Navigating the Energy Transition in Chile:

A reliability-focused approach to the Chilean Energy Transition

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Foreword

The executive summary summarizes the study's results and conclusions and was written by Wärtsilä.

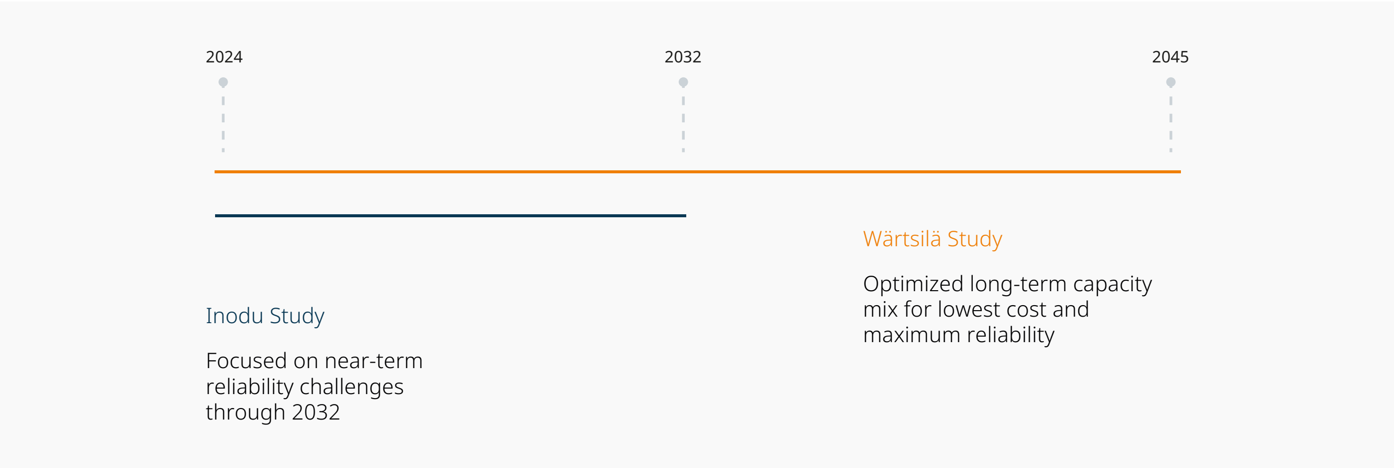
This study is a collaboration between inodú and Wärtsilä who have worked to outline both near-term and long-term challenges in Chile's electric power sector.

Section 1, titled "Potential near-term security of supply risks" was written by inodú. Inodú is focused on providing consulting services & market intelligence since 2012 to improve the sustainability of the energy value chain in North America and Latin America. In the first chapter, the emerging issues of capacity adequacy, short-term ramping, and black start capability are analyzed and explored. The merits of different technologies as solutions to these challenges are also considered.

Section 2, titled "Optimal long-term energy transition path for Chile," was written by Wärtsilä. Wärtsilä specializes in decarbonization solutions that implement flexibility as an enabler of renewable integration. These chapters explore the potential solutions proposed by inodú and analyze the long-term implications of each choice using PLEXOS-software to dispatch each solution from 2024 to 2045, and to compare the results.

Section 3 was written by Wärtsilä and offers case studies on large engine power plants from Australia, El Salvador, and the USA that showcase the value of operational flexibility.

The image below provides a simple outline of the respective study scopes and how they overlap.



Executive summary

With 20% of electricity coming from solar PV and 13% from wind power in 2023, Chile is a global leader in renewable energy development. While emissions have decreased, the rapid growth of renewables has introduced new challenges. Specifically, the inflexibility of coal plants forces the curtailment of solar power, leading to increased carbon emissions and higher systemic costs.

Section 1 of this study, conducted by inodú, used PLEXOS to identify and quantify emerging reliability issues. It outlines a timeline for coal plant retirements and the expansion of wind, solar, and storage resources.

Looking at the horizon until 2032, 4 emerging challenges are identified that, without action, will compromise security of supply. These challenges are:

1 | **Resource adequacy during nights** – reliability issues are emerging during the night. By the end of the decade, due to closure of firm thermal capacity, the system capacity adequacy will be at risk.

2 | **Resources that can cover short term variations efficiently** – the assets capable of ramping to respond rapidly to sudden decrease of wind power are aging, expensive, and highly emissive

3 | **Grid black-start capacity** – Primarily in the north – there are nodes with only one plant capable of restarting of the grid in the case of a black-out and some of those are slated for retirement

4 | **Inertia and short-circuit capacity** - closure of thermal power plants reduces inertia and short circuit capacity, which must be maintained to a standard for grid security.

In the next two years in Chile, a new set of thermoelectric facilities will be retired or reconverted (IEM, CTA, CTH, CTM 1 and CTM 2). The resource adequacy and reliability services provided by thermoelectric facilities are required in the next years, particularly before the HVDC line starts operations. The need for thermoelectric facilities in Chile is driven by security constraints, resilience requirements and economic dispatch in periods with low and high demand, even when considering scenarios where large quantities of short duration energy storage are integrated into the Chilean Electricity System.

A large portion of the gas fleet is approaching 25 – 30 year operational life. Therefore, there is a short timeline to make decisions on how to address the aging of thermoelectric units which will be exposed to demanding operational conditions, with high flexibility requirements.

Addressing adequacy challenges to supply periods with low availability of renewables, high demand and perhaps with some operational limitations in synchronous units requires addressing a deficit of capacity, which could exceed 1000 MWs by 2032 under the scenarios evaluated. The challenge could be exacerbated by the effects of weather conditions on demand, particularly in winter.

After recognizing the near-term reliability challenges in the Chilean energy transition, Section 2 analyzes the long-term economic impact from 2024-2045, addressing the 4 challenges through two different approaches: rehabilitation of existing gas generation assets, or retirement of old assets and investment in new, flexible gas generation capacity.

In each expansion modelling case, the Chilean capacity matrix was optimized for the lowest system-level cost based on constraints such as net-zero targets, pre-existing coal retirement schedules, age of existing thermal capacity, spinning reserve requirements, and transmission limitations.

Owners of aging Combined Cycle Gas Turbines (CCGTs) are rapidly approaching the life-time extension decision in the near future. The study shows that at a reinvestment cost of $400/kW and a lifetime extension of 10 years, the system would benefit from allowing aging CCGTs to retire, and to invest in new capacity that is designed for cyclic operation in a power system with high share of variable renewable energy. From 2024-2045, this decision reduces total electricity generation costs by a cumulative $3.7 billion USD, corresponding to 5 % lower total generation cost. By 2045, 9.5% of total installed capacity will be firm, flexible capacity, while it is responsible of 4% of total annual generation. In the simulation, the firm flexible power plants operate on H_2-derived sustainable fuels after 2035, adding no carbon to the atmosphere. Thermal generation will come on-line primarily during times of stress and low-renewable output.

The study also examines the counter argument that capacity expansion should be driven entirely by solar, wind, and storage. The modeling shows that without the firm thermal component, the other resources need to be overbuilt by almost 50%, adding $17 billion USD in cumulative costs to be distributed among rate payers between 2024 – 2045.

The modelling shows that the cost-optimal decarbonization path uses gas as a transition fuel and later converts the flexible gas power plants to sustainable fuels.

Given the age of the existing gas fleet, the timeline to make decisions on rehabilitation or investing in new firm, flexible capacity is short, so process and tendering efficiency is key. Looking at the mechanisms in place for new investment, the existing capacity market could only address the resource adequacy challenge during night. Because of its ability to directly address 3 challenges and indirectly address the 4th challenge, an ancillary service infrastructure tender is proposed as the most efficient method of acquiring the necessary capabilities 2,3 and 4 below.

Using the same mechanism as the 2023-2024 synchronous condenser auction, Chile could efficiently purchase necessary infrastructure that will address all 4 emerging reliability challenges.

Firm, flexible gas power plants are capable of addressing all 4 reliability issues outlined in section 1 of this study, allowing Chile to address emerging reliability problems with 1 technological solution and 1 tender process.

	Risk	Capacity Market	Ancillary Service Infrastructure Tender
1	Resource adequacy during the night	Yes would involve significant changes to capacity market which has been challenging to modify in past 5 years	Yes The tender could be used to address resource adequacy deficit indirectly.
2	Availability of resources which can cover short term variations effectively	No short term variations are not covered by capacity market.	Yes An ancillary service infrastructure tender for resources which can address short term variability of renewables could be defined.
3	Black start capability limitations in the north	No black start capabilities are not covered by capacity market.	Yes An ancillary service infrastructure tender for black start capabilities.
4	Regional need for inertia and short-circuit capacity	No the capacity market does not cover inertia and short-circuit capacity	Yes an ancillary service infrastructure tender can require 24/7 inertia provision

Background

With high shares of solar and wind power, Chile is a pioneer in the global energy transition away from carbon, navigating the complex process of maintaining acceptable balance between reliability, sustainability, and affordability.

In the early days of the transition, national approaches typically emphasized fast establishment of renewable wind and solar resources. This is also the case in Chile – at the end of 2023, the share of solar and wind was one of the highest in the world, at 20% and 13%, respectively [1].

However, as a consequence of the growth of renewables, a new challenge emerged: the inflexibility of the power system. At and beyond the flexibility limit, which is different in every country, curtailment of solar and wind increases rapidly, and further integration of renewables becomes un-economical for investors. This is currently the situation in Chile, illustrated in Figure 1.

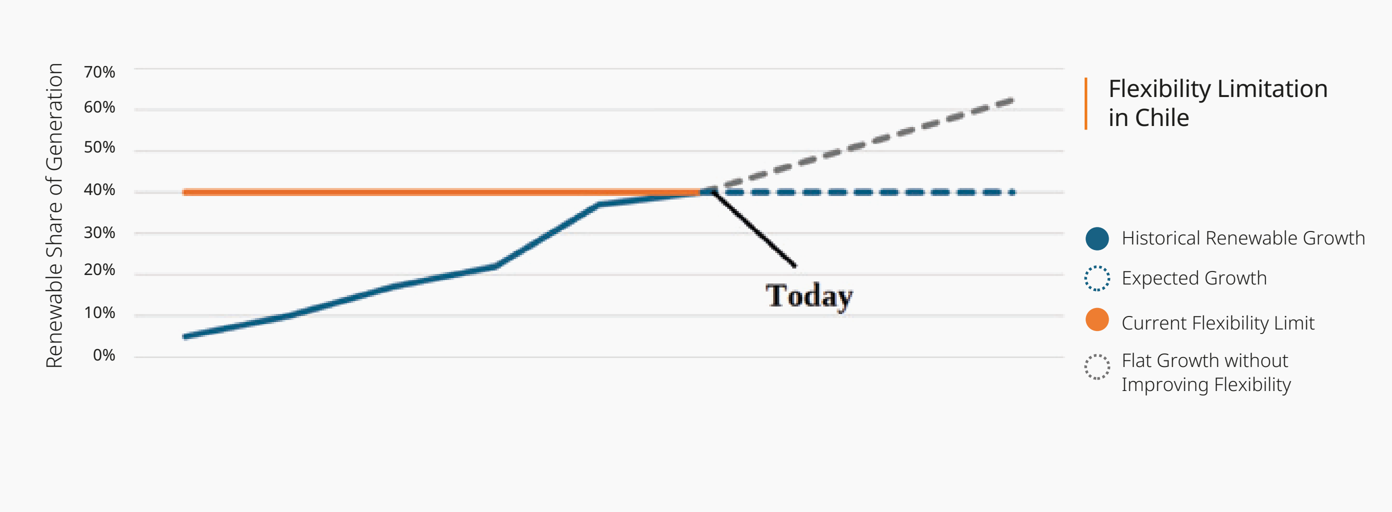


Figure 1 - Power System Flexibility Limit in Chile

Wasting increasing amounts of valuable solar energy every day, while at the same time paying for fuels that are used only because of system inflexibility, have a negative impact on affordability of electricity and sustainability. A key topic in this paper is to demonstrate how to take the next steps in the transition to raise the flexibility limit by sustainably retiring inflexible assets that prevent renewable integration.

While retiring inflexible firm capacity, system reliability cannot be overlooked. So far, there has been enough capacity to provide security of supply, but issues may emerge during the nights when there is no solar power and storage duration is limited. Resolving these issues requires specific action, which this Study attempts to present.

We discuss “Firm Capacity” widely in this document. To ensure a unified understanding, a definition for firm capacity is provided here:

Firm Capacity:

- Can be started from a push-button, when needed
- Can be operated for as long as necessary, even months.

Battery storage, pumped hydro, and demand response cannot provide firm capacity because of their limited duration, while thermal and hydro power plants can. Firm capacity will be needed to supply active power for as long as necessary to complement variable renewables that could be offline for days to weeks.

To manage the transition, Chilean energy strategy requires a nuanced understanding of the "power system triangle," where each corner must receive attention, yet reliability must be placed first to ensure that the other 2 follow.

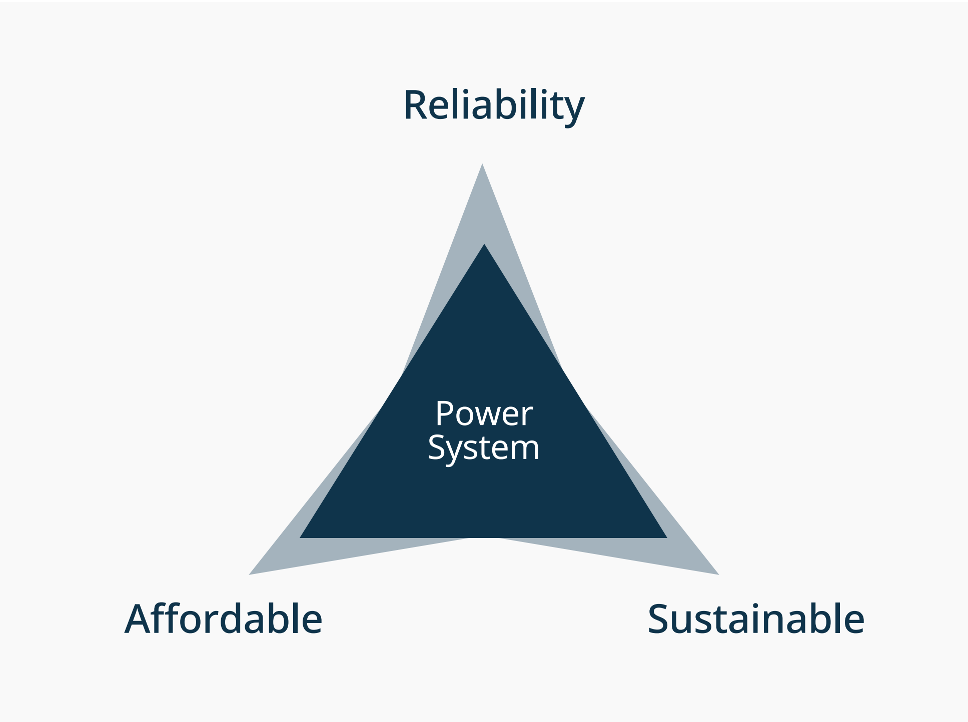


Figure 2 - Three cornerstones of power systems

Section 1 - Potential near-term security of supply risks (inodú)

Short-term study outline

To advance with the decarbonization of the Chilean Electricity System, thermoelectric facilities will have to be retired in the future. However, to retire thermoelectric facilities and transition the electricity system effectively, the following goals must be met:

- A reliable and uninterrupted energy supply must be assured,
- Affordable and accessible energy must be available to all segments of the population,
- System wide emissions reductions must be achieved, and
- The impact on local communities must be minimized.

However, without assuring a reliable and uninterrupted energy supply, pursuing any other goals becomes challenging. Therefore, to decommission the remaining thermoelectric power plants without a reliable and uninterrupted supply, the following requirements should be considered:

1. Sufficient reserve margin
2. Sufficient inertia
3. Sufficient transmission capacity
4. Reliable frequency regulation
5. Reliable voltage regulation
6. Availability of alternative energy sources
7. Grid black-start and restoration support service
8. Periods when the ISO defines maintenance for transmission system. (for example, for 500 kV lines)

The primary objective of the analysis presented in this section was to preliminarily assess the risk of compromising reliable and uninterrupted energy supply in the transition of the Chilean Electricity grid into a more sustainable system. Three challenges which could compromise reliable and uninterrupted energy supply in the transition of the Chilean electricity system should be Chilean were identified. The challenges identified were the following:

1 Addressing adequacy challenges which are emerging early in the morning and the night as a result of the energy transition.

2 Economic challenges faced by the resources in the Chilean Electricity system to respond to increasing short term variability and deviations.

3 Potential system restoration challenges as coal facilities are retired.

The methodology used to address the risks of the energy supply becoming unreliable or interrupted for the Chilean Electricity System were addressed by evaluating four different energy transition scenarios with different levels of reliability stress. The scenarios were evaluated for the 2024 to 2032 time-horizon, and three different hydrological conditions were considered for each of the scenarios.

The four scenarios evaluated covered different levels of stress for the reliability of the Chilean Electricity System. Several key drivers of reliability were evaluated: (1) the evolution of the levels of energy storage integration, (2) amount and concentration of wind generation, (3) schedule to retire coal facilities and (4) development of gas generation.

Four scenarios were constructed by modifying the defined drivers, as shown in Table 1. The scenarios range from the base case, which considered an expected outcome for each of the drivers, to a scenario with a high reliability risk across all drivers. However, the scope of the analysis did not include establishing specific requirements for resiliency, adequacy or to respond to demand variations caused by climate events.

Higher levels of reliability stress ↓

Scenario	Energy storage integration	Amount and concentration of wind generation	Retirement of coal facilities	Gas development
Base Case	Expected	Expected	Expected	Investment to maintain existing gas capacity
No Investment in Gas	Expected	Expected	Expected	No investment to maintain existing gas capacity
Higher Energy Storage, No Investment in Gas & Faster Coal Retirement	Higher than base case	Expected	Faster than base case	No investment to maintain existing gas capacity
Highest Reliability Stress Scenario	Lower than base case	Higher than base case	Faster than base case	No investment to maintain existing gas capacity

Table 1 – Scenarios defined to evaluate reliability risks in the transition of the Chilean Electricity System.

The installed capacity considered in each of the four scenarios is shown in Figure 3. The scenarios are ordered from expected to higher levels of potential reliability stress. In Chile, by 2032, 3.6 GW of gas generation capacity will be older than 26 years requiring significant investments to maintain the units operational. In all scenarios other than the base case, it was assumed that 1.4 GWs of gas capacity are retired in 2029 due to lack of reinvestment in older units, which can lead to higher levels of reliability stress. In two of higher stress scenarios coal facilities are retired faster than the base case. Finally, in one scenario the battery capacity is higher than the base case to counter the faster coal retirements.

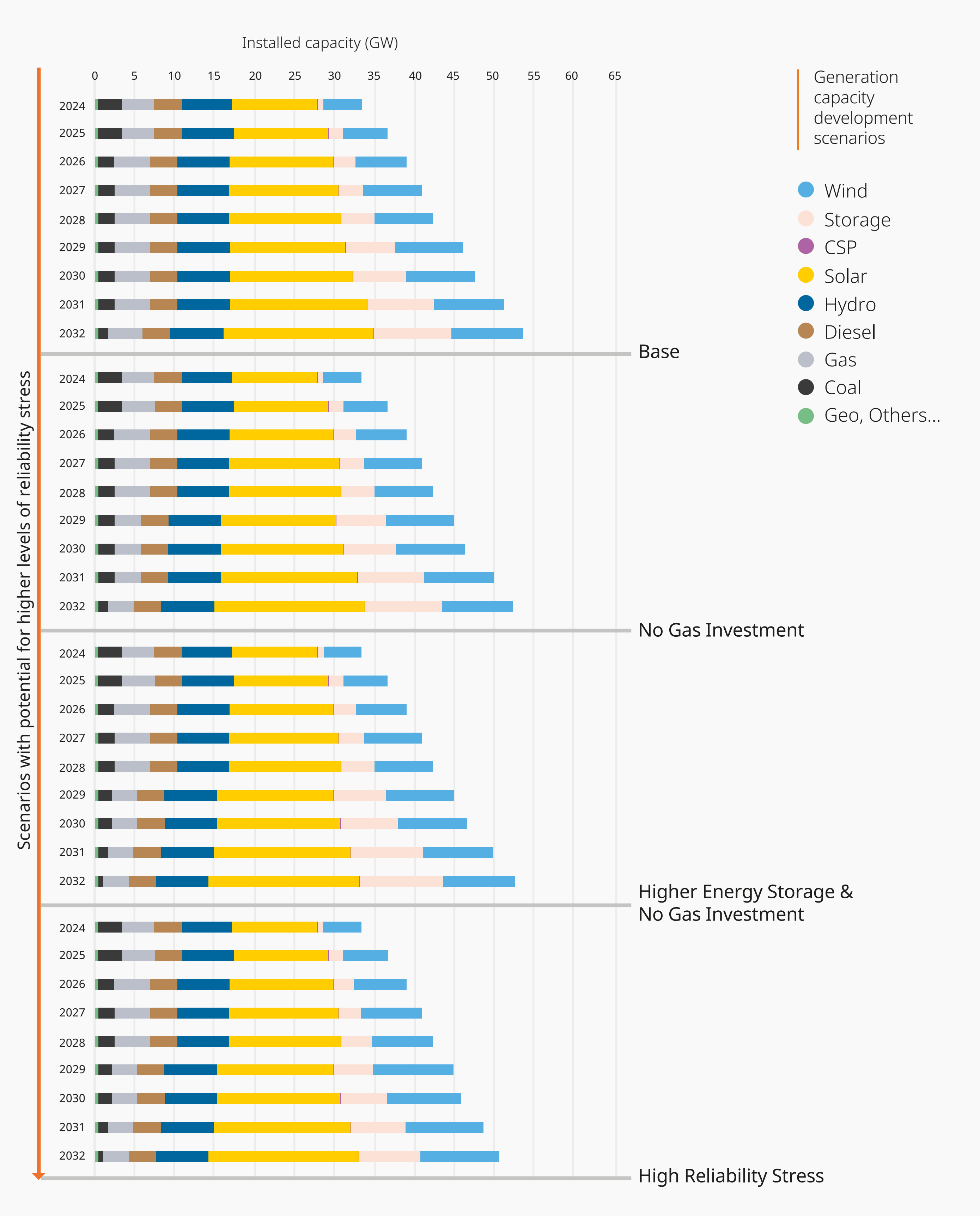
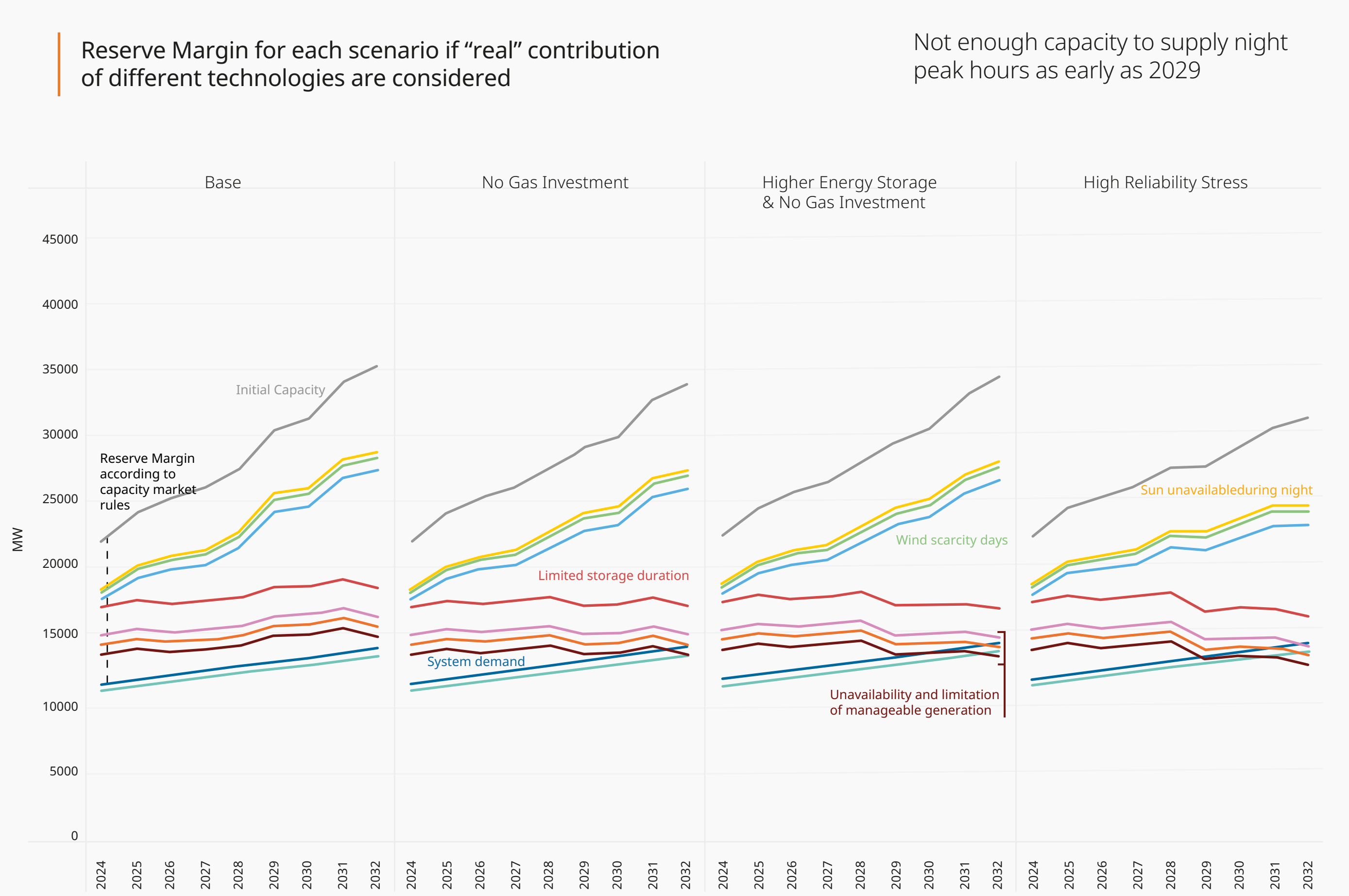


Figure 3 – Installed capacity in each of the four scenarios.

Resource adequacy challenges

Resource adequacy is the ability of the power system to supply enough electricity at the right locations in order to avoid any loss of load which could emerge during the periods when the system is under the most stress, which can occur when the load reaches its maximum levels and/or the system is most constrained.

Considering the four different capacity expansion scenarios, an assessment of the available resources to supply the maximum demand during the night was developed. The amount of initial capacity available calculated with existing market rules leads to a misleading perception of excess sufficiency capacity to supply maximum load during the night in the system until 2032. The current sufficiency capacity calculation assumes that solar generation contributes to supply demand during the night. However, as shown in Figure 4, in the base case, if solar is removed from the initial capacity available, the actual capacity available to meet the peak load during the night is reduced by 17%.



The numbers in red are reserve margin

Base

	2024	2025	2026	2027	2028	2029	2030	2031	2032
Min	1.19	1.20	1.14	1.13	1.12	1.15	1.13	1.13	1.06
Max	2.00	2.11	2.16	2.17	2.20	2.39	2.41	2.53	2.56

No Gas Investment

	2024	2025	2026	2027	2028	2029	2030	2031	2032
Min	1.19	1.20	1.14	1.13	1.12	1.15	1.13	1.13	1.06
Max	2.00	2.11	2.16	2.17	2.20	2.39	2.41	2.53	2.56

Higher Energy Storage & No Gas Investment

	2024	2025	2026	2027	2028	2029	2030	2031	2032
Min	1.19	1.20	1.14	1.13	1.12	1.15	1.13	1.13	1.06
Max	2.00	2.11	2.16	2.17	2.20	2.39	2.41	2.53	2.56

High Reliability Stress

	2024	2025	2026	2027	2028	2029	2030	2031	2032
Min	1.19	1.20	1.14	1.13	1.12	1.15	1.13	1.13	1.06
Max	2.00	2.11	2.16	2.17	2.20	2.39	2.41	2.53	2.56

- Initial Capacity
- No Solar Generation
- Percentile 25% of Wind availability
- Percentile 10% of Wind availability
- Limited stored energy in BESS during night
- Limited Hydro generation
- SING CCGT generation
- Low diesel availability
- Average 52 hours of maximum demand
- Average 52 hours of maximum demand - night hours

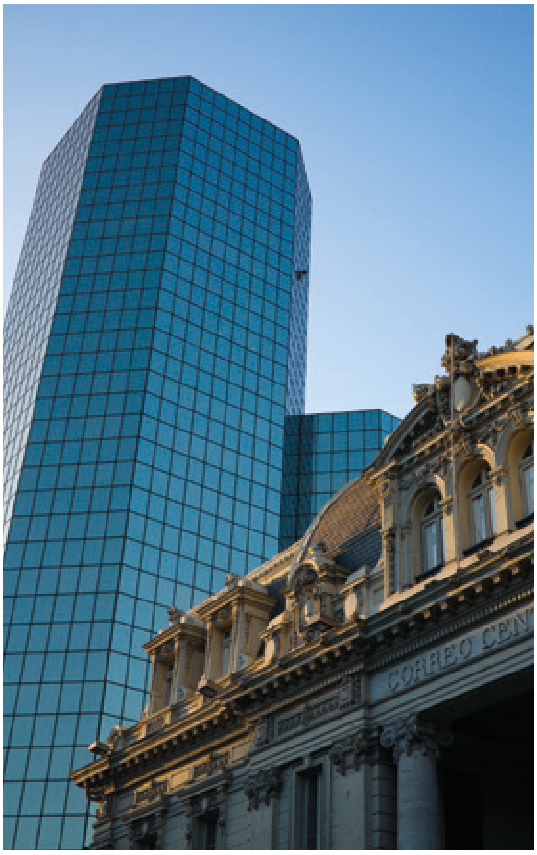
Figure 4 - Estimation of actual capacity available to supply the maximum demand during the night between 2024 and 2032.

Another factor which affects the capacity available to supply the maximum demand during the night is wind scarcity when wind resources aren't available, discounting the wind capacity leads to the green line shown in Figure 4 for all four scenarios. Although the incorporation of 5-hour energy storage improves the situation, even with an optimistic installation schedule through 2032, energy storage cannot supply the full load through the whole night. Furthermore, when the unavailability of dispatchable generation - such as gas and hydro - is considered, the initial capacity to address maximum demand during the night, is reduced further.

Considering all the limitations described, as shown in Figure 2, the discounted initial capacity during the night cannot ensure a 15% reserve margin starting as early as 2026[1]. The reserve Margin could reduce even further as the demand is decarbonized and the effects of weather conditions on the demand increases. At some point in the future, the system could face days or weeks where particular cold weather conditions in winter could add significant stress to the system.

Given the conditions evaluated, there is a need for 1083 MWs of new firm capacity by 2032 under the Highest Reliability and Stress Scenario to ensure maximum demand could be supplied during all hours of the night as shown in Table 2. This considers the following limitations for the capacity available:

1. No capacity recognition for solar during the night
2. Limited wind availability during the night
3. Impact of only having 5 hour duration energy storage to supply the night
4. Limitations of hydroelectric generation
5. Operational limitations of CCGT generation and diesel availability



[1] Reserve margin is the excess capacity available in an electric system or region compared to the expected peak demand. Many markets globally have defined reserved margin targets of between 10% to 20% to meet system reliability requirements.

In 2032, there could be a need for up to 3000 MWs of firm capacity able to be dispatched at any hour during the night, if a 15% reserve margin is required in the most extreme scenario[2].

Capacity surplus relative to maximum demand during night*	2029 (MW)	2029 (MW)
Base Case	2,483	1,429
No Investment in Gas	1,132	78
Higher Energy Storage & No Investment in Gas	750	(460)
Highest Reliability Stress Scenario	381	(1,083)

Below 15% reserve margin

Below average maximum demand during 52 highest hours

Table 2 – Analysis of capacity surplus to maximum demand during the night for 2029 and 2032.

Once the current commitments of retirement or reconvertion of thermoelectric facilities is materialized by 2026, it is important to notice that if Chile does not maintain or adequately replace the thermoelectric capacity that remains in operation during 2026-2032, reliability issues could emerge. In Table 2 above the first scenario considers 5.1 GW gas capacity, the other three consider 3.7 GW after 2029.

[2] Calculated considering 1083 MW deficit in Highest Reliability scenario and additional capacity needed to achieve 15% reserve margin.

Challenges with short-term response to variability & deviations

There are two challenges with the short-term availability of wind resources to supply the night: One is the inherent sub-hourly variability of the wind resource, and the other is the uncertainty associated with the wind resource forecasts. The challenges with the short-term availability of wind can lead to an increase in the need for resources which have to respond in the short-term, especially during the night. In Chile, there are limitations in the availability of fast-response, low-cost resources which can address the short-term availability during the night. If low-cost resources are not available to dispatch and cover the variability, this leads to greater spot price volatility, especially when diesel units have to be dispatched.

Sudden reductions of wind generation in the 15-minute to 1-hour time horizon will increase in magnitude over time as more wind resources are integrated into the Chilean Electricity System. The evolution of the potential wind power output reduction between 2024 and 2032 based on the maximum value, 99% percentile, and 95% percentile are shown in Figure 5. These reductions of wind generation during the night will have to be covered by fast response units; however, in Chile, the availability of low-cost resources is very limited.

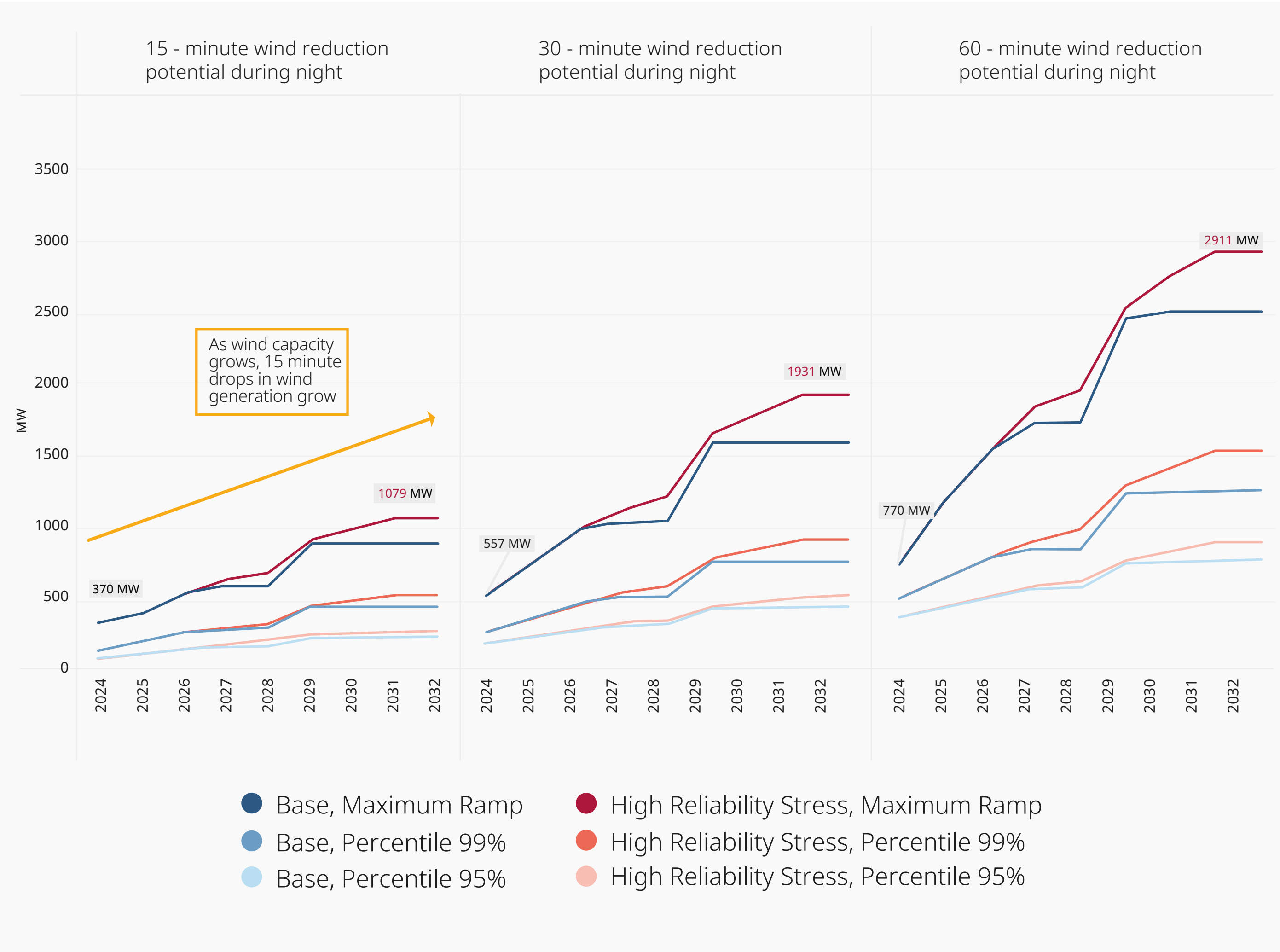


Figure 5 – Evolution of 15 minute, 30 minute and 60 minute maximum reduction wind generation in Chile from 2024-2032.

In Chile, Tertiary Frequency Control (TFC) can be used to respont to sub 60-minute variability and uncertainty of renewable energy resources. As show in Figure 6, once the limitations of the availbility of renewable energy, coal units, hydro and CCGTs during the night are considered, the amount of existing resources which can provide TFC during the night goes down from approximately 13 GWs to close to 1.5 GW. The resouces left to respond during the night are expensive diesel units and open cycle gas turbines (OCGT).

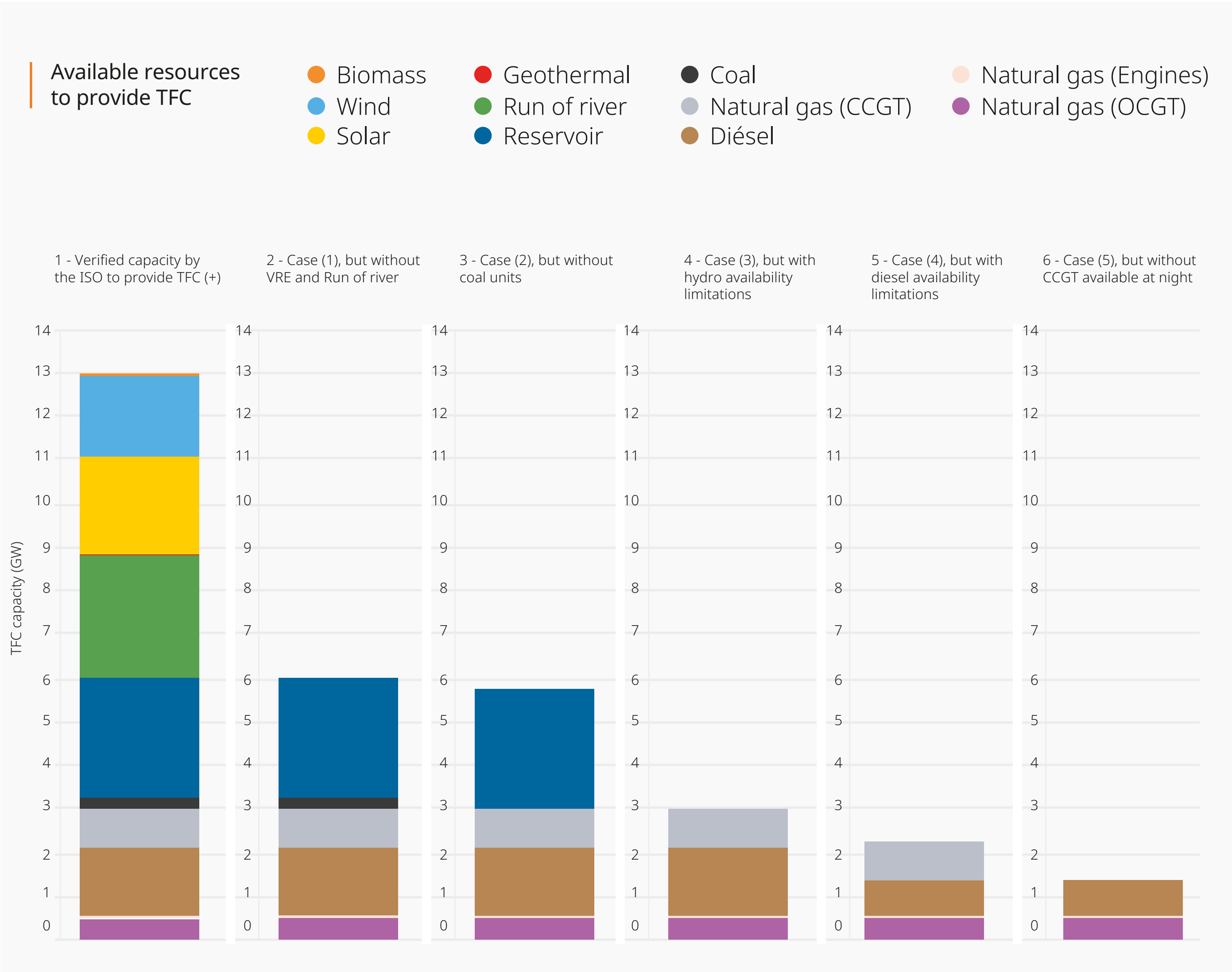


Figure 6 – Current availability of Tertiary Frequency Control in Chile as limitations of units are incorporated.

In the future, the sub-hourly supply gap between maximum reduction in wind generation and the open cycle gas turbines currently in the system could be addressed by

- Energy storage which primary purpose is to respond to unanticipated short term variability
- Diesel generation
- Fast response gas units
- Some hydro resources with the capability to respond to unanticipated short term variability
- Reliable demand response developed at scale.

In 2032, the supply gap caused by 15-minute wind variability could range from 309 to 477 MW, while the 60-minute wind variability could reach 1374 to 1788 MW by 2032. Furthermore, low-cost fast response units will be needed to address the supply gap and the following technology shortcomings :

- Short duration energy storage is not available always to cover these deviations
- Hydro resources are not always available, especially during dry periods
- Demand response has not been defined and will have limitations; it will be difficult to develop reliable system-scale demand response services
- Diesel units are available to respond but it is expensive and the fuel supply chain could be challenged under persistent operations of diesel units.

Conclusions and recommendations

As part of the conclusions and recommendations the three security of supply challenges, which could compromise reliable and uninterrupted energy supply in the transition of the Chilen electricity system, are summarized across different response times, which range from seconds to years. The three security of supply challenges identified were:

1. Addressing capacity adequacy challenges which are emerging during the night as a result of the energy transition.
2. Economic challenges faced by the resources in the Chilean Electricity system to respond to increasing short term variability and deviations.
3. Potential grid restoration challenges as coal facilities are retired.

Summary of security of supply challenges

Addressing security of supply for an electricity system involves having resources which can respond in milliseconds to years as shown in Figure 7. System reliability usually involves the electricity system's capacity to address challenges from the millisecond to the hour time horizon. While resource adequacy involves having enough resources to respond to periods when the system will be most challenged in the long-term.

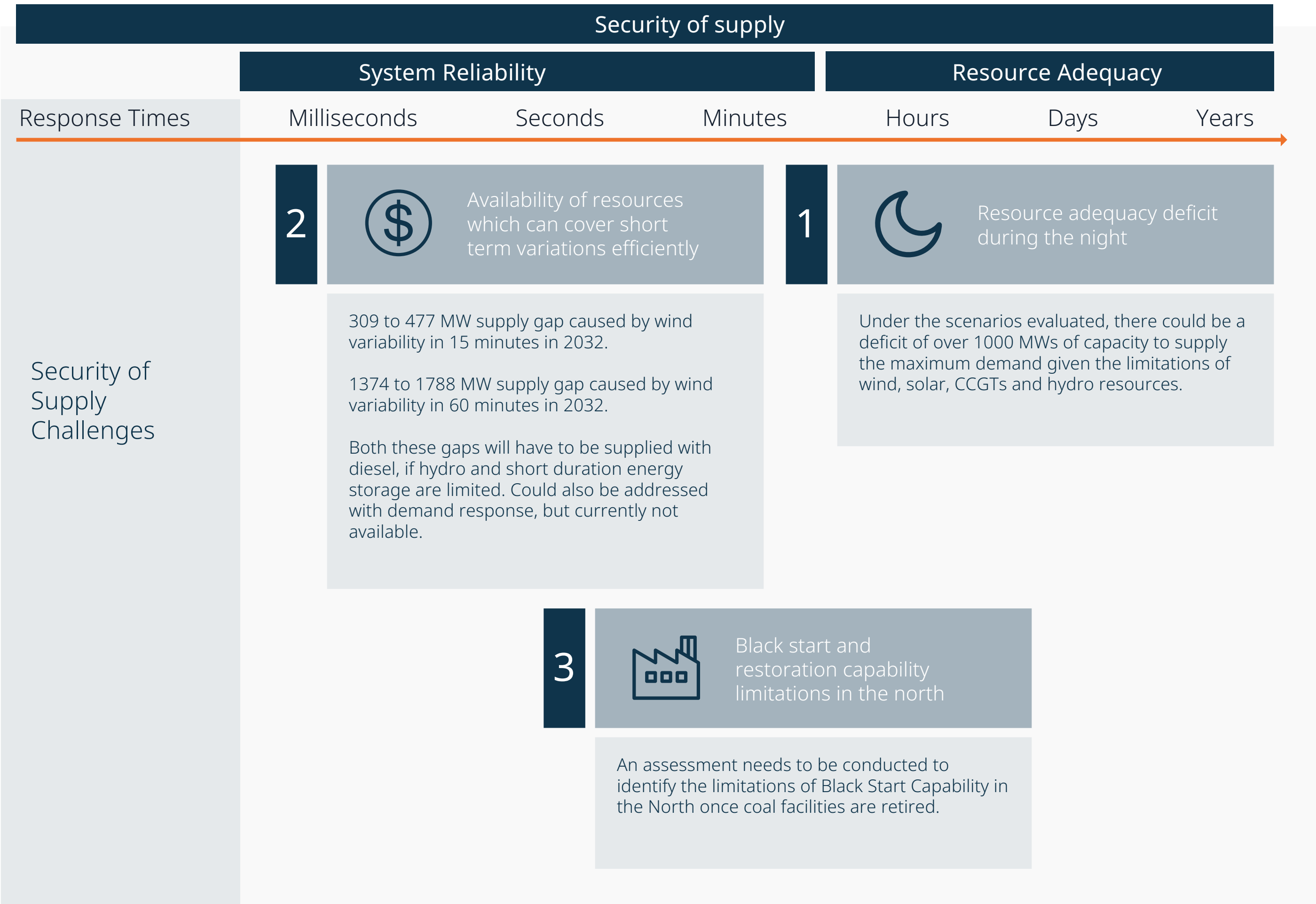


Figure 7 – Time horizon of security of supply challenges identified.

The primary system reliability problem identified was the capability of the Chilean Electricity System to respond to the increasing short-term variability and deviations during the night in an economically efficient fashion. Currently, considering the limitations of hydro and short-duration energy storage to respond to sub-hourly variations of wind generation during the night, the only viable alternatives, are OCGTs and diesel units.

However, in 2032 the sub-hourly supply gap between maximum reduction in wind generation and the open cycle gas turbines, available to respond in 15 minutes, is expected to reach between 309 to 477 MWs under the scenarios evaluated. This supply gap will have to be covered by diesel generators if no new capacity is added to cover such deviations. Further, the 60 minute maximum supply gap is expected to grow and reach between 1374 MWs to 1788 MWs by 2032. Such supply gap could be partially addressed by reliable demand response developed at scale, however demand response is currently not defined in Chile and it will not be easy to find reliable resources at the required scale.

In addition to resource adequacy and system reliability challenges, as coal facilities are retired potential system restoration support challenges were identified. An assessment needs to be conducted to identify the magnitude of the limitations of black start and restoration support capability as the energy transition progresses.

Finally, addressing capacity adequacy challenges to supply maximum demand during the night as a result of the energy transition, requires addressing a deficit, which could exceed 1000 MWs by 2032 under the scenarios evaluated.

The resource adequacy challenge is caused by the growth in demand during the night combined with limitations of wind, solar, CCGTs and hydro units to supply peak demand during the night. The challenge could be exacerbated by the effects of weather conditions on demand, particularly in winter.

Possible technological solutions

There are sustainable solutions to address the three security of supply issues identified, and they are shown in Figure 8. However, flexible gas generation - which can be converted to use green power fuels - and other sustainable flexible dispatchable generation are the only two solutions which can address all three security of supply challenges identified. Long-duration energy storage could address the black start and restoration support capability limitations in the north, however, the ability to do so will always be dependent on the state of charge and the actual duration of the energy storage.

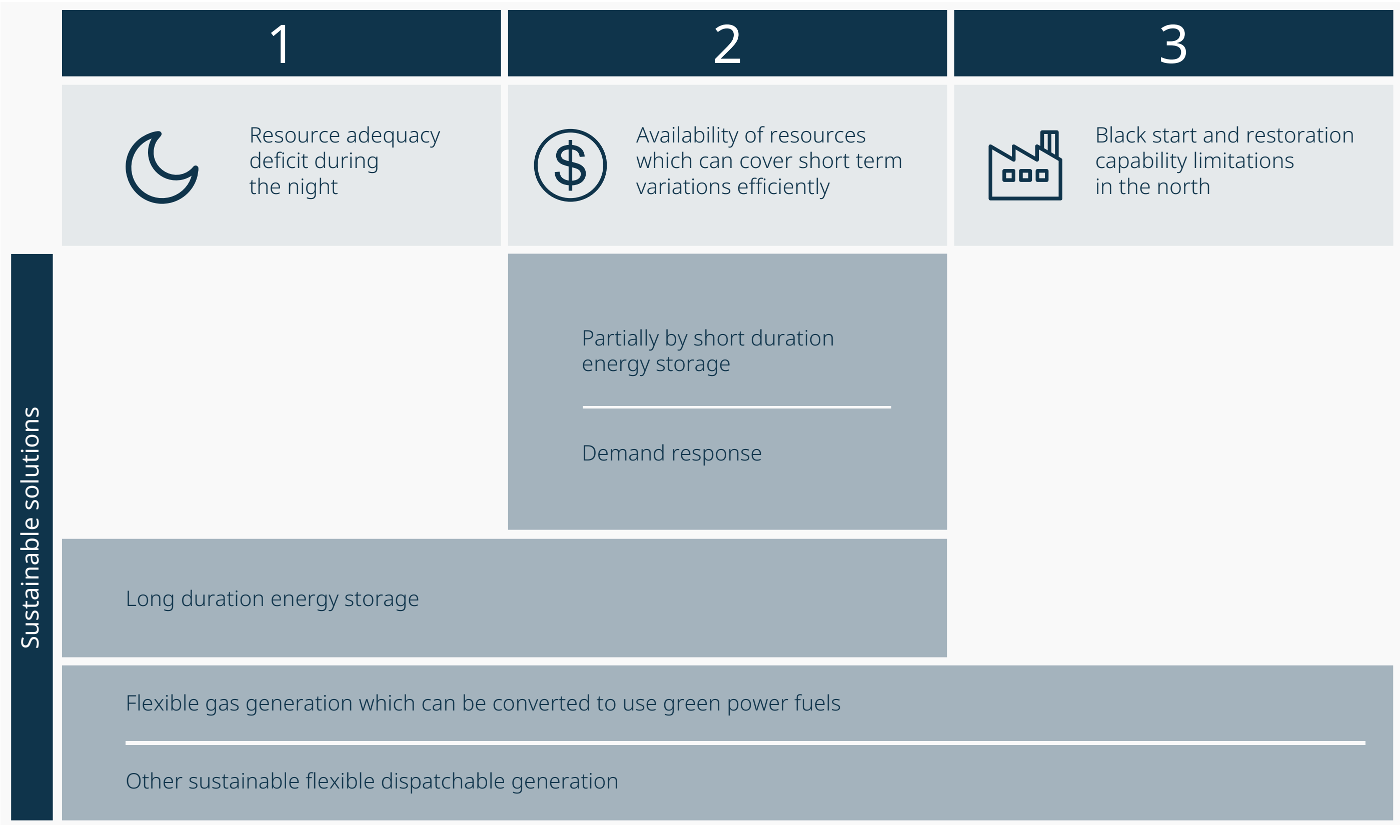


Figure 8 – Sustainable solutions identified.

Section 2 - Optimal long-term energy transition path for Chile (Wärtsilä)

Long-term study outline

While the first section of this study focused on near-term reliability of the power supply until 2032, the second part of the study goes beyond that time frame through 2045, the year the model is programmed to reach zero power-sector carbon emissions.

In the first section of this study, it is concluded that to maintain system reliability until 2032, Chile must maintain at least 5 GW of gas generation capacity until 2032.

Wärtsilä utilized PLEXOS, a power system optimization and dispatch software. Plexos dispatches all generators in the power system against a real demand curve, hour by hour, from 2024 until 2045, to establish the economically optimal capacity additions and retirements. The program resolves the equation considering very complex constraints relating to transmission, fuel prices, water availability, and emissions, etc. Each scenario run took about 10 hours in a supercomputer, processing solutions for trillions of mathematical calculations.

The following modelling approach premises were given:

Goal: To establish the optimal long-term capacity expansion reaching net zero carbon by 2045

- Ensure security of supply at all times
- Provide lowest generation cost

Option to use H_2-based fuels available by 2035

- Power plants are able to convert to sustainable fuels (e.g. hydrogen, eMethanol, or ammonia) when it makes economic sense, and/or when carbon allowances force this change
- The study does not assume a load growth from production of H_2-derived fuels. Fuels are purchased from the "world market".

Key inputs summary:

- Capacity mix until 2032 is sourced from the INODU analysis, first part of this study, including the coal retirement schedule. Then, the capacity mix after 2032 is optimized by Plexos.
- Additional inputs include:

Hourly load, wind and solar generation profiles in 5 nodes until 2045.

Hydro conditions & availability of water – use dry years to define firm capacity needs.

Fuel & technology prices, with learning curves.

Operational parameters for all Power plants.

Main transmission interconnections, 5 nodes.

All coal power plants retired by 2035

Rehabilitate old combined cycle gas generators or invest in new flexible capacity?

In this section of the study, the focus shifts on two questions:

1 Would it make economic sense to rehabilitate the old inflexible combined cycle gas power plants (CCGTs), or should new flexible plants be built instead?

2 After 2032, what is the optimal capacity mix to support Chile's decarbonization path and complete the transition to net-zero?

Rehabilitation extends the lifespan of current assets at a capital cost lower than constructing new capacity, but asset flexibility will not improve, and the lifetime of investment will only be 5-10 years. Conversely, developing new, flexible thermal capacity offers enhanced adaptability and reduced long-term operational risks, though it requires greater initial investment. This section evaluates these trade-offs to identify the optimal path forward.

As presented earlier, there are 3,500 MW of Combined Cycle Gas Turbine (CCGTs) installed in Chile today. These plants are quite old as they were mainly constructed in the 1990s and the early 2000s. In 2024, the weighted average age (weighted by installed capacity) is 22 years.

The average CCGT fleet availability between 2019 and 2024 has varied between 74% and 88%. This is low compared to international statistics, which are typically > 90%. The availability values in the Chilean assets reflect their age and also the constant cycling required by the system over the years. In the future, with the growth of renewables, thermal generators are expected to run less, and cycle even more than they have historically.

Scenario 1: Rehabilitate old CCGT´s

In this scenario, CCGTs are rehabilitated at the age of 27 years

- In the USA, where there are hundreds of CCGTs, the average age of retirement is 27 years [3]. This age was used in the Chile case as the point of time when the plants need rehabilitation.
- Rehabilitation extends the plant lifetime by 10 years, and then they are retired afterwards.

• Cost of rehabilitation varies depending on the age and size of the project. For this study, 400 US$/kW was considered as an average.
• The model assumed that 30+ year old gas turbine models would not have H_2 conversion kits as these models have been out of production for decades.

Open Cycle Gas Turbines (OCGTs) are not rehabilitated, but due to lower running hours, they are retired at a higher age of 35 years. There are 1,065 MW of such OCGT plants in Chile today.

In this scenario, Plexos may add "new flexible gas capacity" to the power system when necessary. Such new gas plants must be H_2-ready i.e. capable of running with hydrogen or hydrogen-derived sustainable fuels. The fuel conversion takes place gradually over time as carbon allowances tighten. The model includes an additional CAPEX cost for the H_2-ready capability, in each technology candidate.

Scenario 2: Build new flexible gas power plants instead of rehabilitating old CCGT´s

In this scenario old CCGTs are retired at an age of 27 years. Plexos can then replace them with the gas technology candidates available in the list provided. In practice this means that Plexos chooses the technology mix that contributes to the lowest total system generation costs considering both CAPEX and OPEX.

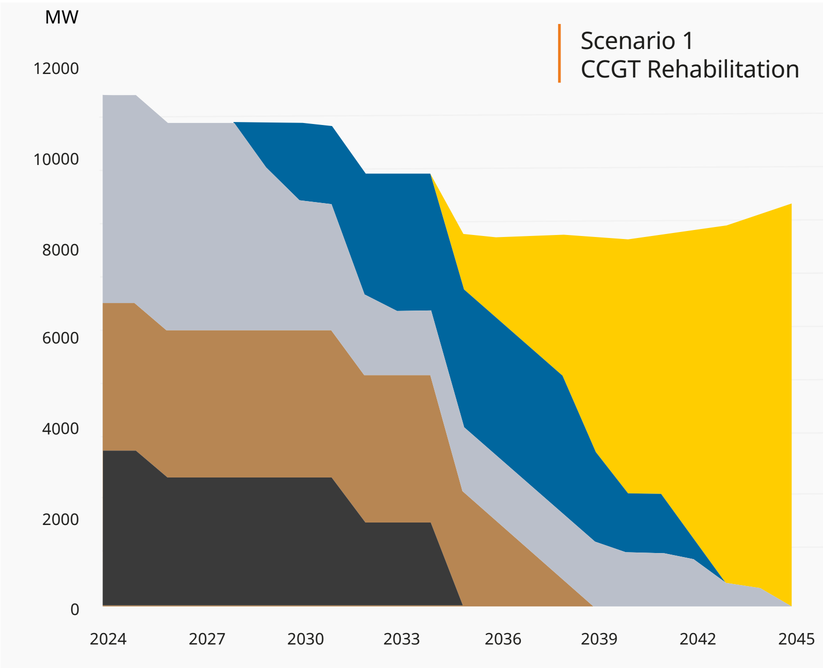
The following are the gas power plant technologies provided to Plexos:

- Combined cycle gas turbines (CCGT)
- Heavy duty open cycle gas turbines (OCGT)
- Aeroderivatives open cycle gas turbines (OCGT)
- Reciprocating engines (RICE)

For this scenario, all new gas plants must be H_2-ready i.e. capable of running with hydrogen or hydrogen-derived sustainable fuels.

Results - Capacity matrix and system generation costs

The figure below illustrates the changes in the firm thermal capacity mix until 2045.



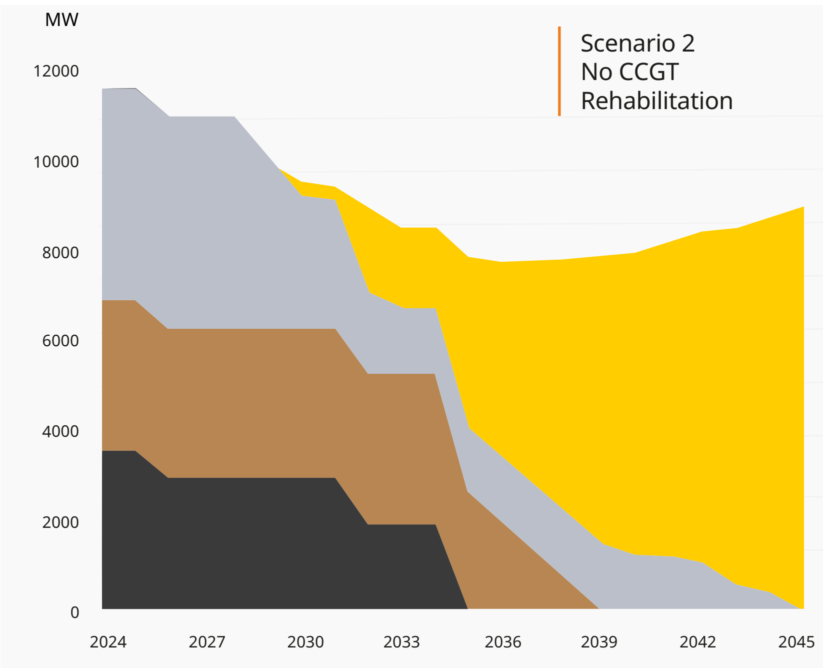


Figure 9 - Evolution of firm thermal capacity in scenarios 1 & 2 from 2024 to 2045

Graphs highlights:

Coal is fully retired by 2035 which reduces carbon emissions from current levels of slightly below 20 Mtoe/year to about 4 Mtoe/year

Diesel oil plants are pushed out during the second half of the coming decade due to tightening carbon allowances

The rehabilitated CCGTs are marked with Blue color and get a lifetime extension of 10 years. In scenario 2, as each CCGT unit reached 27 years of age, they were retired.

New H_2-ready flexible gas generation capacity gradually increases, to maintain the necessary level of firm capacity in the system. In scenario 2 the shift begins earlier as 27-year-old CCGTs are retired without rehabilitation.

- H_2-ready Flexible generation
- Rehabiltated CCGT's Diesel
- CCGT and OCGT gas plants
- Coal

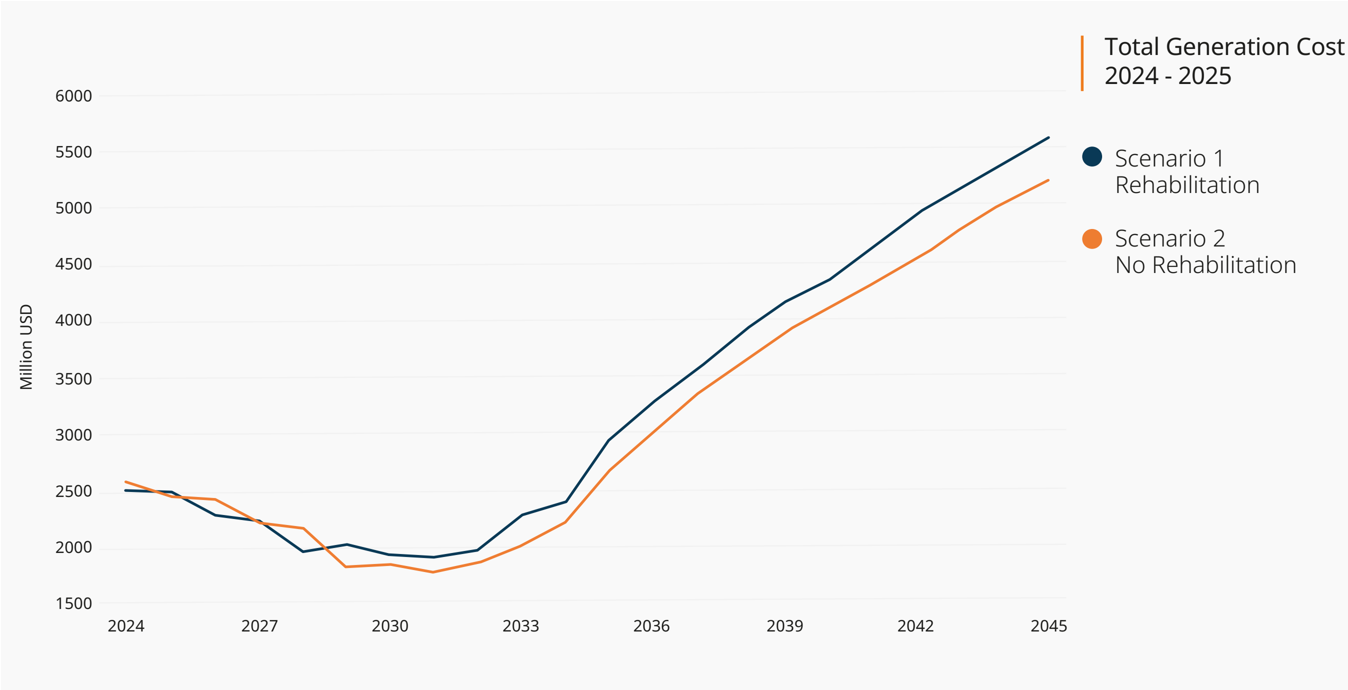


Figure 10 - Total Generation cost comparison of scenario 1 (blue) & scenario 2 (orange)

The cost comparison above illustrates the total annual electricity generation costs of the power system, including both CAPEX and OPEX. High voltage (HV) transmission and medium voltage (MV) distribution grid expansion and maintenance costs are not included. Building new, modern flexible H_2-ready gas power plants is a more economical option as soon as in 2029, when the bulk of CCGT rehabilitations would start. In Scenario 2, where new flexible capacity is constructed, the system generation costs are clearly lower.

Over the whole period from 2024 to 2045 (22 years) when the system reaches net zero, the total electricity generation cost reduction is about 5% corresponding to $3.6 billion USD, without accounting for inflation.

Why is it more economical to build new flexible gas capacity than to rehabilitate existing capacity?

Why do we see this result? Especially, if CCGTs are the most efficient gas power plant technology?
The answer centers on the mode of operation. In a power system with a large and increasing share of variable renewables, the available operation profile for thermal capacity, also known as the net load curve, is highly variable because it must complement the continuously variable wind and solar generation.

In the Chilean power system, gas power plants will need to complement the variable renewables quickly, efficiently and at any time. Gas generators spend most hours offline, waiting to supplement drained batteries. When they do generate, their operation is in multiple short pulses, typically during evening ramps and in the early morning hours. Efficient operation, with low capacity factors (10-30% typically), with hundreds of annual starts, is a fact for future gas plants. In this new "Renewables Balancer" operation mode, technological characteristics that drive value, shift towards:

- Zero/low starting costs
- Capability to restart fast after stop, and to stop running at any point of time during operation (often called short minimum up- and down-times)
- Wide load range and high efficiency at many loads points
- High generating efficiency to minimize fuel costs and use
- Ready for conversion to Sustainable H_2-derived fuels
- Low water use

The table below compares the important capabilities of different gas power plant technologies for future high-RES power systems.

	Benefits	Challenges
Baseload Combined Cycle Gas Turbine	>50% Efficiency Reliable under base load	Designed for Baseload operation High Capex High starting cost Max. 1 start per day Starting time of 1-2 hours
Peaker Open Cycle Gas Turbine	Low Capex 25–30-minute start 2-3 starts/day	High starting cost <40% efficiency 1+ hour minimum up and down times
Renewable Balancer Reciprocating Engine	5-minute start to full load Up to 20 starts/day No starting cost >47% efficiency	CAPEX between OCGT and CCGT

CCGTs were designed for efficient base load operation, not for daily cycling with frequent starts and low capacity factors. They were designed and built for a purpose that is eroding with the increase in solar and wind.
OCGTs were designed for peaking as they provided an inexpensive capacity reserve most of the year, which was in operation only for a few days to weeks during the annual peak load period. In this application, efficiency was less important than CAPEX.

The application of renewable balancers is neither base load, nor peaker. These plants operate in hundreds of short operation pulses all through the year. Their pulses can be required by odd weather behavior, forecast errors, lack of storage capacity, unplanned outages, just to mention a few.

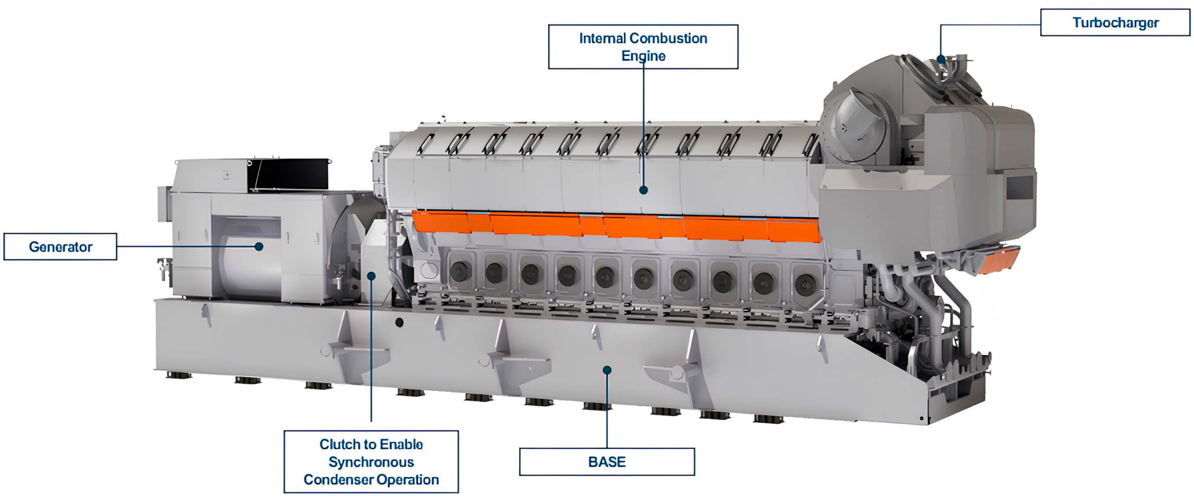
Adding to the role of balancers is the capability to provide ancillary services to the grid when the internal combustion engine is in standby. In this synchronous condenser operation mode, the engine stops, but the generator continues spinning, providing short circuit capacity and inertia to the system without burning fuel. With this operation mode, gas power plants can contribute to both system stability and adequacy. An image showing this configuration is in the attachments.

The cost comparison above illustrates that even though rehabilitation has lower capital costs compared to new flexible plants, rehabilitation brings increased cycling cost, and the relatively short lifetime of a rehabilitated plant. In addition, conversion to H_2-ready fuels may not be available, and would bring additional costs if new H_2 capacity is needed.

The study concludes that the construction of new, modern, and flexible H_2-ready gas power plants is more economical than extending the lifetimes of old baseload plants.

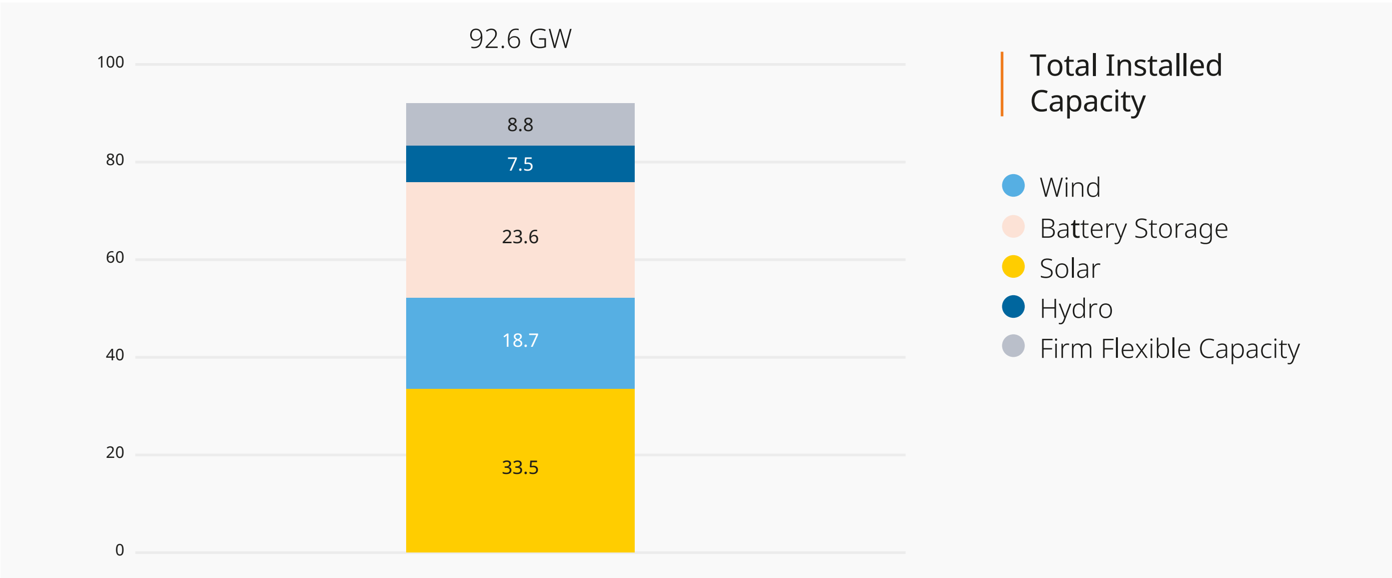
WÄRTSILÄ GENSET

Generator Rating: 10 MW to 20 MW per Genset



Optimal net-zero power system capacity mix in 2045

The figure below shows the optimal installed capacity in 2045. It also highlights the small, but important role of the firm, flexible capacity.



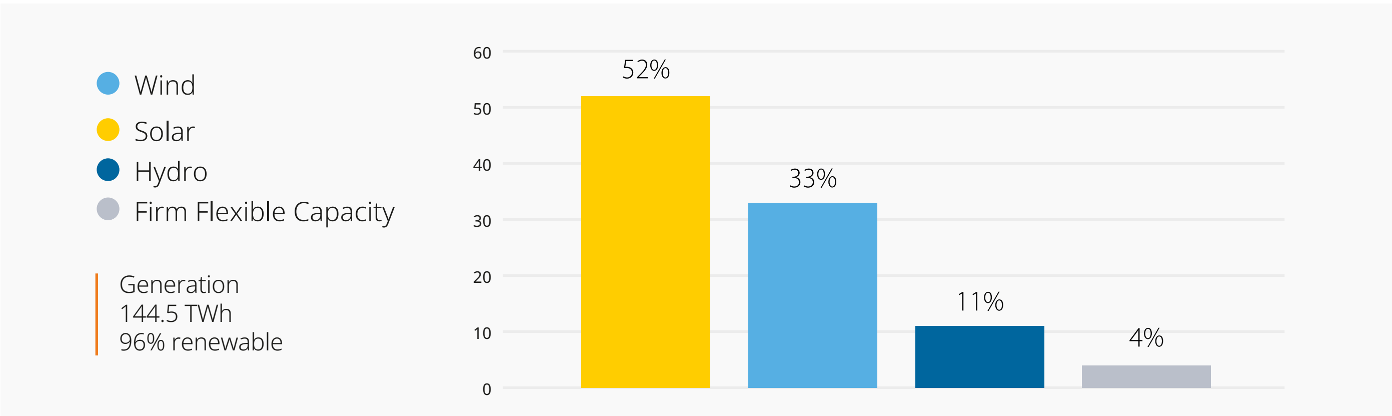


Figure 11 - Optimal Chilean capacity and generation matrix in 2045

To reliably serve the annual peak load of 20.7 GW with zero-carbon electricity in 2045, the optimal total installed capacity is 92.6 GW. The optimal quantity of firm flexible gas generation is 8.8 GW, corresponding to 9% of total installed capacity.

In 2045, firm flexible capacity is dispatched only when the energy storage is discharged. This takes place after longer periods of lower-than normal renewable generation, caused by clouds, rain and/or low winds. During normal days the system runs entirely on wind, solar, hydro and storage.

In 2045, the share of electrical energy produced by the firm flexible capacity is about 4% of the total energy. The average annual running hours of those 8,8 GW flexible power plants is about 600 hours, more in dry years and less in wet years. The average running hours vary across the country from as low as 200 hours in the south to as high as 960 hours in the central regions.

Complementary roles of storage and flexible generation

Why not just retire all thermal capacity, and replace it with only variable renewables and energy storage?

The answer comes down to the storage duration required for security of supply. Battery storage can handle all intra-day power system balancing tasks, from very fast frequency regulation and solar smoothing to providing spinning and non-spinning reserve, and gradually – with growing storage capacity - even shifting solar energy from day to night.

Battery storage is superior to any other generation technology in such intra-day balancing tasks. Unfortunately, battery storage cannot provide firm power due to its time-limited duration.

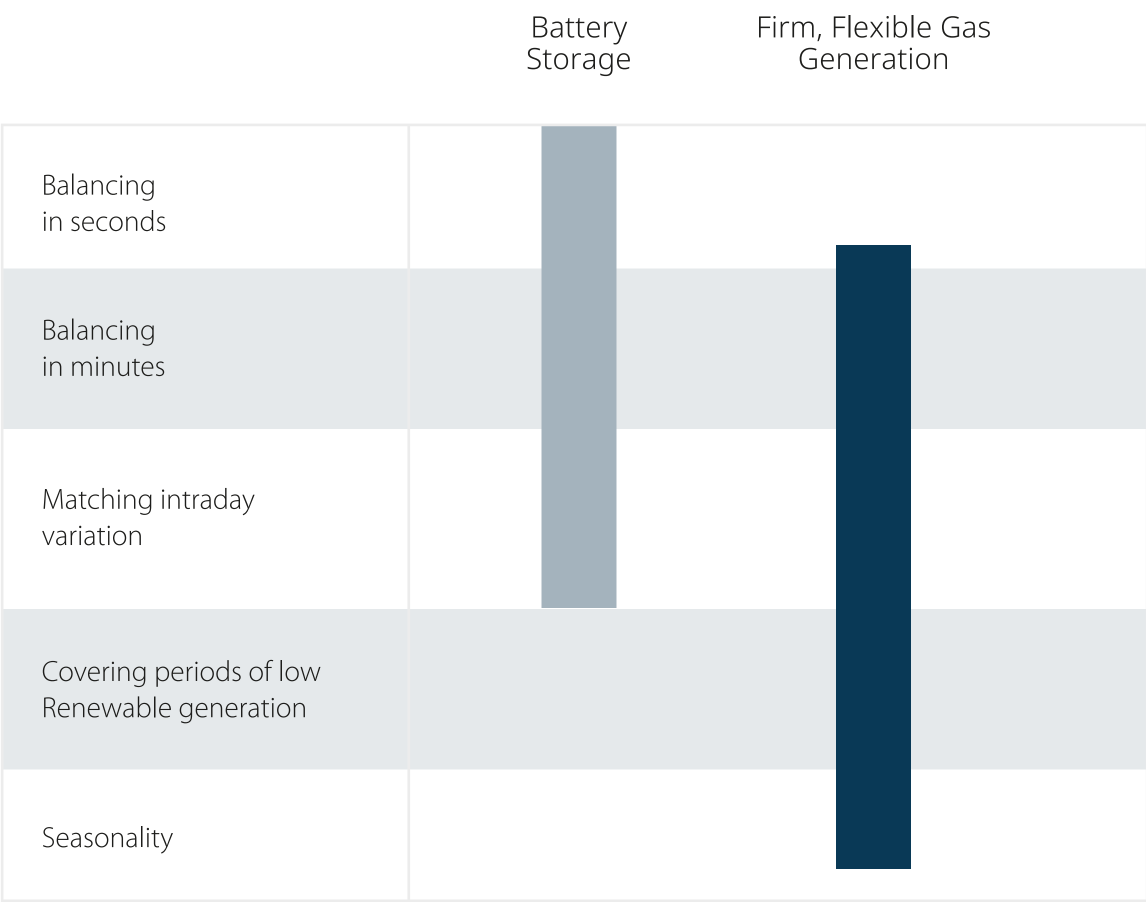


Figure 12 - Complementary roles of storage and flexible gas generation

To expand on the value of firm power - which is available for as long as necessary - Finland and Fingrid (ISO), provide an insightful example.

In Finland, home country of Wärtsilä, wind conditions are favorable, and almost 9 GW of new wind power plants have been built in recent years. Annual peak load of the system is close to 15 GW, taking place during the coldest winter days.

The main job of Fingrid is to always keep the lights on. When asked about their worst-case scenario, they explained that when reviewing historical data, they find a pattern that every 10 years, there has been a windless period of 2 weeks. It is even worse, when this period of no wind occurs during the annual peak load period in January/February. The system must then have the capability to go through such 2 week high load period with something other than wind generation. Obviously, Fingrid could not keep the lights on without a “back-up” system even for the worst-case situation.

Every country has its own worst-case scenarios depending on local conditions. Unusual weather patterns can typically last for days to weeks. A monsoon, drought or a heat wave, for example.

Now the key question: Why is it not realistic to try to manage such 2-week windless period with battery storage? Well, in the case of Finland, 2 weeks represents 14 days and a total of 336 hours. A 336-hour battery, capable of discharging several GWs continuously to the grid without significant charging. The size would not be MWh, not GWh, but several TWh! Given the once in 10 years utilization, the cost would be unreasonable.

When the windless 2-week period starts in Finland, something firm must be started and operated at required output for as long as it takes for the wind power to return. In 2030 there will be 21 GW of wind power in Finland so this firm capacity should stay off-line most of the time, ensuring readiness and capability to handle any and all weather situations.

In this study, Plexos has optimized the quantities of wind, solar, storage and flexible firm capacity to provide Chile with the lowest overall system-level generation costs, including capital expenditure (CAPEX) and operational expenditure (OPEX).

The official decarbonization plan in Chile proposes to gradually close down all thermal power, so there would be no firm & flexible generation capacity operating with sustainable fuels in 2045. The net-zero power system would then consist of only wind, solar, (huge) storage and hydro.

To understand the differences between the official path and the cost-optimized path, Wärtsilä used Plexos to expand the power system with only solar, wind, storage, and existing hydro. The capacity comparison is below.

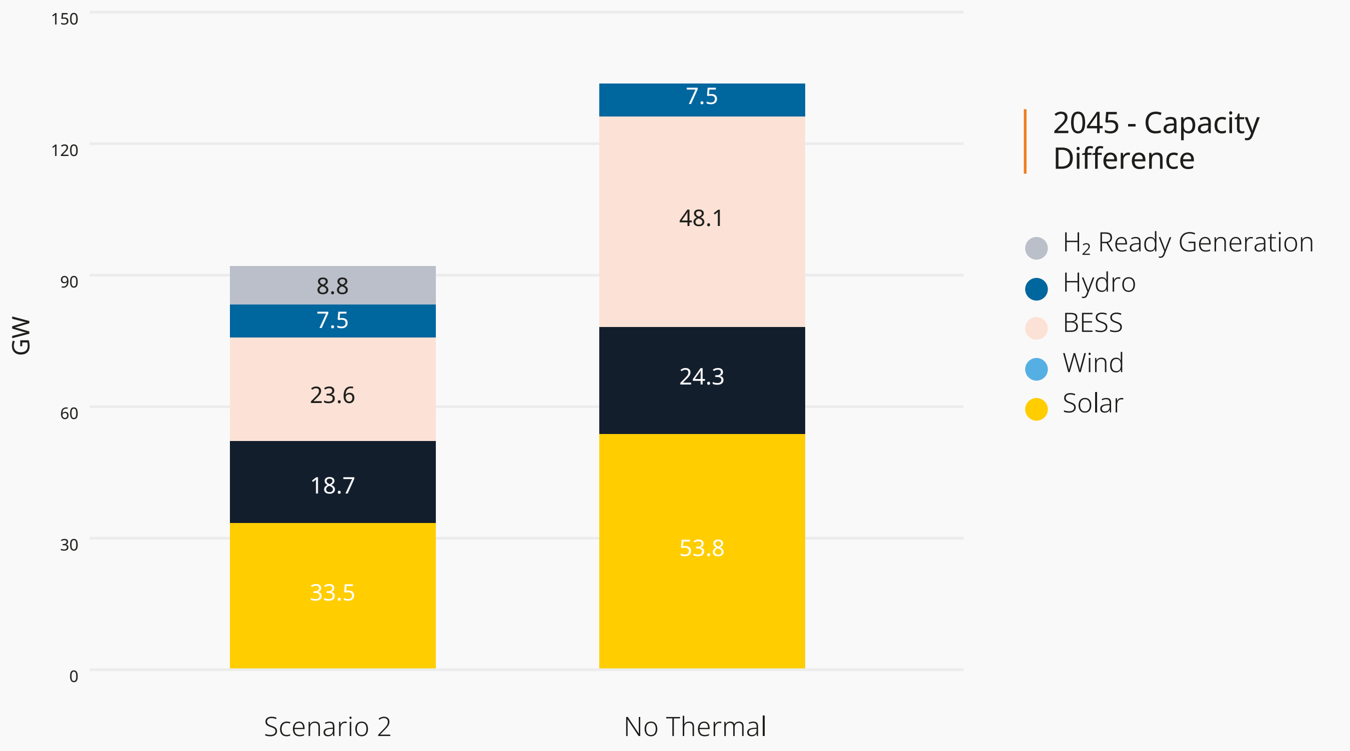


Figure 13 System installed capacity in 2045.

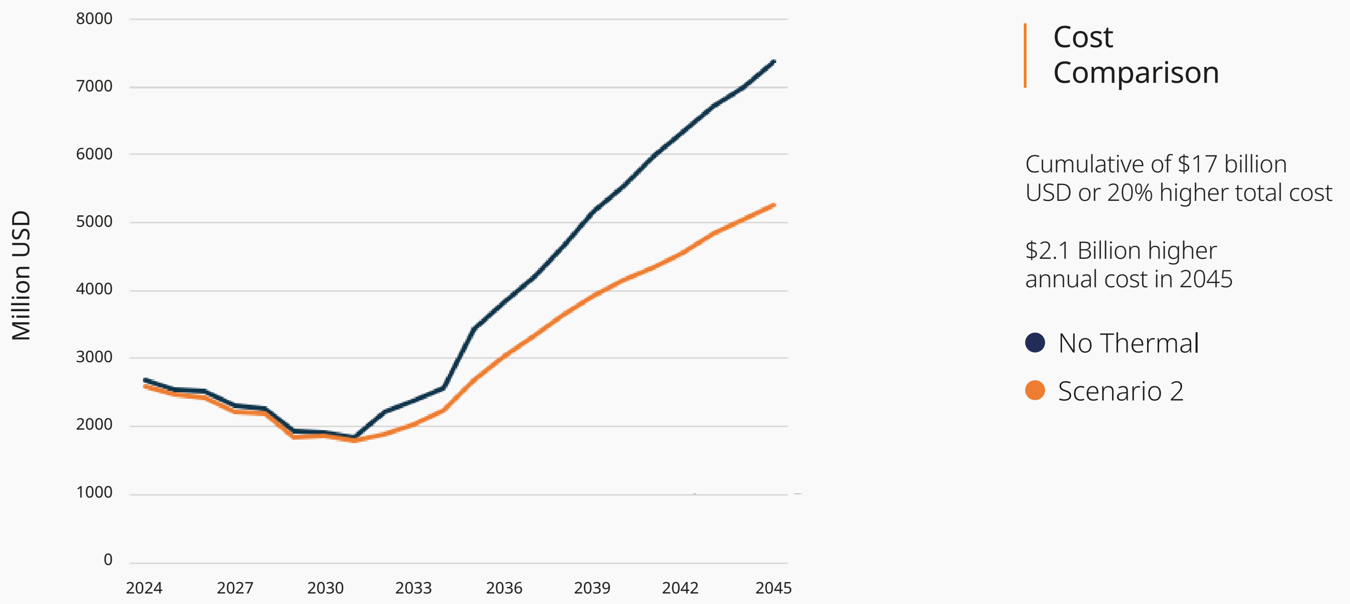


Figure 14 Chile annual generation costs.

Figure 13 & 14 - Chile 2045 capacity mix with and without firm flexible power, and annual generation costs 2024-2045.

To ensure reliable supply of electricity in 2045 without the firm flexible generation, Chile would need to over-build the power system with over 40 GWs of additional wind, solar, and storage capacity. This is to ensure that there is always adequate charge in the batteries to go through longer, windless, and cloudy periods. Then, the utilization of such overcapacity is very low during normal weather, and curtailment of solar and wind are very high.

Figure 14: The graph shows the differences in annual generation costs between these two paths. Annual savings in favor of the cost-optimized system start growing after 2030 when old gas capacity and coal gradually retires. In the "No Thermal" case, additional wind, solar, and energy storage capacities need to be constructed faster and in larger quantity to ensure security of supply.

Annual generation cost savings compound over time, reaching a peak of 2,100 MUSD in 2045. With flexible gas/hydrogen power plants in the system, the total national saving for producing the same amount of electricity would be 17,000 MUSD over the period from today to 2045, not accounting for inflation. Importantly, both of these theoretical power systems are dispatched against the same demand curves and eventually generate the same amount of net-zero electricity in 2045. Same end result, different cost.

With modern, chronological power system expansion software, designing more accurate capacity expansion plans is within reach for all system operators and planners.

As grids around the world continue to navigate the energy transition, the benefits of firm, flexible power plants are obvious especially from the perspective of affordability and security of supply. With the USA as an example, in 2024 alone, about 1 GW of firm flexible reciprocating engine balancer plants have been ordered.

The path forward in 2024

To move forward, the power system flexibility limit must be raised as soon as possible.

This is done by retiring the aging inflexible coal assets, which force curtailment of renewables and are responsible for almost 80% of carbon emissions in Chile.

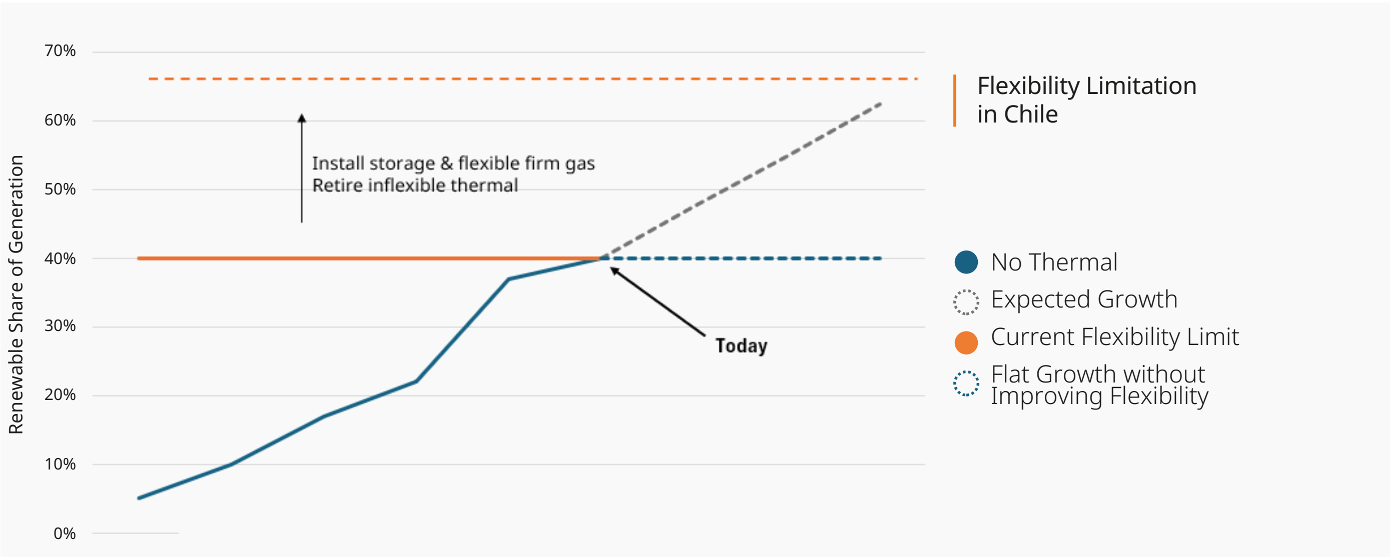


Figure 15 - Increasing the power system flexibility limit

To enable the retirement of coal and thereby raise the flexibility limit, storage capacity needs to be rapidly increased to manage short-duration intermittency. To ensure sufficient adequacy, a minimum of 5 GW of gas generation capacity must be maintained. Whether it is old or new. Even the old gas capacity has the capability to stop in the morning and restart in the evening, allowing for solar power to flow. Coal plants cannot stop daily. Using gas plants instead of coal instantly raises the flexibility limit. This results in near-zero electricity prices during the day and substantially lower side payments with marginal prices in the evening and night, set by storage and gas.

Coal is gradually closed between 2026 and 2035. Faster closure is possible but requires even faster actions to expand storage, wind and solar capacities, and adequate gas capacity.

From the modelling in Section 1 of this study, we can illustrate the optimal capacity mix changes from 2024 to 2032 with the figure below (without rehabilitation of old CCGTs):

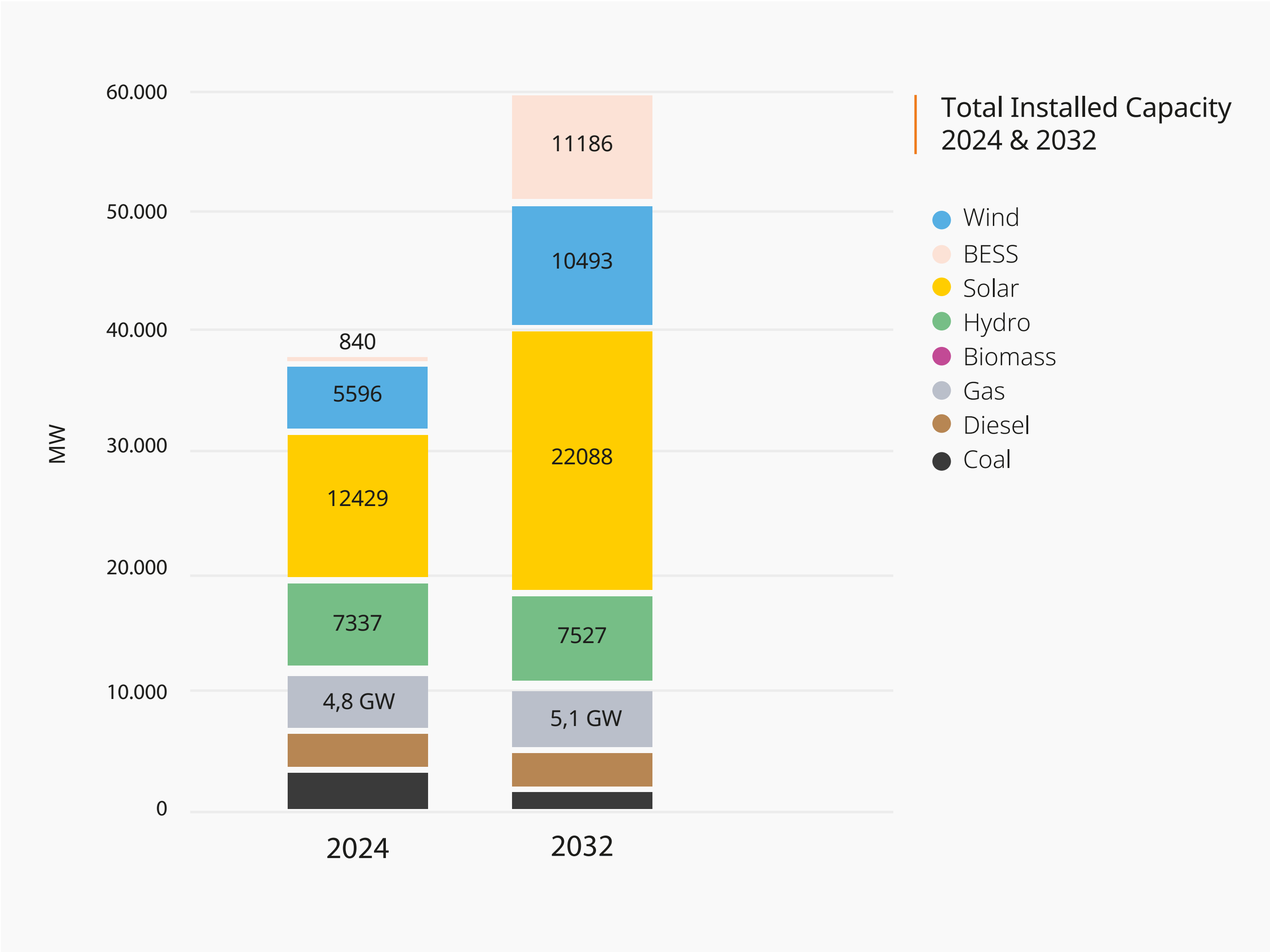


Figure 16 – Installed capacity mix (MW) in 2024 & 2032

Note the major increases in storage, solar, and wind. In scenario 2 aging CCGTs are replaced by new flexible H_2-ready gas capacity at optimal time points.

How to solve security of supply and the need for flexibility with one solution

As addressed earlier, by 2029 major reliability challenges will emerge:

1 | The system will not have adequate generation capacity at nights or early morning hours

2 | The ramping capacity in early mornings and evenings will not be adequate

3 | Grid black-start capabilities need to be strengthened especially in the north

4 | There is need for inertia and short-circuit capacity in selected regions

Although it was not in focus in Section 1 of this study, there is a challenge of inertia and short-circuit capacity, which are both decreasing due to closures of large coal power plants. We did not focus on this in Section 1 because this issue is understood by CEN, the ISO, as the first tender for synchronous condensers was established and awarded in summer 2024.

Reliability risk 1 in the list above could be addressed through the current capacity market, while 2 through 4 – which are ancillary services – cannot be addressed through the capacity market. Instead of attempting to incorporate 2 through 4 into the capacity market, which would require systemic overhaul, it would be more efficient to establish an ancillary services infrastructure tender to purchase these necessary capabilities directly.

Such a tender would not only bring to the system the required capabilities 2 through 4, but the tender would also indirectly solve challenge 1 as those who bid for the infrastructure tender would build new flexible capacity with capabilities 2 through 4.

	Risk	Capacity Market	Ancillary Service Infrastructure Tender
1	Resource adequacy during the night	Yes would involve significant changes to capacity market which has been challenging to modify in past 5 years	Yes The tender could be used to address resource adequacy deficit indirectly.
2	Availability of resources which can cover short term variations effectively	No short term variations are not covered by capacity market.	Yes An ancillary service infrastructure tender for resources which can address short term variability of renewables could be defined.
3	Black start capability limitations in the north	No black start capabilities are not covered by capacity market.	Yes An ancillary service infrastructure tender for black start capabilities.
4	Regional need for inertia and short-circuit capacity	No the capacity market does not cover inertia and short-circuit capacity	Yes an ancillary service infrastructure tender can require 24/7 inertia provision

It is important to understand that the cost of acquiring individual assets to address each of these risks separately would be higher than to purchase them all in one facility. Modern, flexible H_2-ready gas power plants can provide all four of them from the same plant. And as shown before, reciprocating engines offer the optimal solution for this need:

1) Capacity adequacy
As the Plexos study shows, reciprocating engines are the best technology for balancing renewables.

2) Short-term ramping capacity
Gas power plants offer a cost-optimal way to provide fast ramping capacity. Reciprocating engines are the best technology for providing ramping capability even from stand-still as they can come on-line in minutes

3) Grid black-start capability
Reciprocating engine power plants have this capability built in as they do not need any external power for starting

4) Inertia and short circuit capacity
Flexible gas power plants can be equipped with clutches that make them synchronous condensers – the plants provide energy and system balancing capacity while running, and inertia and short-circuit capacity when not. Balancing renewables 8760 hours/year

The energy transition in Chile depends on a strategic blend of renewables, flexible gas generation, and energy storage to achieve a system that is reliable, affordable, and sustainable.

There is no time to waste. For potential investors, steps need to be taken between now and 2029 to have those flexible plants serving Chileans. Regulators must ensure reasonable returns for the investors. IPPs and utilities must evaluate projects and make investment decisions. Plants must be permitted. Finally, plants have to be constructed and commissioned. To bring a project through all stages of development will take at least 5 years or more. This timeline, optimistically, leads to commercial operation in January 2030, after adequacy problems have already begun.

Conclusion

Investment in flexible and sustainable generation, supported by policy incentives and private sector engagement, is critical to maintaining stability as traditional fossil fuel plants phase out. By prioritizing system reliability and examining aspects such as reserve margin and ramping capacity, a path towards net zero emerges. This path integrates net-zero quantities of solar, wind, and storage, retires aging inflexible generation and replaces it with flexible Balancer power plants capable of using sustainable fuels, and reduces ancillary service costs by improving system flexibility.

Section 3 - Case Studies

Australia – Barker Inlet Power Station

Barker Inlet Power Station (BIPS) is a 211 MW, 12 x Wärtsilä 18V50SG engine power plant in South Australia. The South Australian grid, a regional grid under the supervision of the Australian Energy Market Operator (AEMO), is a market with 5-minute intervals and >50% renewables by annual generation as of 2022.

Putting the market under a microscope, interesting trends start to emerge, especially when focus is applied to the thermal generators. Compared to the coal steam generation, combined cycle gas generation, and open cycle gas turbine generators, BIPS starts and stops more often, operates at a wider range of partial load, captures more price spikes and avoids more 0-price hours than its thermal competition. The image below pulls 3-4 days of dispatch data for BIPS and Ladbroke Grove, an 80 MW aeroderivative gas turbine plant. Ladbroke grove operates as a typical peaker, starting 1-2 times per day during peak hours. BIPS, operates and responds to the real-time variations in the market. On the right side of the image, the advantage of modularity and ramping capability is shown. Each engine can be operated independently, which gives the dispatcher 12 different high-efficiency load points, available in 5-minutes, to operate at.

These highly flexible operational profiles are possible in markets with longer settlement periods, as the next example in El Salvador will show. A short-settlement period is just one way to incentivize dispatchable generation to be more complementary to rapidly growing variable renewable energy.

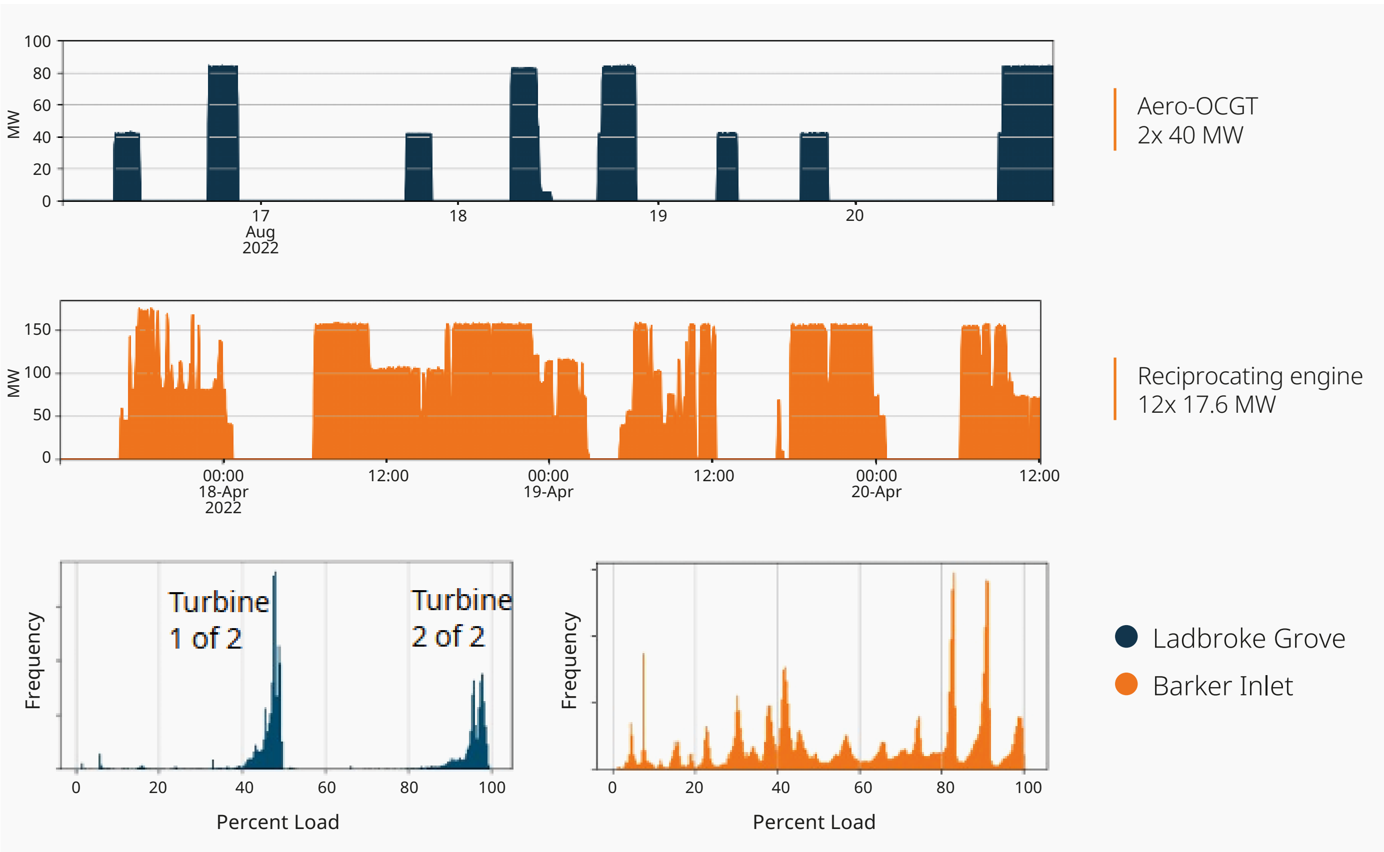


Figure 18 - BIPS vs. Aero GT Operation Profile

Link to the full study here:
https://www.wartsila.com/insights/article/balancing-renewables-is-an-untapped-opportunity-flexibility-in-action-in-south-australia

El Salvador – Energía del Pacifico

Generation in El Salvador is highly seasonal. From April to November, seasonal rains fill up reservoirs and rivers, providing over 600 MW of firm hydro capacity. From October to May, sugarcane bagasse is available in large quantities as a carbon neutral, low-cost fuel for 200 MW of steam generation. In 2022, El Salvador installed Energía del Pacifico (EDP) a 378 MW gas power plant made up of 19 x Wärtsilä 18V50SG reciprocating engines and one 28-MW steam turbine. This plant would serve to balance the seasonal changes in hydro and biomass, as well as the growing solar and wind segments which now represent about 20% of installed capacity.

Since its installation, EDP has reduced the annual share of HFO generation and imports from 45.8% down to 9.4% through June of 2024 while also reducing annual CO_2e emissions by 400,000 tonnes [Castalia].

EDP entered the matrix as lower-cost and cleaner capacity, but it also provides an interesting example of how modularity can be used to support the whole system. Since each engine can be operated independently, Energía del Pacifico and the Unidad de Transacciones (ISO) partnered to assign 4 of the 19 engines to operate under automatic grid control to provide 24/7 frequency control services while the other 15 engines operate under standard merit order dispatch and provide daily/hourly/seasonal ramping services. Below is an example of operational flexibility in practice - one site providing firm long-duration capacity and 24/7 ancillary services simultaneously.

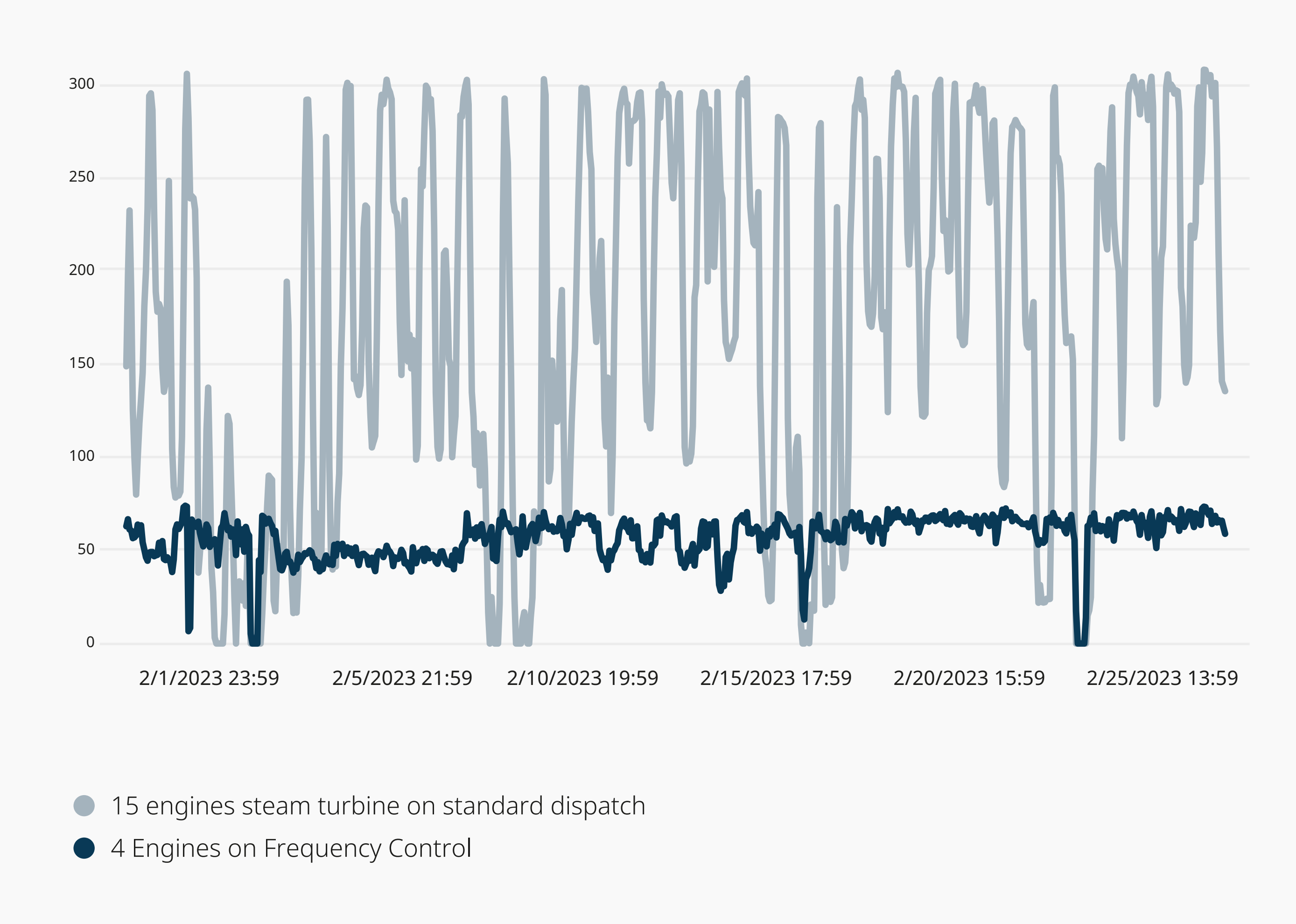


Figure 19 - EDP operational flexibility in February 2023 shown with hourly data, simultaneous frequency control (dark blue) and renewable balancing (grey)

USA – South Texas

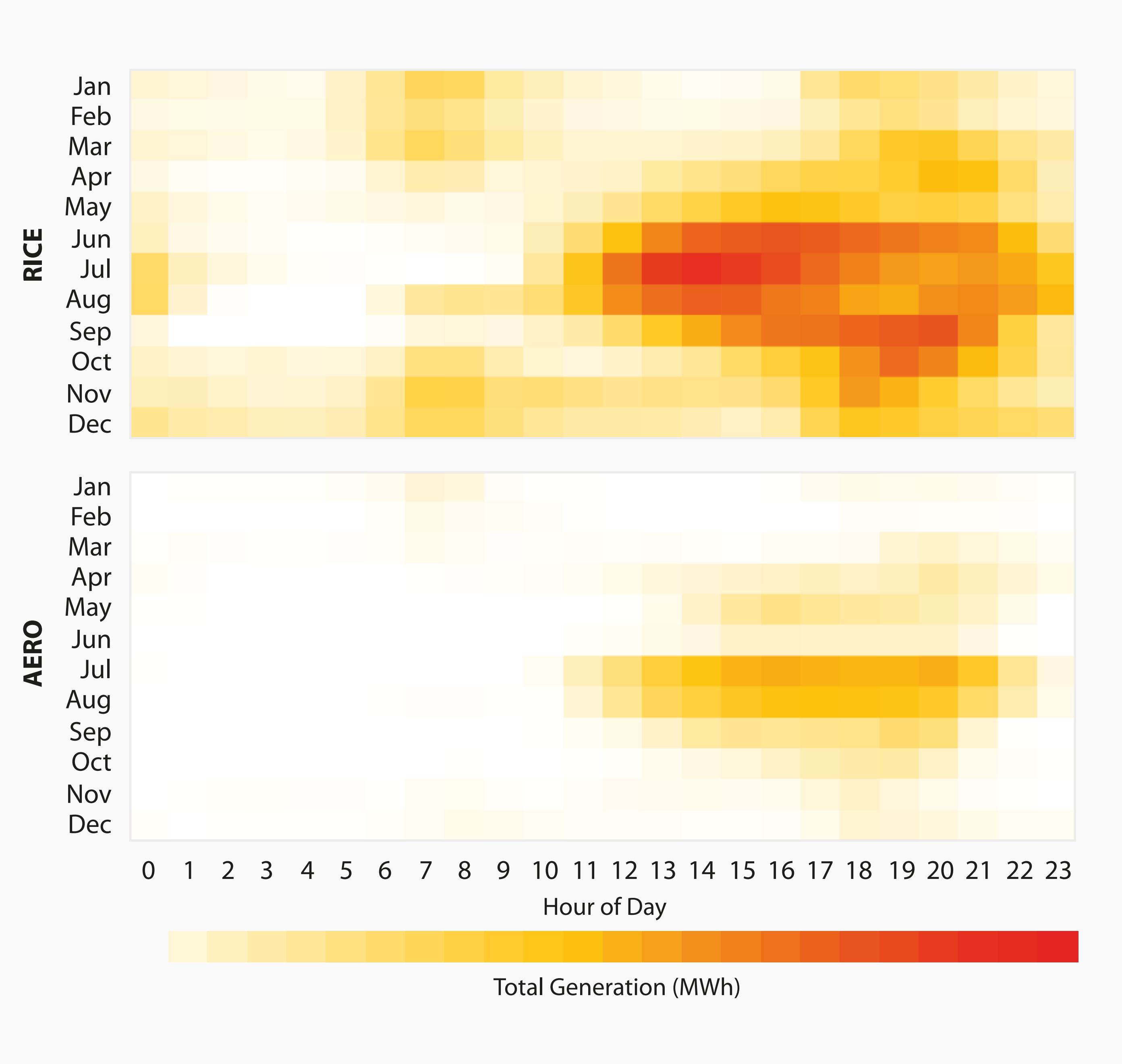
ERCOT, the independent system operator (ISO) in Texas is famous for operating one of the largest 5-minute settlement period scarcity markets. This market structure provides the platform for reciprocating internal combustion engine (RICE) plants to shine when compared to their peaker alternatives.

When it comes to open cycle thermal generators utilizing gas, there are effectively 3 options. Aeroderivative gas turbines (AERO), heavy-duty gas turbines (HDGT), and reciprocating engines. RICE's zero start-up cost and no minimum up or down time, combined with superior thermal efficiency, mean RICE's ability to stop and start as dictated by 5-minute real-time prices is effectively unlimited. The table below shows that the RICE power plants start approximately three times more frequently than the AERO power plants. Not only do they start more frequently, but RICE also runs more frequently with capacity factors 2-5x higher than AERO GTs.

Plant Name	Technology	Nameplate Capacity (MW)	Starts in 2022	Capacity Factor in 2022 (%)	Median DA Price ($/MWh)	Median RT Price ($/MWh)	RT Price Volatility ($/MWh)
Leon	AERO	230	173	9%	$49	$44	$157
Winchester	AERO	242	185	5%	$47	$43	$147
Pearsall	RICE	202	518	28%	$51	$47	$130
Redgate	RICE	224	541	20%	$45	$40	$107

Figure 20 - Dispatch data for 4 different balancer power plants in Texas, USA

Additionally, due to their higher efficiency, high availability, and low start cost, RICE plants operate throughout the year and in higher quantities than gas turbines. Below is a heat map showing average generation distributed across a 24 hour day in each month of the year, for both a RICE plant and an AERO plant. The heat map shows in color the amount of dispatch a power plants get over a year. Red = high dispatch, white = no/low dispatch.



This translates into a technology that offers more financial and reliability value both across seasons and within a day than a traditional peaker plant.

More information is available in the article here: Powermag.com – Peakers to Balancers

Sources

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