries like the United Kingdom (29%), Finland (27%) and Germany (27%), all of which have lower average capacity factors than Kazakhstan.

Kazakhstan has one of the highest capacity factors for new onshore wind, but doesn't capitalise on that enough

Top 30 countries by onshore wind capacity additions



Source: IRENA, Renewable Power Generation Costs in 2025

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Kazakhstan can build wind close to demand and avoid large transmission costs

Kazakhstan does not have the highest wind speeds in the world. The windiest 2% of Kazakhstan's territory has average wind speeds of 8.9 m/s at 100 m. This area covers around 54,000 km², theoretically enough space for 270–430 GW of wind capacity at 5-8 MW/km². That is equivalent to roughly one-fifth to almost one-third (31%) of the 1.4 TW capacity humanity has built as of June 2026.

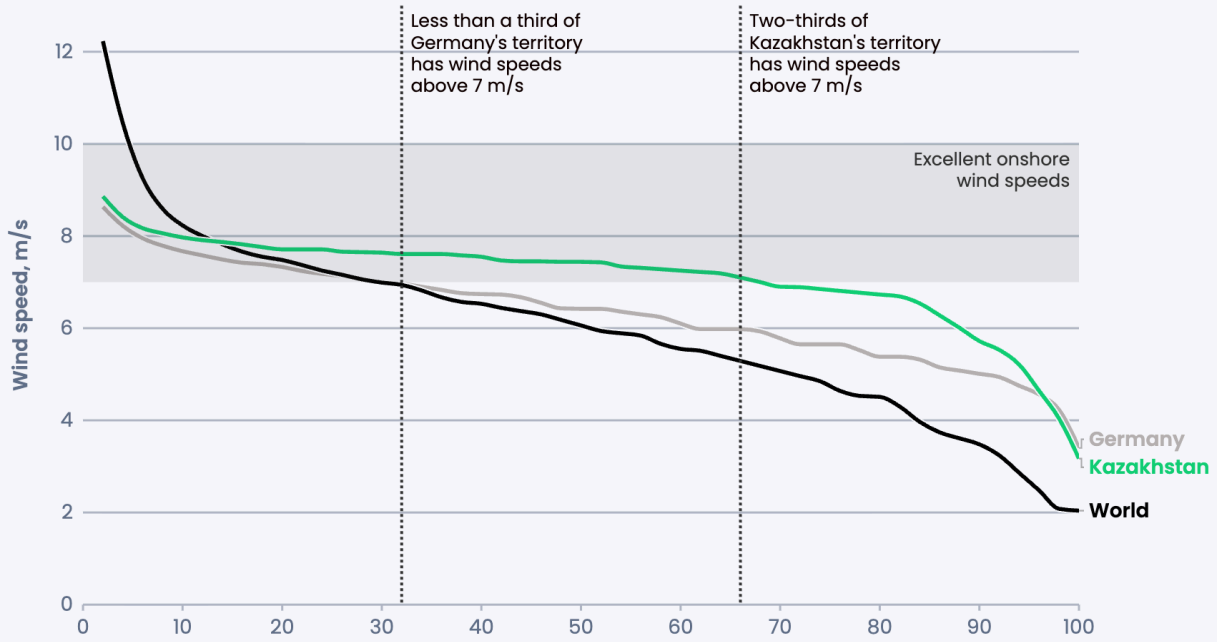
Kazakhstan's geographical advantage lies not in having the world's highest wind speeds, but in the breadth of its wind resource. High-quality wind is available in nearly every region rather than being concentrated on a handful of corridors. So unlike most countries in the world, Kazakhstan does not have to build wind in a few remote areas with high wind speeds and then build long transmission lines to bring it to where demand is. Two-thirds of Kazakhstan's territory has mean wind speeds above 7 m/s at

100 m - well within the 7 m/s to 10 m/s range generally considered excellent for onshore wind.

In Germany, where wind accounted for 27% of all power generation in 2025, less than a third (32%) of its territory has wind speeds above 7 m/s. This means that commercially viable wind can be built close to most demand centres, without adding to Kazakhstan's already large need for new transmission. The country still needs a strong grid, but may be able to avoid the cost and lead time of long new lines to remote sites with strong winds and little demand.

Two-thirds of Kazakhstan's territory has excellent wind speeds

Mean wind speed at 100 m for each 2% of a country's land, ranked from windiest to calmest



Source: Ember analysis of data from Global Wind Atlas

Built near demand, wind hybrid plants can meet 70–90% of it for under $60/MWh

Good wind resources are available close to most major demand centres and existing power lines across all three power zones of Kazakhstan. Pairing wind with solar and batteries makes it possible to provide cheap electricity throughout the year.

2.1 Meeting up to 90% of a typical demand profile is possible at less than $60/MWh with wind, solar and a small battery

Across 15 sites, wind paired with solar and battery can meet 70% to 90% of a typical demand profile at a delivered cost of less than $60/MWh

Ember analysed 15 sites across all three power zones of Kazakhstan. The sites were selected for their proximity to a major demand centre and an existing power line, rather than because they had the country's strongest winds (see Methodology).

At each site, Ember tested 125 combinations of wind, solar and battery capacity, producing a total of 1,875 simulations. Each configuration was simulated hour by hour over a 30-year project life using site specific weather data and a typical hourly demand profile from the Agora Energiewende PyPSA-SPICE dataset. The profile represents national demand patterns and was scaled to a peak of 100 MW. Each site was tested

against the same demand profile, so differences in results reflect weather conditions rather than differences in load.

At a delivered cost below $60/MWh, the maximum share of the typical demand profile met at each site ranged from 70% at the weakest site (near Kordai in the South) to 90% (near Zhanaozen in the West). These figures are averages across the 30-year project life; individual years perform above and below that average depending on the weather and to a smaller extent, equipment ageing.

Across all 15 sites, the average delivered electricity cost is $56/MWh - calculated by dividing the plant's full lifetime cost by the electricity actually delivered to the demand profile. This is significantly cheaper compared to new coal, which costs $70-170/MWh, depending on the region and technology.

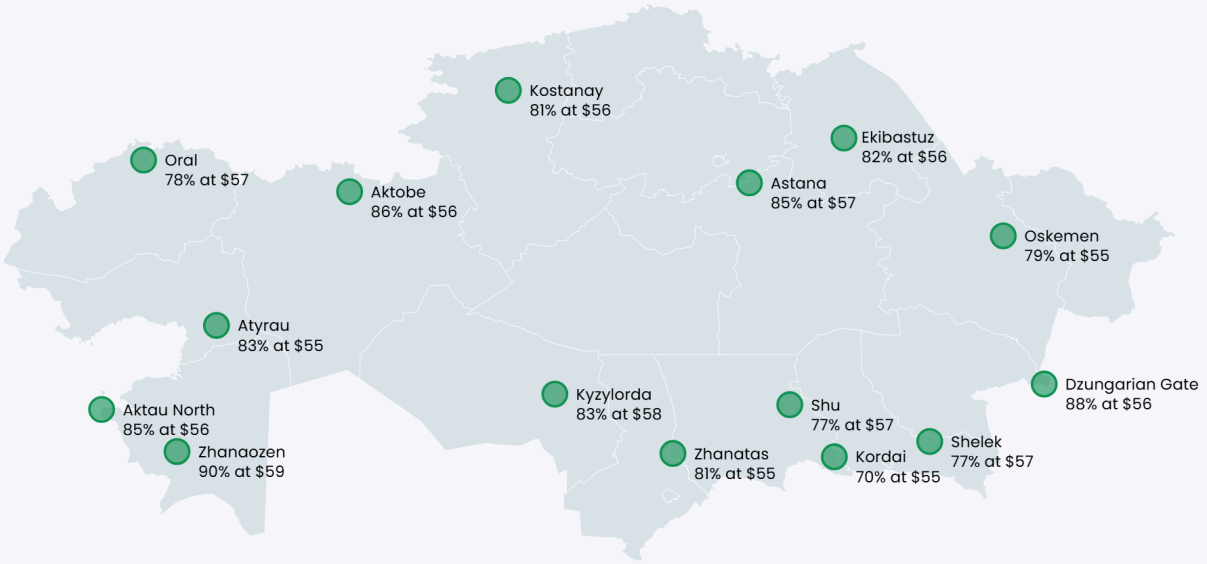
The share of demand met can vary by up to 4.5 percentage points between windier and calmer years, with the highest variation at southern sites.

At Kordai, for example, the share rises from 70% using the calmer 2022 weather data to 74% using the windier 2023 data. Sites in the North, East and West are steadier, varying by about 1–2 percentage points, while the Dzungarian Gate (site in the South zone) barely changes at all. Equipment degradation plays a small role - excluding weather variation, the share of demand met in the final three years is around 2 percentage points lower than in the first three.

Kazakhstan can build wind hybrid plants next to demand and meet 70-90% of it for less than $60/MWh

Labels show share of a typical demand profile met by wind-solar-battery hybrid plants across their 30-year project life (%) and the cost of delivered electricity ($/MWh)

Green dots mark the simulated sites with local hourly weather data, named after a large nearby city



Source: Ember analysis using Converge Hybrid tool for hourly simulations based on site-specific ERA5 hourly weather data and Global Wind Atlas wind speeds; demand profile from Agora Energiewende PyPSA-SPICE, normalised to a 100 MW peak. • For each site, the dot label shows the cost and share of demand met by the best wind-solar-battery configuration that meets the largest share of demand at a delivered cost below $60/MWh, chosen from 125 configurations per site dispatched hourly over 30 years.

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Curtailment by design minimises battery needs and makes it possible to meet over 70% of winter demand at most sites

The configurations that meet the highest share of demand for less than $60/MWh deliberately build more wind and solar capacity than can be absorbed by the demand profile every hour. Across the 15 sites, an average of 23% of annual generation is curtailed (15–30% depending on the site), mainly in spring and summer when solar is strongest. The curtailment in these results is a design choice and is hence fundamentally different from grid-ordered curtailment without compensation.

Its cost is already reflected in the delivered price: average generation cost is $45/MWh, compared to the delivered cost of $56/MWh. The $11/MWh difference represents the cost of curtailment which helps make the plants flexible enough to meet a high share of demand. Curtailed electricity could also support more flexible demand, including from

new sources like electric vehicles (EVs) with smart charging, or be exported to neighbouring countries.

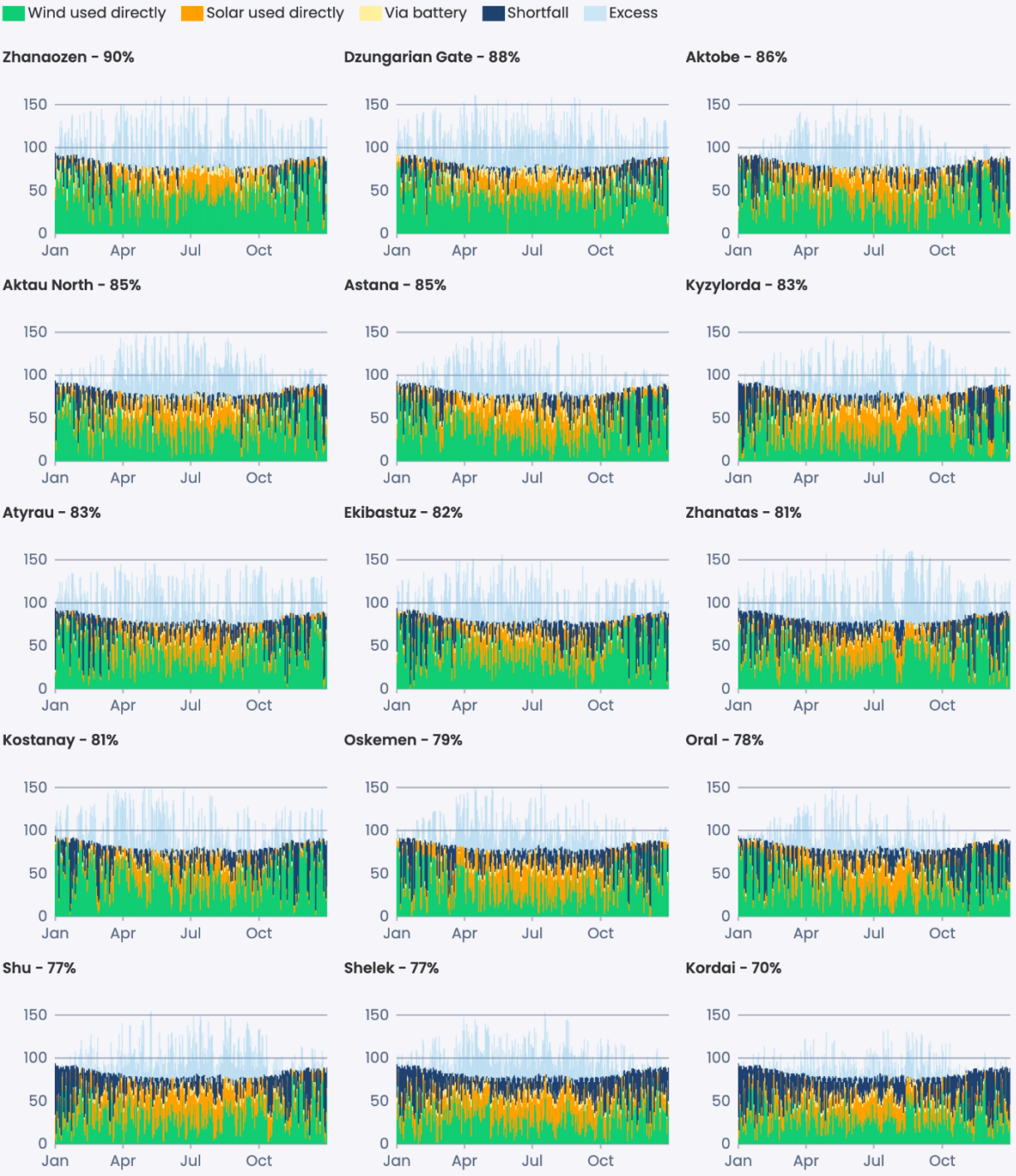
In summer (June-August), these configurations meet 78–95% of demand. Winter (December to February) is the hardest season at most sites, as solar output is low and demand is at its highest. Even so, the plants meet 61–87% of winter demand, and over 70% at 13 of the 15 sites, thanks to strong wind in winter. The exceptions are in the South, near Kordai and Shu. At Kordai, the weakest site in winter, the plant meets 61% of winter demand, with wind directly supplying 44 percentage points, solar 15 percentage points and the battery, 2 percentage points.

Deep shortfalls, defined as hours when the plant meets less than 20% of demand, occur between 4.5% of the time in the best-performing site (Zhanaozen) and 15.6% in the worst (Kordai). They occur on 90–249 days per year but tend to be relatively short, lasting 4–7 hours in winter and 2–4 hours in summer.

Filling these hours at plant level would mean overbuilding wind, solar and storage and higher cost of delivered electricity, as discussed in the next section. Connected to a flexible grid, which Kazakhstan has yet to build, the same gaps shrink: when the 15 simulated sites are considered together, the number of hours in which less than 20% of demand is met, to about one hour a year, because calm spells rarely cover the whole country at once. Section 2.2 further sets out what this means at the system level.

At $60/MWh, wind - with some solar and a small battery - can meet 70-90% of annual electricity demand across 15 key areas in Kazakhstan

Daily average supply, by source (MW)



Source: Ember analysis using Converge Hybrid tool for hourly simulations based on site-specific ERA5 hourly weather data and Global Wind Atlas wind speeds; demand profile from Agora Energiewende PyPSA-SPICE, normalised to a 100 MW peak. • 2022 weather year is displayed

Each panel shows data for the hybrid plant that meets the largest share of demand at a delivered cost below $60/MWh, chosen from 125 configurations per site. The percentage (%) shown next to each site name is the share of demand met across the 30-year project life, not over a specific single weather year

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2.2 Meeting 91-97% of a typical demand profile is possible but the costs rise steeply

Higher shares, even 100%, are technically possible with extremely high overbuild, but moving closer to 100% gets progressively more expensive. Each additional percentage point above 70% requires more and more wind, solar and storage, and much of their output is curtailed, which raises the cost of every MWh delivered.

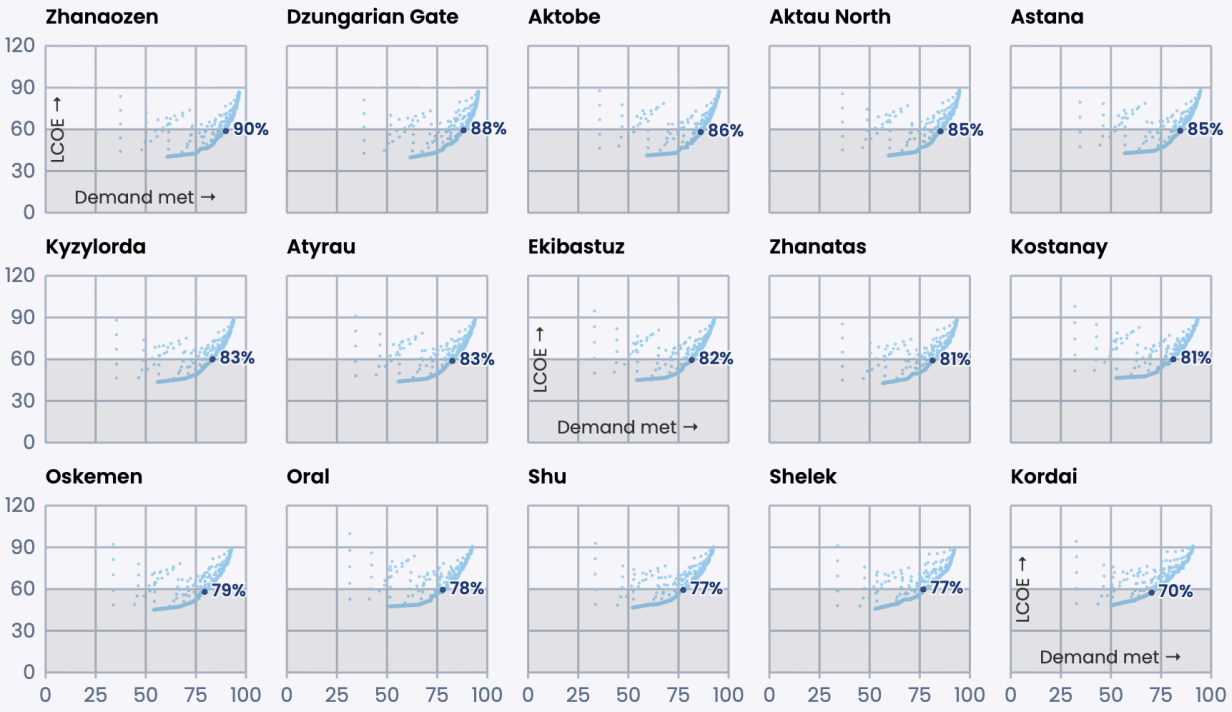
The simulations show this clearly. At each site, the cheapest configurations cost $40–48/MWh with almost no curtailed output but meet only 50–61% of demand. The best configurations below $60/MWh meet 70–90%. Beyond that, costs climb steeply. The largest configuration tested has 180 MW of wind, 250 MW of solar and 480 MWh of battery. It meets 91–97% of demand, depending on the site but at $87–91/MWh, around 50% more than the $60/MWh configurations. Each extra MWh of electricity gained by moving from the best $60/MWh configuration to the largest configuration costs $205–430/MWh.

Coverage over 70% is possible even at Kordai, the weakest site: but it costs $69/MWh to meet 80% of demand and $86/MWh to meet 90%. At the best sites, Zhanaozen and the Dzungarian Gate, 90% is within reach at around $60/MWh.

Meeting 91–97% of a typical demand profile in Kazakhstan is possible but the cost rises steeply

Demand met (%) and cost of delivered electricity (LCOE-delivered, USD/MWh) by different wind, solar and battery configurations

% labels represent the highest share of demand met below $60/MWh LCOE-delivered; the line traces the cheapest option for each demand level.



Source: Ember analysis using Converge Hybrid tool for hourly simulations based on site-specific ERA5 hourly weather data and Global Wind Atlas wind speeds; demand profile from Agora Energiewende PyPSA-SPICE, normalised to a 100 MW peak. • Each dot is one of 125 wind (36–180 MW), solar (50–250 MWac) and 4-hour battery (0–480 MWh) configurations, simulated hourly over 30 years using three weather years (2022–2024), including degradation. Delivered LCOE is lifetime cost per MWh of demand met. Costs reflect 2026 Kazakhstan prices, adjusted for cold climate, plus up to $150,000 per turbine for distance from the Jambyl factory.

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Meeting the remaining 10-30% of demand requires flexibility at system-level

At system level, a single project does not need to meet all demand with 100% reliability on its own. The modelled wind hybrid plants provide cheap and abundant energy that already covers 70-90% of a typical demand profile for less than $60/MWh, but in reality they do not exist as isolated demand islands. The remaining 10-30% of demand that a single hybrid plant does not deliver can be provided more efficiently by an integrated

power system with diverse generation sources, storage, transmission and demand-side flexibility Currently, Kazakhstan's power system has limited flexibility due to both institutional and structural factors. Building a more flexible power system and making flexible hybrid plants a core part of it is a key task for the coming decade.

Spreading plants across the country does not eliminate the need for back-up power generation, but it reduces the amount needed because weather fluctuations are less likely to affect all sites at once. To cover all but the worst 1% of hours (about 90 hours a year), a single plant needs back-up capacity equal to 81–91% of peak demand; all 15 plants together need 48%.

The economically optimal level of wind and solar share at a system level, accounting for all sources of flexibility including other generation sources, demand side flexibility and interconnections, requires a much broader analysis beyond the scope of this report. A recent study has shown wind and solar could reach 23% share of generation in Kazakhstan by 2035, while maintaining power system reliability and affordability.

2.3 Batteries provide value beyond individual project-level energy shifting

In our simulations, the optimal battery is small and does most of its work by bridging shallower shortfalls, especially in summer evenings. The battery size is not fixed and depends on what is optimal for each site's weather conditions. Across 14 of the 15 sites, it varies between 12% and 25% of the combined wind and solar capacity of the hybrid plant (37% at Zhanaozen). Each battery provides four hours of storage. The legal requirement for auction winners since 2025 is for a much larger 30% of capacity, but just two hours of storage, which may be suboptimal for a specific project.

Each battery is only used to store its own project's wind and solar output for hours when generation falls short of meeting target demand. That leaves the battery underutilised. Across the 15 sites, batteries supply 3-7% of delivered electricity, cycling 120–250 times a year - similar to China's co-located batteries, which averaged 199 cycles in 2025 and well below the general best practice of 350 cycles per year.

At the project level, adding more battery capacity is not economical, as they remain underutilised due to the large number of days without a large enough surplus to charge

the battery in winter. Batteries that only shift their own plant's output could sit idle for much of the year, so realising their full system value is key.

Batteries are a powerful multitool that can respond to a sudden loss of generation within a fraction of a second, helping maintain grid stability. The August 2026 Central Asian blackout demonstrated this in practice. The outage affected the power systems of Kazakhstan, Kyrgyzstan, Uzbekistan and Tajikistan. The outage cut power to Almaty and a large part of the South power zone in Kazakhstan. While parts of Uzbekistan were also affected, according to Uzbekistan's Ministry of Energy, batteries helped prevent a full national blackout. Uzbekistan is a regional battery leader with over 1.5 GW of batteries installed as of 2025, or 13% of peak demand, and aims to reach 4.5GW by 2030. Meanwhile, Kazakhstan's first battery system is expected to come online by 2029, alongside TotalEnergies' Mirny wind farm.

Chapter 3: What this means for Kazakhstan

Unlocking Kazakhstan's unique wind potential with smart hybrid plants

Kazakhstan's wind is strong, steady and available almost everywhere at low cost. It can be at the core of the capacity build-out needed to meet the country's fast-growing demand and replace old and inefficient infrastructure. National targets underestimate its potential and risk missing the opportunity.

While in sunny countries like India, solar and batteries can supply around the clock electricity economically, in Kazakhstan the vast untapped wind potential provides a unique opportunity.

Wind is already leading progress toward 15% renewables by 2030 target

Kazakhstan has a national target to reach 15% renewable electricity share by 2030. The target includes wind, solar, bioenergy and small hydropower, but excludes large hydropower plants. By that definition, renewables reached 7% of generation in 2025, up from 4.5% in 2022. Renewable generation rose 1.7 times over that period, beating the interim national target of 1.5 fold increase.

Wind is already leading the progress towards the target. It accounted for 4.7% of 2025 generation, according to Ember data, more than doubling from just 2% in 2022. Installed capacity has surpassed 2 GW as of Q2 2026, with over 5 GW in the pipeline, of which 4 GW is expected to come from four large wind-plus-battery projects, each with 1 GW wind and 600 MWh battery.

Costs are already competitive. Kazakhstan's first auction for wind with storage, a 1 GW project in Kostanay region, cleared in April 2025 at 18.72 tenge/kWh ($42/MWh at the September 2026 exchange rate of about 450 tenge to 1 USD), and the negotiated dollar tariffs for the TotalEnergies and Masdar projects are $39.9/MWh (18.0 tenge/kWh) and $44.9/MWh (20.2 tenge/kWh). These prices are generation prices and comparable with the $41–49/MWh generation cost of the hybrid plants in this report.

Smartly operated hybrid plants can be a source of system flexibility

Wind and solar are a source of abundant cheap electricity. Some curtailment is not only economically acceptable - it is the key to making hybrid power plants a source of flexibility, but only if it is by design and paid for. A fleet of hybrid plants spread across the three power zones adds flexibility of its own. When operated smartly, hybrid plants stop being a flexibility liability and become part of the solution: cheap power where demand is, with the flexibility to keep the lights on.

Interconnections extend the same flexibility benefits across borders that can create green energy corridors that unlock the renewable potential and strengthen energy security for the whole Central Asia and the Caucasus region.

Batteries need to be able to stack revenues to provide their full value

Kazakhstan is already considering a law on energy storage systems. 2.4 GWh of batteries are already due to come online in the next few years at the four large wind-plus-battery projects. To ensure these batteries provide system-wide value and to incentivise future investment in smart hybrid projects, new rules need to be in place as soon as possible and ensure the possibility for revenue stacking. That means access to an ancillary-services market (frequency regulation, reserves, black start), access to the balancing market, and arbitrage under market rules rather than regulated charging and discharging tariffs. China's regulatory journey from storage mandates to new market mechanisms that allow revenue stacking is a potential source of key learning for Kazakhstan. The mandates began in 2017 and required new wind and solar projects to add storage but co-located batteries were used little, cycling just 80 times a year in 2022. Since 2022, China has opened spot, ancillary-service and capacity payments to batteries, supporting a notable increase in utilisation and in February 2025 scrapped the mandates.

Without a target beyond 2030, Kazakhstan risks slowing progress

Kazakhstan does not have a dedicated renewables target beyond 2030. Instead, the 2050 target is for 50% renewable and other alternative sources, which include nuclear. The lack of a specific renewables target risks undermining progress once the 2030 target is reached. There are already valid concerns that integrating more variable renewables beyond the 15% by 2030 target will be challenging due to insufficient system flexibility. Kazakhstan's coal plants have slow ramp rates and cannot run below about 70% of capacity, while other sources of flexibility like demand response and hydropower, remain untapped due to market rules that do not pay for flexibility. The grid operator, Kazakhstan Electricity Grid Operating Company (KEGOC), has argued for a pause on new renewable projects until flexible capacity catches up.

Increasing system flexibility while keeping up the pace of renewable deployment is the central task of the next decade. A clear and ambitious post-2030 wind and solar target would be a clear signal to investors that the pipeline does not stop at 15%.

Supporting materials

Methodology

The Converge Hybrid optimisation software

Ember used Converge Hybrid's optimisation software to evaluate the energy and cost performance of different hybrid power plant configurations in meeting electricity demand based on site-specific weather data, using hourly-level dispatch resolution across a 30-year project life. Each configuration combines wind, solar and battery and is simulated for every hour of the project life against an hourly demand profile, with a linear-programming (LP) dispatch model setting the battery's hourly charge and discharge to match demand as closely as possible before charging surplus or curtailing. Two modes were used: optimisation sweeps, which run over 120 full 30-year simulations per site to identify the least-cost combination meeting a given reliability target; and individual simulations of a chosen design, which additionally produce the full energy, cost and financial analytics.

Data sources for simulations:

- **Demand**: All simulations and optimisations use an hourly demand profile based on Agora Energiewende PyPSA-SPICE dataset, normalised to a 100 MW peak. This is a full 8,760-hour time series with genuine seasonal, weekly and daily variation — not a single representative day repeated — applied across the 30-year horizon.
- **Wind**: All simulations use hourly wind speed data from the ERA5 reanalysis. The ERA5 series tends to underestimate actual wind speeds, so it was scaled to the Global Wind Atlas (GWA) long-term mean, using the windiest 20% of a 3×3 km area around the site at hub height. Wind speed at the 100 m reference height is extrapolated to the 120 m hub height with a site-specific Hellmann exponent and corrected for air density. Three weather years (2022-2024) are repeated across the 30-year horizon, so inter-annual variability within that window is captured but extreme years outside it are not.
- **Solar**: All simulations use hourly global horizontal irradiance and ambient temperature data from the ERA5 reanalysis at each of the same 15 sites. It is converted to output for a single-axis tracking solar plant using 720W bifacial modules.

Selecting the 15 sites:

The simulations used wind and solar data for 15 sites across Kazakhstan's North, South and West zones. Each site was selected based on proximity to existing demand centres and existing power infrastructure, rather than wind speeds. Then, the exact location of the site was moved to the windiest developable land within 20 km. The adjustment of the site did not take into account land use, protected areas, slope or road and crane access, so the corrected coordinates should be read as the starting point for a developer's own siting, not as final turbine positions.

Technical and cost assumptions

Costs are 2026 estimates adjusted for operational conditions in a cold climate.

- **Wind**: The simulations use a generic 6 MW, 175 m-rotor cold-climate turbine (IEC Class IIIa), with low specific power (249 W/m²) chosen for moderate-wind, high-shear steppe conditions. The turbine cost ($6.15 million) assumes equipment delivered from China and assembled locally at a wind-turbine factory in the Jambyl region (near Taraz), southern Kazakhstan. The turbine cost already includes a base logistics cost covering standard transport to site. On top of that base, an additional logistics allowance of $50,000, $100,000 or $150,000 per turbine is added purely to reflect the extra long-distance road haulage within Kazakhstan, with each of the 15 sites assigned to one of three bands according to its road distance from the factory. Foundations ($600,000), intra-array cabling ($200,000) and roads and civils ($400,000) are also added per turbine. The operational performance of the turbine includes specific loss factors for availability, wake loss effects, electrical losses, etc, applied to gross output.
- **Solar**: The simulations assume 720 W bifacial modules at $110 each ($0.153/Wp), central inverters at $90,000 per MWac, single-axis trackers at $180,000 per MWac and balance of plant at $100,000 per MWac, giving $553 per kWac installed. A combined loss factor of 0.88 is applied.
- **BESS**: The simulations assume 4-hour lithium-ion battery blocks of 10 MW / 40 MWh each, at $3.0 million per block, $150,000 for the energy-management system and $2.8 million for balance of plant including a cold-climate enclosure allowance. The resulting capital cost comes at $149 per kWh installed. Round-trip efficiency is 84.5%, the battery may cycle over its full state-of-charge range, capacity degrades at ≈2% a year and the battery is replaced once in year 15 at 70% of the original cost.

- **Grid connection**: The simulations assume a 126 MVA substation for the 100 MW export point at $15 million; The plant is assumed to sit at the connection point. If overhead lines are needed, an additional $250,000 per km would have to be added to the total project cost.
- **Financials**: The total project cost includes a 5% developer premium, 0.75% construction insurance and 5% contingency on the equipment subtotal, plus $3.0 million of EPC management and $2.5 million of O&M mobilisation.

Hourly simulations

For each site, 125 configurations were simulated (wind 36–180 MW, solar 50–250 MWac, battery 0–480 MWh in four-hour blocks). The hourly simulations were run over a thirty-year period. In each hour, available wind and solar first serve demand directly; the linear-programming dispatch then operates the battery to close the gap between generation and demand — charging when generation is in surplus and discharging when it falls short — co-optimised over a rolling multi-day horizon so that stored energy is used where it displaces the most unserved demand. Export is capped at the 100 MW grid connection, and any generation that can be neither delivered nor stored is curtailed. Dispatch assumes foresight of generation and demand over the planning horizon, so the results reflect a well-run plant rather than real-time forecast error.

Losses and degradation

Combined losses of 16.5% for wind (covering wake, availability, electrical and cold-climate effects) and 12% for solar are applied to gross output. The four-hour battery has a round-trip efficiency of 84.5% and is cycled across its full state-of-charge range.

Solar degradation is assumed at 0.5% a year, so the array produces about 85% of its initial output in year 30. The battery loses 2% of its capacity a year, ending the 30 years at roughly 70% of its rated energy, and is replaced once, in year 15.

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Reviewers

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Cover image

Wind turbines installed across a rural plain in Kazakhstan during sunset.

Credit: Ruslan Konev / Pexels

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