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Reducing curtailment in Chile: key to unlocking the full potential of renewable energy

Chile has become a global leader in electricity generation from renewables. In 2024, solar and wind accounted for one third of the total electricity generated, a milestone for the country. Batteries, grids and demand-side response can help Chile stop wasting its abundant renewable electricity generation through curtailments, saving millions of dollars.

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About

Drawing on Chilean and international experience, this policy paper proposes a package of measures to reduce solar and wind energy curtailment in Chile over the next five years, maximising the use of current and projected installed capacity.

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Summary

Reducing solar and wind energy curtailment represents an opportunity to reach the maximum potential of renewable generation in Chile, reducing the need for expensive gas and coal generation.

The increase in the share of variable renewable energies in the electricity mix poses technological and market operation challenges to harness the full potential of clean generation. For every percentage point Chile manages to reduce its curtailments, 295.5 GWh of clean electricity would be available for use in the market per year, enough to supply electricity to more than 120,000 homes for a year.

- **The capacity factor of solar generation plants in Chile is double the world average.** Chile is among the countries in the world with greatest potential for renewable energy; in solar, some regions achieve a capacity factor above 30%, double the world average, and in wind, 34%, in line with the world average.
- **Solar and wind energy curtailments in 2024 were equivalent to 6.6% of all electricity generated in Chile.** 5,642 GWh of solar and wind energy were curtailed in 2024, corresponding to 19% of all electricity supplied by these sources during the year.
- **Since 2022, curtailments have represented losses of $562 million dollars.** 11,900 GWh of renewable electricity was curtailed between January 2022 and May 2025, leading to underutilisation of renewable generation infrastructure and causing a reduction in income for investors.
- **Large infrastructure projects that will reduce curtailments will come online after 2029.** The main transmission project, the 1,400-km Kimal-Lo Aguirre line, will significantly increase renewable energy dispatch capacity,

but will not be operational for another four years. In the meantime, measures are needed to manage curtailment.

- **1 GW of new installed battery storage capacity would reduce curtailment by almost a quarter.** Under current conditions, increasing installed battery capacity by 1 GW, with 4 hours of storage duration, and locating them in areas of high grid congestion, could prevent 1,300 GWh of solar and wind generation from being curtailed annually, saving $67.6 million dollars annually.
- **The installation of dynamic line rating (DLR) systems could increase effective line capacity by 10-30%.** The implementation of a national programme for the mass installation of DLR, focusing on the lines with the highest levels of congestion, could take less than three years and have a direct impact on reducing curtailment.
- **Demand response markets, with strengthened transmission and increased storage capacity,are key to reducing curtailment**. The electricity markets that better manage curtailment empower consumers with information and incentives to participate in formal demand response markets, complemented by sufficient transmission capacity and storage systems located at key points to capture excess generation and deliver electricity during peak demand hours.

Summary of recommendations

Short term (less than 2 years)

- Design of a National Curtailment Reduction Plan
- Minimum storage requirement for new solar and wind projects in areas of high congestion
- Structuring an enabling environment to achieve utility scale energy storage targets
- Massive DLR (Dynamic Line Rating) installation programme

Medium term (2-4 years)

- Incentives for new projects located near areas of high demand and/or low grid congestion
- Creation of a formal demand response market

Long term (up to 5 years)

- Mass implementation of demand response projects
- Definition of the political and regulatory framework to consolidate an electricity exchange market with Argentina and Peru

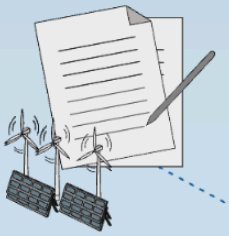
Unlocking Chile's renewable potential

Unlocking Chile's renewable potential requires planned action on flexibility. Cutting solar and wind curtailment will maximise clean generation while reducing both the need for and cost of gas and coal.

Short term (within 2 years)

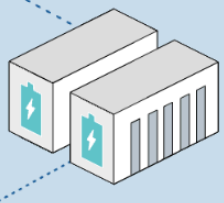
National curtailment reduction plan

Design and formalise a plan with explicit targets for the progressive reduction of variable renewable energy curtailment.



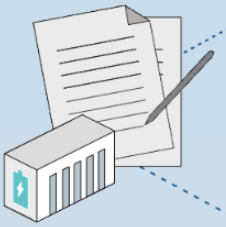
Mandatory storage for new projects

Set minimum storage requirements for new solar and wind projects as a condition for obtaining a grid connection permit at critical nodes in areas of high congestion.



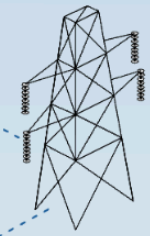
Enable energy storage

Create an enabling environment to enable multi-service revenues for BESS.



Massive DLR rollout

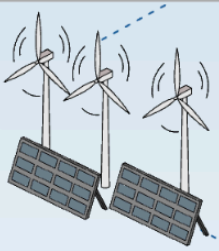
Rollout Dynamic Line Rating on congested lines to boost transmission capacity by 10-30%.



Medium term (2-4 years)

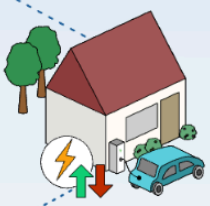
Targeted project incentives

Offer incentives for new RE projects in high-demand or low-congestion areas.



Formal demand response market

Create a clear regulatory framework with incentives for users to participate in demand response programs.



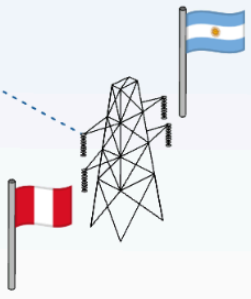
Long term (up to 5 years)

Mass demand response projects

Launch pilots for regulated and free users in priority areas to prepare for national rollout.

Electricity exchange with Argentina and Peru

Define political and regulatory framework to consolidate and strengthen the market with Argentina and advance interconnection with Peru.



Source: Ember
Infographic by Jivan Zhen Thiru and Lauren Orso.
Written by Wilmar Suárez.

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Chile has become a global example in solar and wind generation. The next step is to make sure that this clean energy is fully harnessed, instead of being left unused. By reducing curtailment, the country can bring more renewable power into people's homes and businesses, making electricity more reliable, affordable and sustainable. This also drives innovation, such as modern grids, energy storage and smarter ways for consumers to participate in the market while reinforcing Chile's role as a regional and global clean energy leader.

Wilmar Suárez
Analyst for Latin America, Ember

Section 1: Solar and wind energy curtailment in Chile: a challenge for maximising the use of renewable generation

The Chilean electricity system has not achieved sufficient flexibility to benefit from the remarkable growth in installed solar and wind generation capacity. Differing curtailment by introducing storage, new productive uses, exports and demand flexibility can transform what is currently seen as a loss into a driver of competitiveness.

1.1 Solar and wind generation has increased significantly, but so have curtailments

Chile's generation mix is dominated by renewables. In 2024, solar and wind energy contributed 34% of electricity generated, hydroelectricity 30%, and other renewables 6%. Regarding fossil generation, coal supplied 16%, while gas generated 12% and other fuels generated 2%. The electricity market is a competitive wholesale market, where generators can sell their electricity either on the spot market, at a marginal price, or to non-regulated customers through bilateral agreements, or to regulated customers.

Hydroelectric reservoir plants, located mainly in the south-central region, allow for rapid dispatch adjustments, providing flexibility to the system, as do gas-fired combined cycle plants, which provide rapid ramp-up and reliability. Coal-fired

plants are not very flexible, they serve as a base generation and provide slow ramp-up times. Liquid fuels serve as backups, and although they provide flexibility, their electricity generation costs are high. Coal's share of electricity generation has dropped significantly, from 42% in 2013 to 16% in 2024, and its retirement is scheduled for 2040.

The growth of solar and wind power generation in Chile has been remarkable in recent years. While in 2016 these two sources accounted for 6.6% (4.8 TWh) of national electricity generation, by 2024 they reached 34% (30.5 TWh), making them the largest sources of electricity in the country. Compared to other Latin American countries, Chile has the highest share of solar and wind energy combined, surpassing Uruguay (30.5%), Brazil (24%), and Argentina (13%).

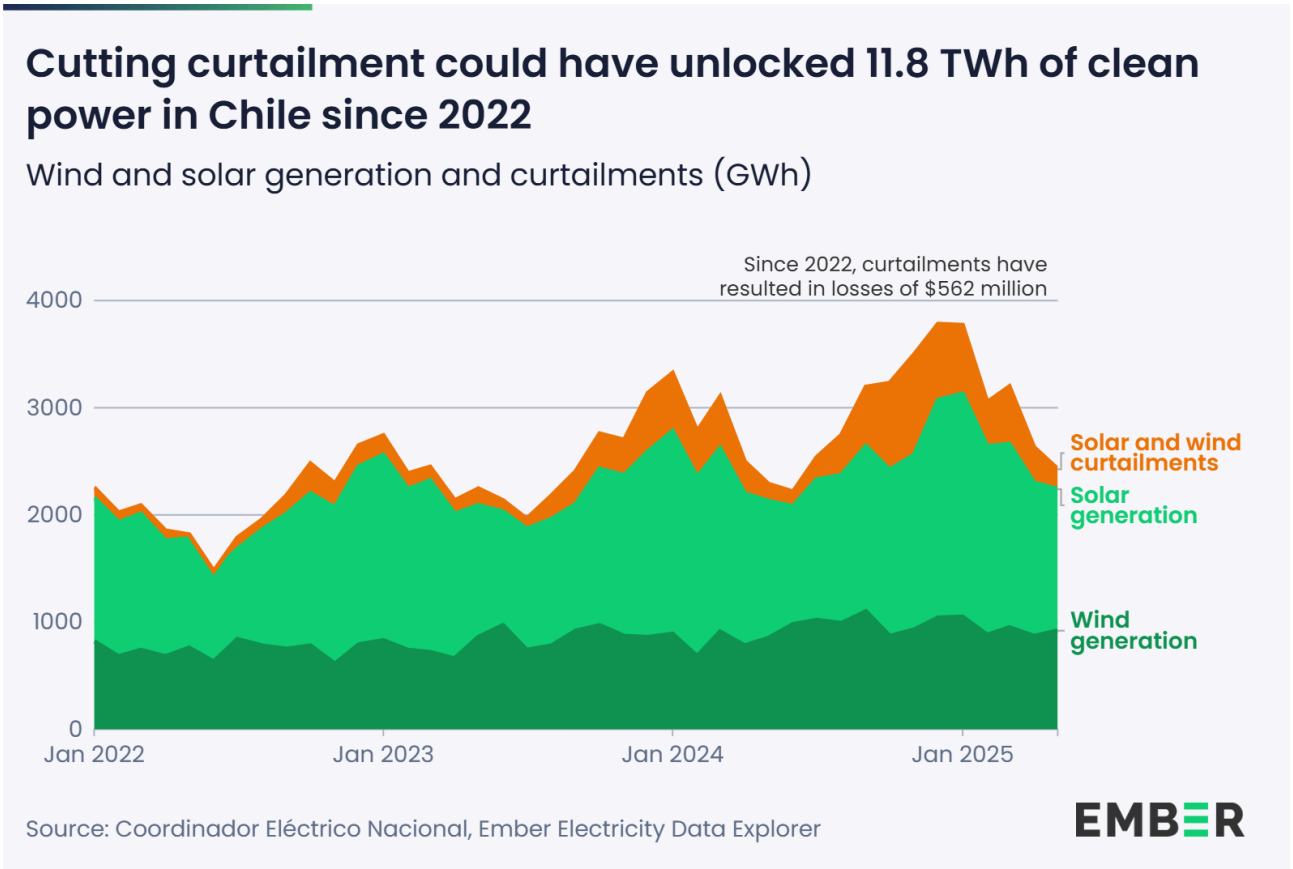
A high share of variable renewable energy (VRE) in the electricity mix poses technological and market operation challenges to maximise the use of clean generation. This requires increasingly flexible electricity systems that combine battery storage, robust transmission and distribution networks, and demand response mechanisms that allow energy consumers to play an active role in the electricity market.

In electricity systems with low flexibility, the injection of available electricity from VRE can be restricted for technical, economic or market reasons. This reduction is known as curtailment, and is a tool used by electricity system operators to maintain grid balance and security.

In Chile, solar and wind energy curtailment has grown significantly in recent years, quadrupling in just two years. In 2022, 1,417 GWh were curtailed, representing 6.3% of solar and wind generation for that year, while in 2023 curtailments increased by 81%, reaching 2,667 GWh, equivalent to 10% of the solar and wind energy generated. The reductions continued to grow in 2024, reaching 5,642 GWh, 19% of solar and wind generation, or 6.6% of the total electricity

generated in Chile in 2024. Without curtailment, solar and wind would have provided 41% of Chile's electricity in 2024.

To put the magnitude of the curtailments into perspective, the electricity curtailed during the last year could have supplied the demand of a region such as Antofagasta. Generating 5,642 GWh with a coal-fired plant would require continuous operation for one year (capacity factor 85%) of a thermal power plant such as Guacolda, which has an installed capacity of 760 MW and would need to burn around 2.4 million tonnes of coal, mostly imported at an estimated cost of $264 million dollars, generating emissions of 5.36 millions of tons of CO2.



In Chile, renewable generators receive no compensation for the electricity curtailed, so the restriction on utilising their total electricity produced means a reduction in their income. From the perspective of average marginal generation cost, curtailments represented economic losses for the generators of an estimated $85 million dollars (MMUSD) in 2022, $126 MMUSD in 2023, and $226 MMUSD in 2024. Between January and May 2025, 2,107 GWh were curtailed, with an estimated cost of $125 MMUSD. Failure to implement solutions to manage discharges can lead to ever-increasing levels and impacts.

1.2 Challenges for the Chilean power system to efficiently manage its curtailments

The main reason for the high curtailment level in Chile is the country's unique geography, which requires very long transmission lines from north to south and makes it difficult to implement radial systems. Furthermore, Chile's initial energy transition plan prioritised the installation of renewable generation systems, leaving the integration of the flexibility tools needed to fully harness clean generation on the back burner. Furthermore, the expansion of the transmission network has not progressed at the expected pace and planning to relieve congestion at some important nodes has not been efficient, meaning that excess local renewable generation does not have the infrastructure to be evacuated.

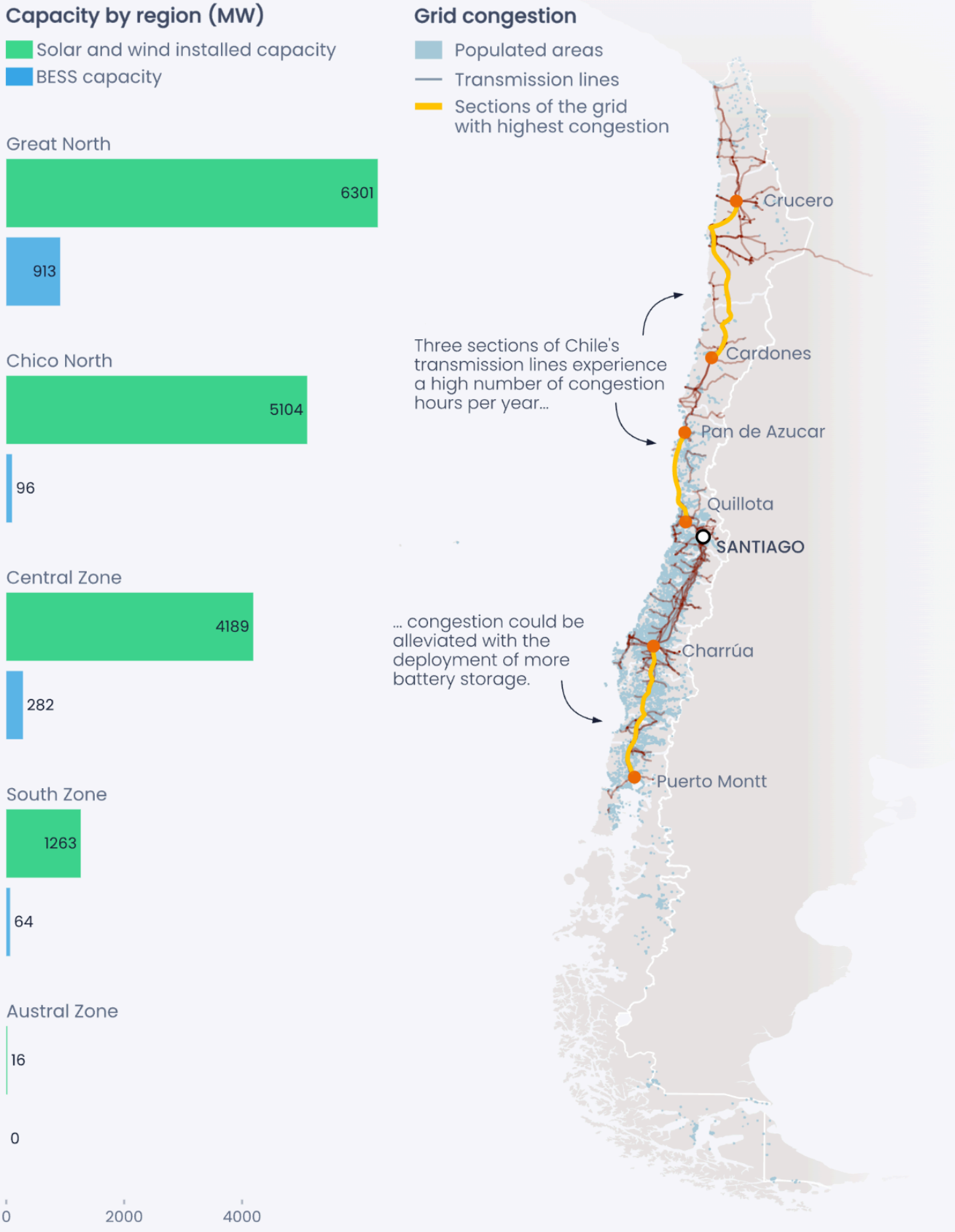
Curtailment in Chile is not due to problems with the availability or operation of solar and wind plants, but to the limited transmission and storage capacity, and the need to strengthen a market-enabling environment that allows the full use of the generation potential of VRE. Indeed, Chile’s renewables plants operate very effectively: the capacity factor for solar generation systems in some regions in Chile is more than 30%, well above the global average of around 15%, while for wind farms the figure is in line with the global average of 34%.

1.2.1 Lack of interconnection between generation and demand centres

While nearly half of Chile's total installed capacity of generation is located in the north of the country, the main demand centres are located farther away, in the central region, which accounts for 29% of the generating capacity. This creates an almost total dependence on the transmission infrastructure to evacuate excess electricity generated in the north of the country.

Renewable power is generated far from Chile's populated areas, putting central-region grids under pressure

Top three congestion hotspots in Chile's electricity grid are highlighted



Source: Generadoras de Chile, Energia Maps, Humanitarian Data Exchange

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Transmission lines have limited capacity in certain sections and are often saturated during peak solar generation hours, as is frequently the case with the sections from Charrúa to Puerto Montt, Crucero to Cardones, and Pan de Azucar to Quillota. In addition, nodal congestion, at network interconnection points, also increases ERV restrictions. This is mainly due to the lack of capacity on short low voltage sections, where several projects are connected to the same node, creating competition to inject electricity into insufficient capacity. Some of the most critical nodes, with recurring capacity restrictions, are Diego de Almagro, Cardones, Quillagua and Lagunas.

In the Transmission Expansion Plan, the most notable project is the construction of the 1,400 km Kimal-Lo Aguirre (HVDC) line, which is scheduled to come into operation in 2029 and is expected to significantly increase transmission capacity from the north to Santiago, transferring significant volumes of surplus solar energy.

Similarly, the line from Nueva Maitencillo to Nueva Pan de Azúcar (2x500 kV), which runs from Antofagasta to Coquimbo, will also strengthen the capacity to transport solar generation from the north to the centre, reducing congestion mainly in Cardones. This 250-km line is scheduled to come into operation in 2029.

To reinforce the regional grid, two projects are expected to come online in 2030: Línea Nueva Los Pelambres - Nueva Illapel - Nueva Pan de Azúcar (2×220 kV), which will reduce congestion at local substations in the Coquimbo Region, and the line from Nueva Pozo Almonte to Parinacota (220 kV), which will reinforce the evacuation of solar energy in the north. Neither of these two projects has been awarded.

1.2.2 Insufficient storage capacity

The initial planning for the deployment of VRE was not linked to initiatives or requirements that would promote energy storage for times of excess generation or arbitrage scenarios in which batteries are charged when electricity is cheap and discharged during peak demand at higher prices. According to Generadoras de Chile, 1,355 MW (5,162 MWh) of battery energy storage (BESS) were in operation as of May 2025, mostly located in the northern part of the country. This BESS capacity, installed on critical nodes of the system, could absorb 6.2% of all solar and wind generation, a low figure compared to the 19% of electricity curtailed in 2024.

Compared to countries like China and Australia, Chile's ratio of installed BESS capacity to installed solar and wind generation capacity is similar, at around 5%, while Ireland's is 11%, and California's is over 50%. While there is no single recommended ratio, optimal storage levels depend largely on the flexibility of the electricity system. Places with robust transmission networks and well-established demand response (DR) programmes generally require less storage capacity than those, such as Chile, with sections of congested networks and incipient demand participation in the electricity market.

How batteries help get the most out of transmission lines between solar power plants and where electricity is needed

	Case 1 - No batteries at the generation or demand end	Case 2 - Batteries at both generation and demand ends
Solar generation	Soaring solar generation during daytime peaks cannot all be transmitted so the excess is curtailed	Surplus solar during daytime peaks charges batteries at the solar end
Transmission line usage	Day: Transmission line usage is maxed out at peak solar generation Night: Transmission lines are underutilised	Day: Transmission lines are not maxed out due to surplus being stored in batteries Night: Transmission lines are used to transfer stored energy from the solar end to where electricity is needed to meet demand and charge batteries
Battery use	No use of batteries at the solar or demand end	At the solar end, batteries charge during surplus and discharge during peaks. Demand end batteries charge overnight from the solar end
Curtailment	High curtailment (wasted solar power)	Reduced curtailment (surplus stored in batteries)
Gas-fired power station usage	Gas-fired power stations must be turned on to meet demand	Gas-fired power stations stay off as demand is covered by stored solar and battery discharge
Overall efficiency of the system	Low: wasted generation and fossil backup needed	High: maximises cable use and avoids gas power
Carbon emissions	Higher (due to gas-fired generation)	Lower (gas avoided; solar maximised)

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In 2022, Law 21,505 allowed storage to participate in the Chilean electricity market and be remunerated for the services it provides to the electricity system, including electricity injection at the transmission and distribution level, and capacity availability. The goal is to reach 2 GW of storage by 2030, although this

value is expected to be reached early in 2026, and 6 GW by 2050, which at the current rate of growth in installed capacity will not be difficult to achieve.

Some technical operating and connection conditions, system usage charges, and technical and tariff conditions for tenders for supply to regulated customers still need to be defined. The most representative project planned is Colbún BESS, with a capacity of 500 MW (2,000 MWh), located in the Atacama Region and with an estimated start-up date in 2027. This project is expected to reduce solar curtailment, offer complementary services such as frequency control and voltage regulation, and be able to operate in energy arbitrage mode.

From 2023, storage systems may be eligible for concessions on public land, allowing companies to apply for storage projects without associated renewable generation, participating as assets that provide flexibility to the electricity system.

According to Ember estimates, under the current conditions of the Chilean electricity system, adding 1 GW of BESS capacity with 4 hours of autonomy, in areas of high grid congestion could reduce annual curtailments by almost a quarter, from 19% to 14.6%, avoiding the curtailment of 1,300 GWh of renewable generation yearly.

1.2.3 Hourly oversupply of electricity and low flexibility of the electricity market

In Chile, there is a geographical decoupling between supply and demand, and at certain times of the day, the available solar and wind generation capacity exceeds instantaneous demand in specific areas, forcing the operator to restrict renewable generation. This phenomenon occurs mainly during peak solar hours, between 12:00 and 15:00, when solar irradiance is high and consumption is low. The typical electricity demand curve in Chile peaks in the morning between 7:00 and 9:00 a.m. and at the end of the day between 6:00 and 10:00 p.m.

Flexibility in the electricity market allows for rapid response to instantaneous changes in generation and demand, especially when the share of VREs is high. It is essential for absorbing electricity surpluses and using them when demand requires it, as well as for maintaining the frequency and stability of the electrical system.

Currently, in the Chilean electricity market, the role of demand is incipient, mainly due to the lack of attractive incentives for its connection to DR markets. Likewise, the lack of technological diversity in the market for flexible complementary services, driven by storage and rapid secondary regulation, limits investments that can help create an enabling environment that provides greater flexibility to the electrical system.

The Flexibility Strategy for the National Electricity System was designed, but to date there is no demand response (DR) market operating in Chile, mainly due to the lack of a regulatory and technical framework. A legal definition of demand aggregators and remuneration mechanisms for DR is needed. Currently, there are no clear price signals or incentives for users, and hourly metering is not well developed

1.3 Chile has higher curtailment than other electrical systems with similar share of solar and wind generation

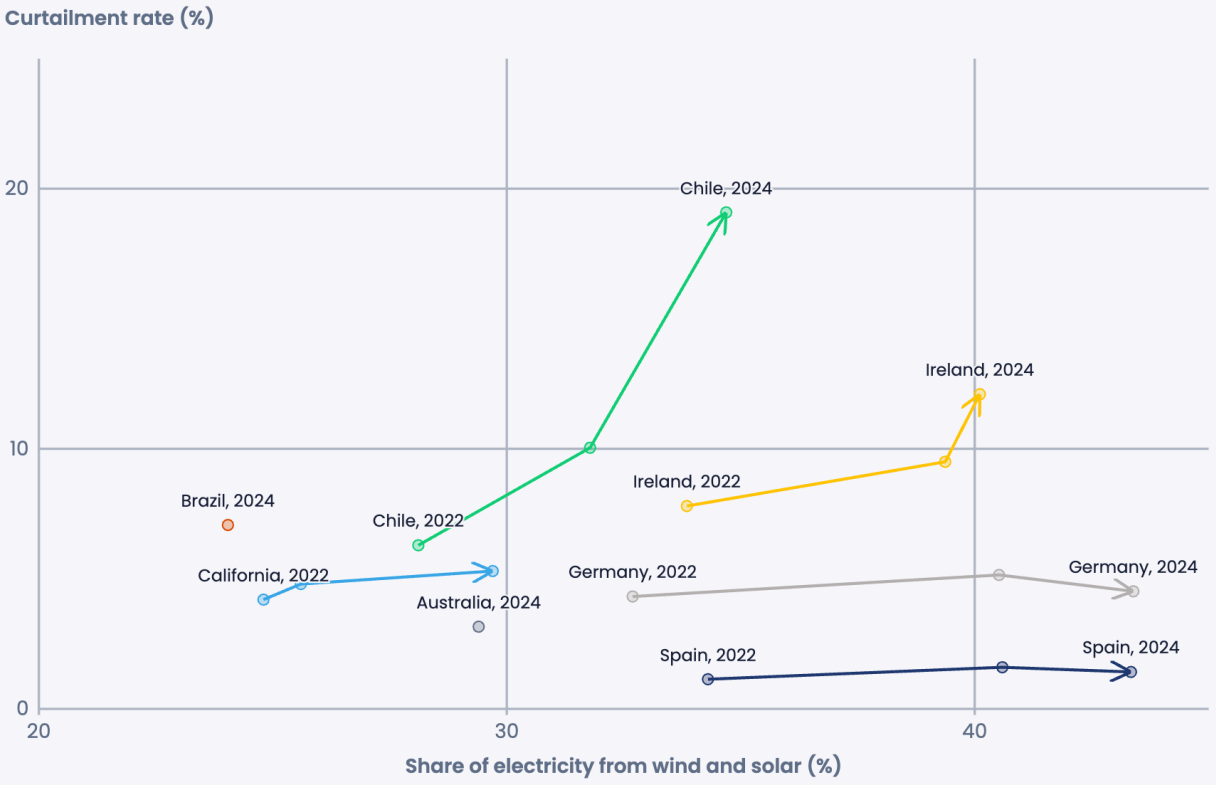
As the share of VRE in an electricity market increases, in most cases their curtailments tend to increase due to a greater likelihood of transmission congestion or oversupply at certain times. It is therefore important to analyse the percentage of energy curtailed in a country or region, compared to the share of VRE in total electricity generation.

There is no standardised optimal curtailment level because geographic conditions, the electricity market, the generation mix, and the context of

electricity systems vary across countries or regions. However, taking as a reference systems with high participation of VRE and with various flexibility tools implemented, curtailment rates above 10% could be associated with infrastructure investment needs, primarily in grids and storage.

Chile has a higher curtailment rate than places with a similar share of electricity generation from wind and solar

Curtailment rate and share of electricity generation from wind and solar (%), 2022-2024



Sources: Comisión Nacional de Energía de Chile, Red Eléctrica de España, International Energy Agency, Clean Energy Wire, CAISO, EIRGRID, Operador Nacional do Sistema Elétrico, AEMO

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The graph compares energy curtailment in Chile with electricity markets with VRE penetration above 20%. Curtailment in the Chilean electricity market is significantly higher compared to markets with similar levels of VRE participation. Countries such as Spain and Germany have managed to stabilise their curtailment below 5%, while the share of solar and wind in annual electricity generation has reached levels above 40%. For solar and wind penetration levels of 34% like Chile's, Ireland had curtailment of around 8%, Germany 4.5%, and Spain 1.2%, values well below the 19% experienced by Chile in 2024.

Although each electricity market has unique conditions, there are some characteristics that can be attributed to lower curtailment rates in certain markets compared to the Chilean case.

i) In Spain, flexible hydroelectric reserves with pumped storage, electricity interconnections with France and Portugal, flexible combined cycles with rapid operation modulation, real-time constraint management, real-time dispatch for solar and wind generation, and self-consumption programmes with demand management.

ii) In Germany, robust networks, decentralised power assets, interconnections with 11 neighbouring countries, active redistribution mechanisms, advance network planning, demand response programmes, push for co-located battery storage.

iii) In California, payments for reducing generation (*decremental bids*), exchanges in the Western Energy Imbalance Market to export excess generation, large-scale BESS, transmission planning to reduce bottlenecks.

iv) In Australia, implementation of renewable energy zones, storage with stability functions, reduction of excess generation through a minimum load system, flexible demand programmes.

Section 2: What has been done in other electricity systems to reduce curtailment as renewable generation grows?

Increased curtailment is a widespread challenge faced primarily by regions with high penetration of variable renewable energy. Measures such as electricity market adjustments, demand response, international interconnections and storage incentives have been implemented in different electricity systems.

Measures taken in electricity systems to reduce curtailment as renewable generation grows

Country	Demand response	Transmission	Storage
China	●●● Industrial incentives, ToU tariffs, demand programmes, hydrogen/ammonia/data centres	●●● Extensive UHV build-out and provincial grid strengthening	●●○ Mandatory storage in new RE, CHP retrofits
Ireland	●●○ Demand participation in DS3 + auctions	●●○ Some progress (Greenlink), but interconnector delays	●●● Strong focus: auctions for BESS and hydrogen
California (USA)	●●● ELRP, EV aggregation, VPPs	●●○ Cluster reforms, but major project delays	●●● Leading deployment: >6,600 MW BESS, hybrids, VPPs
Brazil	●●○ Voluntary DR programme (237 MW)	●●○ 4,000 km new lines, 500 kV expansion	●○○ Still early-stage, only proposals
Uruguay	●○○ No explicit DR	●●● Strong interconnections with Brazil & Argentina	●●○ Hydro as “virtual battery”
Costa Rica	●○○ No explicit DR	●●● Regional SIEPAC trade system	●●○ Hydro balancing with RE

Source: Full case studies in 'Reducing curtailment in Chile', Ember

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2.1 China

China is the world leader in solar and wind power generation, with 839 TWh and 997 TWh generated respectively in 2024. This growth has posed multiple challenges for its electricity system, including the management of high levels of curtailment. In 2016, wind power curtailment averaged 17% across the country. In provinces located in the "three northern regions", where more than 70% of China's wind capacity is concentrated but less than 20% of national electricity demand, curtailment was much higher, reaching more than 30% in Gansu and Xinjiang. The challenge faced by China in having its main solar and wind generation systems far from consumption centres is similar to what is happening in Chile.

The main causes of high curtailments were: i) lack of transmission capacity to send electricity from northwest to east; ii) competition for dispatch in areas where wind and thermal power plants coexisted; and iii) rapid growth of renewable projects in areas with low electricity demand and poor transmission capacity.

Measures implemented to reduce curtailments:

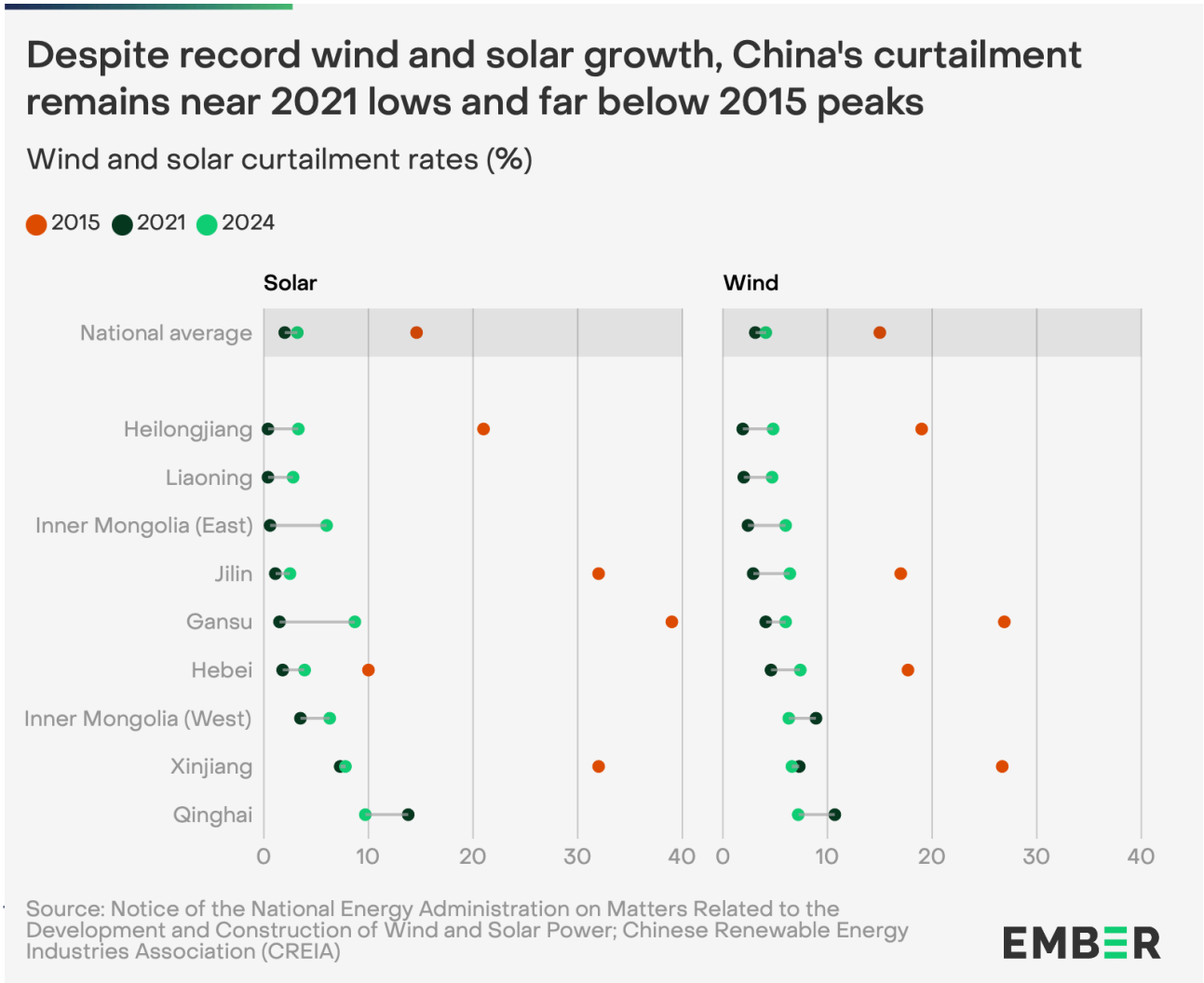
1. Strengthening, in 2016, the principle of "**dispatch priority**" for renewables, reinforcing the obligation to absorb all available renewable generation, except in cases of justified technical restrictions.
2. Mandatory **compensation for curtailments** when they occur within the guaranteed purchase volume. If the cause is system failures, the grid operator is responsible for compensation, financed mainly by the national renewable energy fund.
3. Promotion of the **expansion of the national electricity transmission network** through the UHV Transmission Development Plan (2016-2020), emphasising the construction of ultra-high voltage (UHV) lines to transport large volumes of electricity from areas of high renewable generation in the

north of the country to areas with higher demand. The goal was to build more than 30,000 km of lines by 2020.

4. Strengthening **internal transmission networks** within provinces with high renewable generation, improving connections between generation plants and provincial consumption centres, and reducing dependence on long-distance UHV networks.
5. Setting **targets for reducing curtailment**. The target was set to reduce curtailment to 5% per province, and if the target was not met, the construction of new generation projects in the area would be restricted. This measure led network operators to prioritise congestion management and the injection of clean electricity generation. The plan implemented a renewable energy consumption **quota policy**.
6. Establishment of **an interregional spot market for renewable energy**, facilitating real-time trade in clean energy between different provinces or regions. Sellers are mainly provinces with high discharge rates and buyers are mostly large energy consumers, marketers or local network operators.
7. Inclusion in the *Five-year Plan*, a planning document for the country's economic and social development, of the requirement that all **new renewable energy projects must be linked to UHV transmission projects** under construction or planned. This prevented an excess of renewable energy projects in areas with no transmission infrastructure, low demand or low electricity interconnection.
8. In areas with high solar and wind generation, **older coal-fired power plants providing combined heat and power were modernised** to operate at high load levels in winter, thus increasing system flexibility in the short term and reducing renewable energy curtailment.
9. **Incentives, through industrial policies, to increase electricity demand** in regions with high wind and solar generation but low energy consumption, seeking to reduce congestion on long-distance transmission lines. Provinces such as Xinjiang, Gansu and Inner Mongolia were prioritised, and **reduced electricity tariffs** were designed for energy-intensive industries that consumed local renewable energy. Green hydrogen and ammonia

projects were also promoted, and the establishment of data centres was encouraged to take advantage of excess renewable energy in the area.

10. Requirement to **install storage systems** in new wind or solar generation projects through provincial or local policies. Capacity equivalent to a percentage of installed power was required. For example, Qinghai Province required solar projects to have 10% storage capacity and a minimum runtime of two hours, while Hunan required wind projects to have 15% storage capacity and a minimum runtime of two hours.
11. Creation of **demand response** programmes. In provinces with high renewable generation, during hours of excess generation, electricity-intensive industries receive incentives to increase their production, residential heating systems are programmed to operate for longer periods, and aggressive time-of-use tariffs are used to absorb demand peaks.



The implementation of the strategies presented allowed China to significantly reduce its wind and solar energy curtailment, reaching national averages below 5% by 2024.

2.2 Ireland

The power system of the island of Ireland (Republic of Ireland + Northern Ireland, which operates a single electricity market straddling two countries) experiences high levels of VRE curtailment. In 2024, solar and wind energy restrictions reached 12%, with these technologies accounting for 40% of the total electricity generation. While the challenges Ireland currently faces in reducing curtailment are similar to those in Chile, especially due to the high grid congestion in the areas with high renewable generation, it is important to highlight the short- and medium-term measures that have been adopted, primarily market-based, to ensure that reducing curtailment does not depend solely on infrastructure projects that take several years to implement.

Curtailments are mainly due to: i) grid constraints in areas with high renewable generation, caused mainly by delays in projects such as the *North-South* interconnector; ii) operational safety limits regulating the instantaneous share of renewables that can be accepted into the power system (instantaneous non-synchronous penetration - SNSP); iii) reserve requirements for certain thermal power plants, forcing curtailments in renewable generation; and iv) limited energy export capacity due to saturated or non-existent interconnectors.

Measures implemented to reduce curtailment:

1. Creation of the DS3 (*Delivering a Secure, Sustainable Electricity System*) programme to **efficiently manage the operation of an electricity system with high levels of variable non-synchronous generation**. Its objective

was to include new network services and make existing ones more efficient (virtual inertia, voltage and frequency control) and implement advanced operational tools, as well as optimise dispatch under high non-synchronous penetration. DS3 increased the SNSP in the electricity system from 50%, which was the initial precautionary measure, to 65% and then to 75%, as a result of a constant learning process that has allowed for greater injection of wind and solar electricity into the grid. The final target of the network operator is to increase the SNSP to 95% by 2030.

2. Tools were put into operation to enable **real-time, continuous and automatic dispatch**. Intra-hour forecasting of solar and wind generation was achieved, transmission capacities were calculated in real time (Dynamic Line Rating), economic dispatch was carried out considering security constraints (SCED) and real-time contingency analysis (RTCA) was performed to monitor critical system stability scenarios. Its implementation had an immediate impact on reducing curtailment by allowing the system to be anticipated and stabilised before peaks in oversupply. It also increased non-synchronous generation capacity through real-time control of network limits and congestion. It is estimated that between 2014 and 2016, curtailments were reduced by almost 23%, coinciding with the implementation period of the aforementioned tools. In recent years, as wind and solar generation has increased, curtailments has also grown.
3. Implementation of **the ultra-fast response mechanism with unlimited supply** (*Volume Uncapped Gates*). This authorised BESS and active demand to supply ultra-fast power, competing in continuous auctions with no volume limits. This made it possible to capture excess renewable generation and reduce preventive shutdowns of solar and wind power plants. The implementation of the mechanism redefined the order of merit for economic dispatch, first activating the ultra-fast response, then renewables and, finally, thermal generators.
4. Design of **auction mechanism and contracts for differences for stationary batteries and green hydrogen electrolysers**. Bidders must have environmental permits and a grid connection offer. BESS projects mainly seek to store surplus solar and wind energy, while green hydrogen

electrolyser projects seek to divert curtailment to production processes. The first auction in March 2024 awarded 10 stationary battery projects and 3 green hydrogen projects.

5. Strengthening transmission capacity with the construction of the Greenlink interconnector, a 200 km **HVDC submarine and land cable** connecting Ireland with Great Britain. This private investment project commenced operations in the first quarter of 2025 and allows the exchange of electricity with Great Britain, reducing congestion in areas with high wind generation, decreasing preventive disconnections of wind farms, and levelling market prices. While the main objective of building this transmission line is not to manage curtailment but to increase energy security, energy exports help reduce curtailment events. Greenlink supplemented the two existing interconnectors with Great Britain, and there is also a planned interconnection with France called the Celtic Interconnector.

2.3 California, United States

California is the leader in solar generation in the United States, accounting for 26% of all solar energy generated in the country in 2024. As the share of solar and wind energy has increased, curtailments have also grown. In 2024, 5.3% of renewable generation was curtailed, 93% of which was solar energy.

Most solar farms in California are in desert and rural areas far from large consumption centres such as Los Angeles and San Francisco. The growth in transmission capacity has not kept pace with the increase in renewable generation projects, creating congestion in local grids, which prevents the full potential of clean energy generation from being dispatched. Major transmission projects have suffered significant delays due to permitting, litigation and regional management. Furthermore, at certain times of the year, such as in spring and early summer, energy supply exceeds demand, as well as the grid's

export capacity and storage capacity, forcing renewable generation to be curtailed.

California can be considered an important case study on the integration of BESS in the electricity market. It went from having less than 500 MW of installed storage in 2019 to more than 13,000 MW in 2024.

Measures implemented to reduce curtailments:

1. Implementation of an **Energy Storage Resource Model** *(ESR)* to regulate the role of batteries in the market, allowing them to participate as generators and as loads. This enables them to be a remunerated bidirectional resource in energy markets, as well as offering complementary services. The grid operator, CAISO, uses real-time optimisation algorithms that send signals to decide when it's most attractive to charge or discharge batteries, based on price, congestion, and reliability needs. This way, batteries can contribute to the power system when they're most needed.
2. Implementation of *the Hybrid Resource Model (HRM)* so that **solar and wind power plants associated with BESS, which are connected to the same interconnection point, can participate in the market as a single resource**, simplifying dispatch and maximising the use of the interconnection point. The plant is registered as *a "Hybrid Resource"* and can offer energy and services such as fast ramps, frequency regulation and spinning reserve under a single supply curve. Hybrid plants combine renewable variability with the immediate response of the battery, improving system reliability and reducing dependence on fossil generators at peak demand. Currently, more than 90% of registered large-scale solar projects are hybrid with storage.
3. Obligation to allow **distributed energy resources to participate in wholesale energy, capacity, and ancillary services markets**. The aggregation of multiple small resources as a single entity in the market is

recognised, allowing residential batteries and electric vehicles to absorb excess solar energy and release it during hours of high demand. In this way, the grid is supported by millions of distributed nodes, rather than relying on large, centralised projects, reducing local transmission congestion. This solution, while helping to reduce curtailment, also poses significant challenges in maintaining system balance by having multiple distributed nodes actively participating in the market.

4. **Simplification and acceleration of interconnection processes for solar and wind energy projects**. Previously, interconnection studies were requested individually, even if several projects were in the same area. Now, interconnection clusters are used, grouping requests and conducting joint feasibility, network impact, and cost studies. In addition, strict filters have been introduced to refine the list of interconnection requests and thus eliminate speculative projects that take up space and prevent more robust and mature projects from moving forward. These projects are grouped in "Renewable Energy Zones," for which the interconnection process is prioritised in accordance with the Transmission Planning Process, reducing the possibility of projects becoming trapped in areas with poor network capacity.
5. Creation of the Energy Imbalance Market (EIM) to enable **real-time energy exchange between grid operators in different states**, facilitating the balance between forecast generation and actual demand. Under this market, CAISO reviews the integrated grid every five minutes, verifies where there is excess or need for energy, and automatically dispatches the cheapest available resources.
6. Creation of the Emergency Load Reduction Program *(ELRP)* in 2021, when California experienced power outages due to lack of grid capacity during an extreme heat wave. This programme, which is outside traditional market mechanisms, provides **incentives to all types of users to make rapid reductions in their energy demand at critical times**. The programme has been used as a rapid emergency tool during several heat waves, allowing demand to be reduced during peak hours. It currently allows the participation of electric vehicles and load aggregators.

2.4 Latin America

In Latin America, the extensive infrastructure for hydroelectric generation existing in several countries allows their reservoirs to be used as virtual batteries, reducing the discharge of solar and wind energy. Likewise, electrical interconnection between countries allows the exchange of surplus generation, mainly under bilateral agreements, taking advantage of the complementarity of electricity generation resources.

2.1.1 Brazil

1. **Strengthening transmission capacity**. In 2023, contracts were signed for the construction of more than 4,000 kilometres of transmission lines. Similarly, with the commissioning of three 500 kV lines, the electricity export capacity from the northeast to the southeast and centre-west increased by 12%, and by almost 30% to the north. This measure seeks not only to allow the integration of the VRE, but also to allow hydroelectric generation to reach the southeast.
2. Implementation of **voluntary demand reduction mechanisms** as part of the demand response programme, allowing industries and companies to be remunerated for reducing their electricity consumption at critical times for the system. In 2024, an average reduction of 237 MW was achieved during the 69 days that the programme was active.
3. Creation in 2025 by the Federal Government of a **working group** (WG) to diagnose, design strategies and propose regulatory and operational measures to reduce renewable energy curtailments in the country, which currently reach 7%. The group is made up of the main organisations in the Brazilian electricity sector, as well as renewable energy associations. Among the main measures proposed to reduce curtailments in the short term are the publication of data on curtailments, the acceleration of transmission works, the installation of synchronous compensators to improve the operational stability of the systems, the review of the methodology for the participation of storage systems, the development of

regulatory proposals for the participation of distributed generation, and the evaluation of fair compensation for curtailments.

2.1.2 Uruguay

1. **Strengthening electricity export schemes**. There are specific regulations on technical parameters, protections and dispatch for interconnection with Brazil, a 125 km long line with 525 kV capacity, and four interconnection lines with Argentina. In 2024, Uruguay exported 2,026 GWh (more than 11% of its total generation) to Brazil and Argentina, mainly wind and hydro surpluses, worth more than $100 million.
2. **Use of reservoirs and hydroelectric plants as virtual batteries**, providing flexibility to its electricity system. When wind and solar generation is high, these technologies are dispatched, while hydroelectric plants are used as backup, adjusting flows according to the generation provided by the VRE. The implementation of operational tools associated with hydrometeorological forecasting allows dispatch decisions to be made to maximise the use of VRE, manage exports and reduce curtailments.

2.1.3 Costa Rica

1. **Management of renewable energy surpluses**, mainly through exports to the Central American Electrical Interconnection System (SIEPAC). In 2024, more than 92% of Costa Rica's total exports in the Regional Electricity Market (MER) were made in the short-term market, allowing for control of renewable electricity curtailments. The MER determines prices and issues signals during periods of excess generation at nodes, allowing market agents to determine when to export and make efficient use of their generation sources.

Section 3 Recommendations for reducing solar and wind energy curtailment in Chile

The recommendations seek to provide solutions to increase the flexibility of the Chilean electricity system and are framed within the logic of the clean flexibility tools designed by Ember.

3.1 Clean Flexibility Tools

As fossil fuels play an increasingly less important role in electricity generation, a new version of flexibility is required to make the transition to clean electricity systems. Clean flexibility allows for the management of the variability and unpredictability of electricity supply and demand, everywhere and at every moment, achieving efficient use of variable renewable generation.

Making power clean every hour: 9 clean flexibility tools

Renewables are the heart of a clean power system, and clean flexibility is the brain that keeps it balanced. These nine tools—across four categories—can reduce reliance on fossil fuels and are ready to deploy.

Store
Four clean flexibility tools store electricity across minutes, hours and days to save renewable power for times with less sun and wind.

Shift
Two clean flexibility tools incentivise consumers to shift non-critical demand to windy and sunny hours, lowering their bills and providing grid stability.

Share
Power cables are a clean flexibility tool that carry excess solar and wind power to where they are needed, balancing supply and demand across space.

Supply
Two clean flexibility tools enable all power sources to ramp up and down quickly, maximising wind and solar use in a cost-effective way.

How to read the graphic

When clean generation exceeds demand
→ direction of supply demand response

When clean generation falls short of demand
→ direction of supply demand response

STORE

Pumped hydro storage and enhanced hydropower

Electric pumps use cheap, abundant electricity to raise water to an elevated reservoir, releasing the water back down through turbines produces electricity like a traditional hydropower plant when demand is high.

▶ In 2024, China completed the world's largest pumped storage station (3.6 GW), saving a potential 1.2 million tons of CO_2 annually.

STORE

Long duration energy storage (LDES)

Emerging LDES technologies can store electricity for up to several weeks. This includes newer battery technologies, thermal storage, gravity-based storage and compressed air storage. Most are in the early stages of research and demonstration.

▶ In April 2024, China launched a 300 MW compressed air storage project, cutting a potential 490,000 tons of CO_2 annually.

SHIFT

One-off payments/Peak shaving

Consumers are offered payments to alter their consumption – either to reduce electricity use if electricity is in short supply, or to increase it if renewable electricity is so bountiful it risks being wasted.

▶ In India, some consumers can sign up for text alerts to reduce demand during system stress, earning rewards for participation and helping to reduce the need for spare coal power plants.

SHARE

Power cables

Grids and interconnectors let places with high wind and solar potential to fully develop and share it with places that need the electricity. They also help exploit variations in weather conditions and electricity demand across countries and regions.

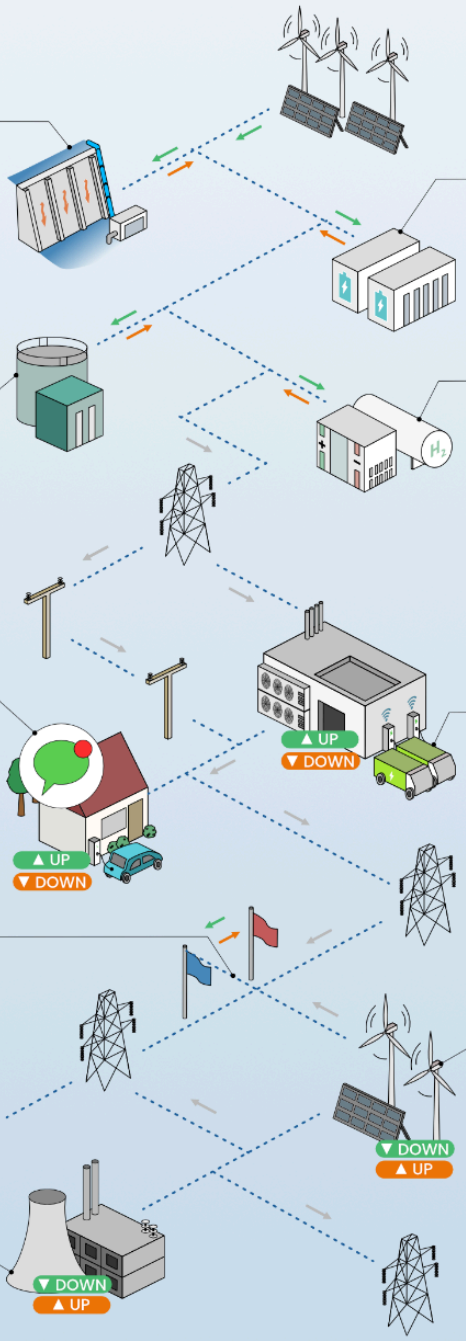
▶ The European electricity system is the world's largest interconnected grid, linking 39 countries. In 2021, cross-border trade saved €34 billion by reducing price volatility compared to isolated national markets.

SUPPLY

Improve downward fossil flexibility

Technical upgrades and removing contractual obligations allow fossil plants to reduce output faster and operate safely at lower capacity.

▶ India is improving its thermal plants to be able to run safely at a lower rate, from 70% to 55% of their capacity, saving an estimated $311 million annually in system costs.



STORE

Batteries

Batteries can store excess renewable energy during periods of abundance and low demand as chemical potential energy and release it when supply is scarce, typically within a day or two.

▶ California's battery capacity grew 13-fold in five years, reaching 10 GW by April 2024. With batteries shifting solar power to evenings, batteries routinely met close to a fifth of California's daily peak load in the evening hours in 2024.

STORE

Green hydrogen

Electrolysers use renewable electricity and water to make hydrogen, which can be burned to produce electricity. High energy losses in the process make this a viable storage solution only when there is no cheaper option.

▶ In 2023, around $2.9 billion USD was invested worldwide in electrolyser projects under construction — five times the amount invested in 2022. However, large-scale deployment is still not taking place.

SHIFT

Dynamic tariffs/ Smart electrification

Digitalised technologies can enable consumers to effortlessly shift demand patterns to better match cheaper windy and sunny hours. This can help meet rising electricity demand from new electric vehicles, heat pumps and air conditioners with renewable power.

▶ In Norway, consumers can earn €70–100 a year by simply enabling smart charging of their EV, on top of any potential cost savings from dynamic tariffs.

SUPPLY

Smarter wind and solar

Wind and solar can be temporarily and quickly turned off or down. In high-renewable systems, some curtailment, if managed smartly, is often more cost-effective than aiming for zero curtailment.

▶ In California, a 300 MW solar plant without storage was curtailed by 30 MW from its available peak capacity to have manoeuvrability to increase its output on demand and stabilize the grid more efficiently than gas.

For more insights on clean flexibility, visit our website www.ember-energy.org or scan the QR code.

Source: Ember
Infographic by Reynaldo Dizon.
Written by Beatrice Petrovich, Kostantsa Rangelova and Alison Candlin.

EMBER

Ember's clean flexibility kit is a package of tools that enable the grid to remain balanced when VREs exceed or cannot meet demand, making the most of renewable energy. These tools ensure that excess clean energy is not wasted but can be used later, taken where it is needed, or matched to demand.

3.2 What measures could Chile implement in five years to manage solar and wind energy curtailment?

These recommendations seek to provide solutions that can be progressively implemented within a time frame of up to five years, some of them much faster, allowing progress to be made in increasing the flexibility of the Chilean electricity system and creating an enabling environment for managing curtailments, while large transmission and storage projects that are planned or under construction come online. The recommended measures will continue to generate benefits in the long term, thus enhancing the impact of major infrastructure projects planned and/or under construction.

For every percentage point that the current level of curtailment in Chile (19%) is reduced, the availability of 295.5 GWh for use in the Chilean electricity market would increase, which would serve to supply the electricity demand of more than 120,000 homes for a year. That is why it is important to implement various flexibility measures, without relying solely on large infrastructure projects.

3.2.1 Short term (less than 2 years)

If Chile is to reduce curtailment over the next two years, it is important to set clear curtailment reduction targets, take measures to relieve congestion at critical nodes in areas with high renewable generation, and create a favourable environment for achieving the 2030 storage capacity target.

- **Design of a National Curtailment Reduction Plan**

A formalised plan, linked as a tool for implementing existing policies in the Chilean electricity sector (Energy 2050 or the National Strategy for Flexibility in the Electricity Sector), with explicit targets for the progressive reduction of VRE curtailment. The plan would be aligned with the milestones for increasing transmission, storage and flexibility capacity, as well as with new demand response and electricity market management initiatives. The average reduction target for curtailment should preferably be national, but indicative regional targets could be set according to the current level of curtailment in specific areas of the country, as well as the potential impact of initiatives such as the Regional Energy Plans. China implemented a similar plan with regional goals.

The design of the plan should be led by the Ministry of Energy, but the establishment of a working group with public and private stakeholders and relevant energy sector associations would be useful to build consensus on the setting of targets and monitoring and follow-up strategies.

- **Minimum storage requirement for new solar and wind projects in areas of high congestion**

As a condition for obtaining grid connection permits in critical congestion areas and therefore with high curtailment rates, developers of new solar and wind projects should install associated storage capacity. The required storage capacity should be linked to a percentage of installed generation capacity and to an autonomy time in hours. In principle, conservatively based on the experience of other countries, an installed storage capacity equivalent to 10% of solar and wind generation capacity with a minimum runtime of two hours could be required. Countries such as India and Mexico have moved in this direction, seeking favorable conditions for the growth of VRE generation.

The validity of this measure should be validated when large transmission projects such as the Kimal–Lo Aguirre line come into operation, and its impact should be reviewed periodically in terms of the reduction in curtailments.

Beyond energy arbitrage, the installation of storage systems offers benefits for investors in VRE generation projects. Reducing curtailment would allow them to improve the real utilisation rate of generating plants and thus increase their revenues. They would also be able to access more favourable financing conditions by ensuring more stable and predictable cash flows, reducing the uncertainty generated by curtailment. They would also be able to participate in capacity markets.

- **Structuring an enabling environment to achieve energy utility scale storage targets**

Reaching 6 GW of installed capacity of storage by 2050 is a realistic goal for the Chilean power sector, which as of May 2025 had 1,355 MW of BESS. Achieving this goal requires the creation of the necessary conditions to provide technical and financial certainty to investors. California is a prime example of the integration of BESS into the electricity market and the establishment of ambitious storage goals; 8.2 GW of new battery capacity is planned to come online between 2025 and 2028.

2 GW of storage capacity, with a duration of 4 hours, would allow for the absorption of approximately 7.2% of Chile's total solar and wind generation, which by 2030 could reach 36 TWh, achieving a share close to 38% of the electricity mix. Failure to increase current storage capacity could lead to curtailment reaching levels of 24%, according to a study by the National Electricity Coordinator.

Currently, most BESS in Chile are financed by spot price energy arbitrage, which is highly volatile. So, it is important to create an enabling environment that

provides certainty to investors to assure that the deployment of storage in Chile can be carried out within the expected timeframe. This may require initiatives such as:

- Enabling multi-service revenues for BESS, designing regulations so that batteries can receive revenues from energy arbitrage, frequency regulation, operating reserve, ancillary services, and capacity markets.
- Accelerating testing and connections, reducing the time between connection requests and commissioning, streamlining land use procedures, environmental licensing and connection permits, establishing testing protocols and minimum technical requirements, and speeding up pre-operational and operational testing times.
- The integration of storage with transmission and flexibility needs, coordinating location, operation and market signals, so that storage systems help to free up grid capacity, reduce curtailment and defer investment in transmission and distribution in areas and nodes with high levels of congestion.

These measures could be linked to Law 21.505 as a basic framework and institutionally anchored to the National Strategy for Flexibility in the Electricity Sector.

- **Massive DLR (Dynamic Line Rating) installation programme**

The DLR is a technology that allows for a temporary increase in the capacity of power transmission lines, making better use of existing infrastructure, reducing congestion, and helping to integrate more renewable energy, without the immediate need to build new lines.

This technology allows real-time calculation of the maximum transport capacity of a transmission line, adjusting its capacity based on direct measurement of variables such as temperature, wind speed and solar radiation. Its calculation

algorithm estimates the maximum permissible current before reaching the safety limit, allowing effective capacity to be increased in critical corridors. DLR performs better in locations with long lines, winds and no extremely high temperatures, making it ideal for Chile. Several European electricity systems have used DLR to increase their transmission capacity.

This measure would allow for an immediate reduction in curtailment without the need for major infrastructure works and has a low cost compared to the installation of new lines or reinforcements. It can also be included as a complementary service that could be remunerated through the reduction of curtailment and marginal operating costs.

A national programme for the mass installation of DLR on the most congested lines could take less than three years, given that the physical infrastructure already exists and the work would mainly focus on installing sensors and software. This would allow it to be operational before the large transmission projects come online. Priority could be given to the Mejillones-Crucero-Cardones line (220 and 500 kV), the Cardones-Maitencillo- Pan de Azúcar node, the Pan de Azúcar-Polpaico-Charrúa corridor (220 and 500 kV), and the Quillagua-Crucero-Pozo Almonte node.

On average, based on the experience of projects previously developed, the DLR can increase line capacity under normal conditions by between 10% and 30%, allowing more electricity to be injected and consequently reducing curtailment.

The programme should be designed by the Ministry of Energy, while the CNE would be responsible for regulatory aspects and for approving the DLR as an eligible reinforcement so that it can receive tariff recognition. The operation, technical supervision and prioritisation of the lines would be the responsibility of the National Electricity Coordinator.

2.2 Medium Term (2-4 years)

It is a priority to encourage the development of solar and wind projects in areas with the capacity to absorb the highest volume of electricity generated, as well as to define the conditions for industrial, residential and commercial users to begin to play a more active role in a demand response formal market. This should be combined with the optimisation of the use of existing networks.

- **Incentives for new projects located near areas of high demand and/or low grid congestion**

Creation of incentives for new solar and wind energy projects developed in areas with available or under-construction grid capacity and/or close to large centres of electricity demand, discouraging the installation of new generation plants in saturated areas with high levels of curtailment. Priority areas should be aligned with the Regional Energy Plans, transmission expansion planning, proximity to load, and seasonal complementarity between sun, wind, and rainfall. Australia is doing something similar with its renewable energy zones.

Incentives may be regulatory and economic in nature and could include i) priority or fast track treatment by the National Electricity Coordinator (CEN) for the management of studies and permits for connection to the grid ii) access to public funds or state guarantees for projects in strategic development areas, iii) differentiated transmission tolls, offering preferential prices for projects in prioritised areas and imposing surcharges in areas of high congestion, iv) competitive advantage in accessing government land for renewable energy and storage projects, v) payment of a premium price for energy fed into the grid in prioritised areas, probably with lower solar or wind resources, compensating the investor for a lower capacity factor.

The incentives, which should have a predetermined duration, be transparent and targeted, can be created through a decree of the Ministry of Energy and

regulations of the National Electricity Coordinator to define the criteria for fast-track connection to the grid and differentiated tolls.

- **Creation of a formal demand response market**

Design a demand response (DR) market, providing efficient electricity price signals to residential, commercial and industrial consumers so that they can benefit from flexible consumption. This would allow consumption to be shifted or created during hours of high solar and wind generation and reduced during peak demand. A DR market helps provide flexibility and reliability to the electrical system, reducing operating costs and enabling greater integration of generation with VRE. European electricity markets are a good example of active demand participation and its benefits.

A formalised market requires a clear and stable regulatory framework that recognises DR as a market resource. It is necessary to define who can offer DR, generally large consumers and aggregators, and what the rules for remuneration are. For it to function properly, it is necessary to implement measurement and communication infrastructure, including smart metering, communication protocols between the market operator and those offering DR, and a platform that allows verification of the reduction or increase in demand.

The Ministry of Energy should be the entity that proposes the DR market as a public policy, defining its general guidelines, objectives, access principles, and remuneration.

Among the demand response programmes that could be implemented are i) differentiated tariffs (*Time-of Use pricing* or *Critical Peak Pricing*) to encourage consumption during hours of peak renewable generation, mainly in areas with high emissions such as Atacama, Antofagasta and Coquimbo ii) flexibility contracts with large consumers, ideally copper and lithium mining industries located in the north, to shift some of their processes to times of peak renewable

generation, iii) promotion of the installation of charging stations for buses and electric vehicles in areas with high emissions, becoming a permanent demand for surplus renewable energy, iv) promoting the installation of new industries, such as data centres, in areas with high renewable generation.

It is important to allow electric and plug-in hybrid vehicles to be part of the DR market. In 2024, there were more than 11,000 vehicles of this type in Chile, which could mean an electricity storage capacity of more than 450 MWh, almost half of the capacity of the BESS currently in operation. It is estimated that by 2030, these vehicles could reach 150,000 units. Electric and plug-in hybrid vehicles can participate both in the DR market by adjusting their charging to price signals or operator requirements, as well as in the complementary services market by acting as storage resources.

2.2 Long term (up to 5 years)

Over the next 5 years, it is important to consolidate a demand response (DR) market with clear metrics for costs and impact. It is also crucial to define the technical, political, regulatory and financial conditions for stable electricity exchange markets with Argentina and Peru.

- **Mass implementation of demand response projects**

Implementation of projects, focused by area, to test the mechanisms established in the formal DR market, validating the interest of stakeholders, as well as their operation and efficiency in reducing curtailments. This measure would allow the initial design of the DR market to be adjusted before scaling up to the national level.

In the north of the country, where the highest solar curtailments are concentrated, the willingness of local industries such as mining and cement to shift or increase their consumption during hours of oversupply could be

validated, using a flexibility remuneration mechanism. In large urban centres, it would be strategic to test a peak shaving programme involving large commercial and industrial customers to reduce their consumption during peak demand between 6pm and 10pm, allowing the capacity of the DR as a resource to increase system reliability to be validated. In Santiago, in areas with the highest solar energy use, the efficiency of sending dynamic price signals to load aggregators to manage residential batteries, electric vehicles, air conditioners and electric heaters could be tested, allowing the technical feasibility of aggregation in Chile to be validated.

The main impact indicators to be validated could be: avoided curtailment (MWh), cost avoided by curtailment ($/MWh), increase in the local transmission network utilisation factor (%), flexible consumption provided by the industrial, commercial and residential sectors (MWh), reduced demand during peak hours (MWh), and flexibility managed by aggregators (MW).

- **Definition of the political and regulatory framework to consolidate an electricity exchange market with Argentina and Peru**

Having a stable electricity market with Argentina and moving forward with concrete agreements with Peru requires planned and coordinated work between the countries.

Exchanges are already in place with Argentina, with bilateral planning and operating protocols using the 345 kV Andes-Cobos line. Progress is needed in automating data exchange, implementing a binational intraday market, and harmonising transmission tariff criteria and export tolls. Likewise, shared financing mechanisms must be established to strengthen the current infrastructure and plan new higher-voltage interconnection lines.

No interconnection line is in operation with Peru. The 220 kV Arica-Tacna project is undergoing feasibility analysis. Progress must be made in defining the interconnection technology, achieving regulatory harmonisation, and designing market operation. It is important to establish a binational planning committee to conduct long-term flow studies and identify potential restrictions for the interconnection line.

Conclusion

Chile has made an admirable effort to deploy solar and wind generation, allowing these two technologies to reach a 34% share of the country's total electricity generation by 2024.

To fully leverage the current and projected potential for clean generation, short-, medium-, and long-term measures must be implemented to reduce the curtailment of renewable energy.

While large projects to increase electricity transmission capacity come into operation, it is important to create the right conditions to incentivise investment in energy storage systems and thus achieve the established goals.

Likewise, the formalisation of a demand response market is especially important, allowing consumers to make decisions based on price signals or incentives to increase or decrease their electricity consumption and thus contribute to the flexibility of the electricity system.

Other countries have taken similar decisions to make the integration of variable renewable energy more efficient, and this report presents a series of options that could be beneficial for Chile to maximise its abundant renewable resources.

Supporting information

Methodology

The recommendations for reducing curtailment were developed based on the international experiences analysed and validating their applicability in the Chilean electricity system, under the current political and regulatory framework, giving priority to Law 21.505, the National Strategy for Flexibility in the Electricity Sector, Chile's Energy 2050 energy policy and the Transmission Expansion Plan.

To estimate coal-fired power generation, a calorific value of 22.8 MMBtu/ton was assumed, and to estimate emissions, the factor used was 0.95 tCO_2/MWh. The cost of imported thermal coal was assumed to be $110 USD/ton.

To estimate BESS capacity, a charging and discharging efficiency of 90% was assumed.

An average annual electricity consumption of 200 kWh per household in Chile was assumed.

To estimate the reduction in investor income resulting from curtailment, the approximate average marginal cost of generation was used as an input, assuming the following values: $70 USD/MWh (2022), $59.57 USD/MWh (2023), $51.51 USD/MWh (2024), and $77.20 USD (January to June 2025). It was assumed

that 30% of solar curtailment was during hours with zero marginal generation cost.

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