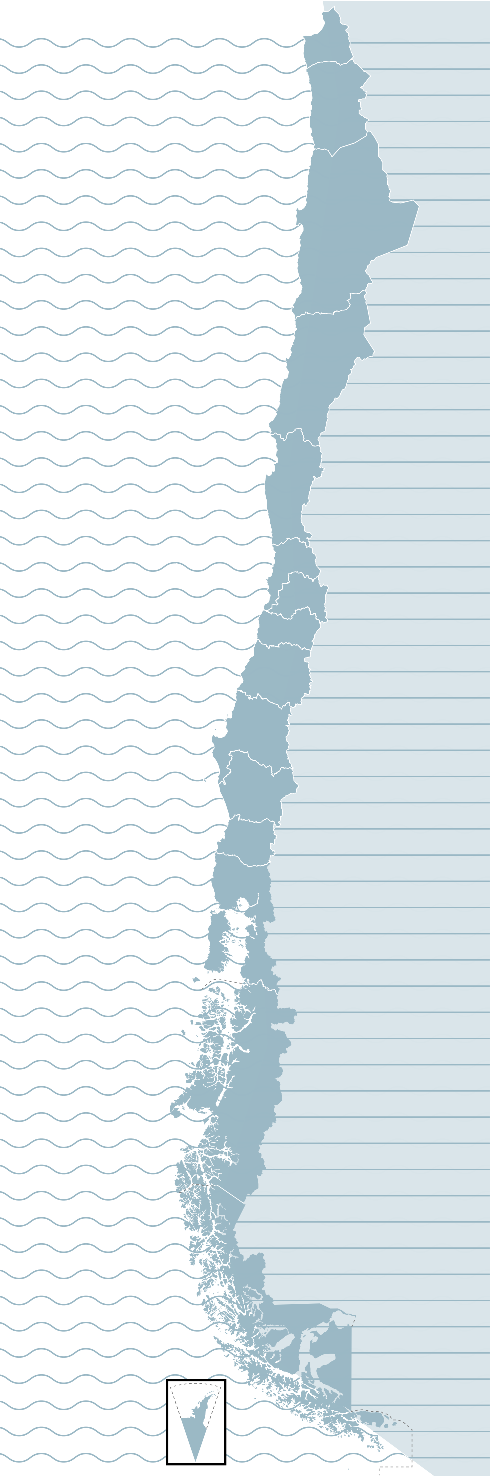
WÄRTSILÄ

# CHILE

## LEADING THE WORLD TO A 100% ZERO CARBON POWER SYSTEM

# EXECUTIVE SUMMARY

**Chile has set some of the most ambitious decarbonization targets in the world. This analysis presents a realistic decarbonization path for Chile which reaches the country´s carbon reduction targets, serves the load without black-outs, and provides lowest cost for the rate payers. The study will present the stages and important capacity mix-related decisions necessary for efficient decarbonization. The main stages of decarbonization are:**



## 2021–2023

### Comprehensive planning and policy setting

## 2023-2030

### Building the foundation

To enable retirement of high-carbon emitting coal and diesel-oil power plants, Chile needs to build a power system capable of serving the load without such plants. This high-renewable system must also be able to handle different weather forecast scenarios such as extreme droughts or weather patterns. This can be accomplished by:

- Adding wind and solar power to produce a growing share of clean energy
- Using battery storage for ancillary services, and gradually increasing storage use for daily solar shifting into the night as battery and solar prices are reduced
- Adding flexible gas generation to avoid curtailment and to provide the necessary firm capacity.
  Note: These power plants must be capable of later conversion to sustainable fuels

**▶ The power system is ready for coal closure in 2030**

## 2030-2049

### Final steps to 100% renewable electricity

- Continue adding renewables, storage and flexible gas generation to cover load growth
- Align the power system development with the National Green Hydrogen Strategy to enable use of hydrogen and/or hydrogen-derived sustainable fuels such as ammonia and methanol
- Convert the gas-fired flexible power plants to sustainable fuels

## 2050

### Carbon neutral system

By 2050, Chile will produce and utilize only carbon-neutral electricity, without any fossil fuels. The future power system will consist of renewables, short-term storage using batteries, and long-term storage with green hydrogen-derived sustainable fuels, used in the flexible power plants. The study shows, that during the transition, the cost of generated electricity drops 39% compared to the cost in 2021.

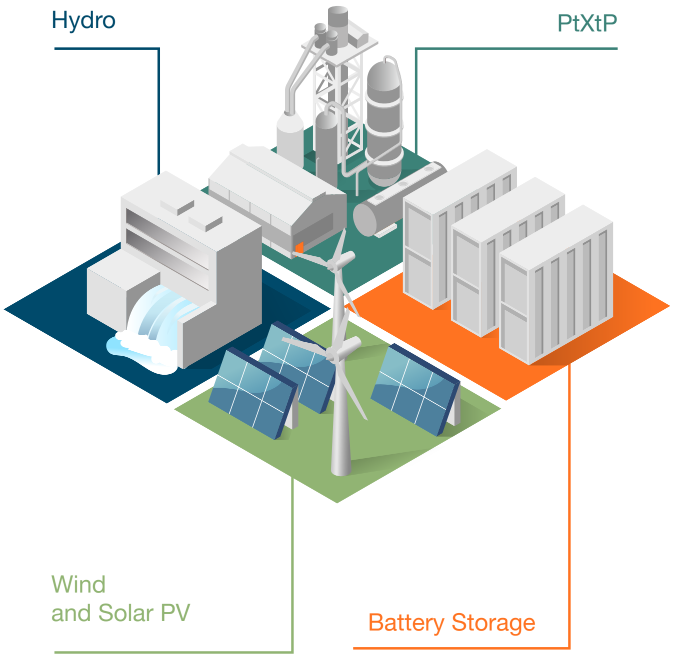
# THE CARBON NEUTRAL POWER SYSTEM OF THE FUTURE

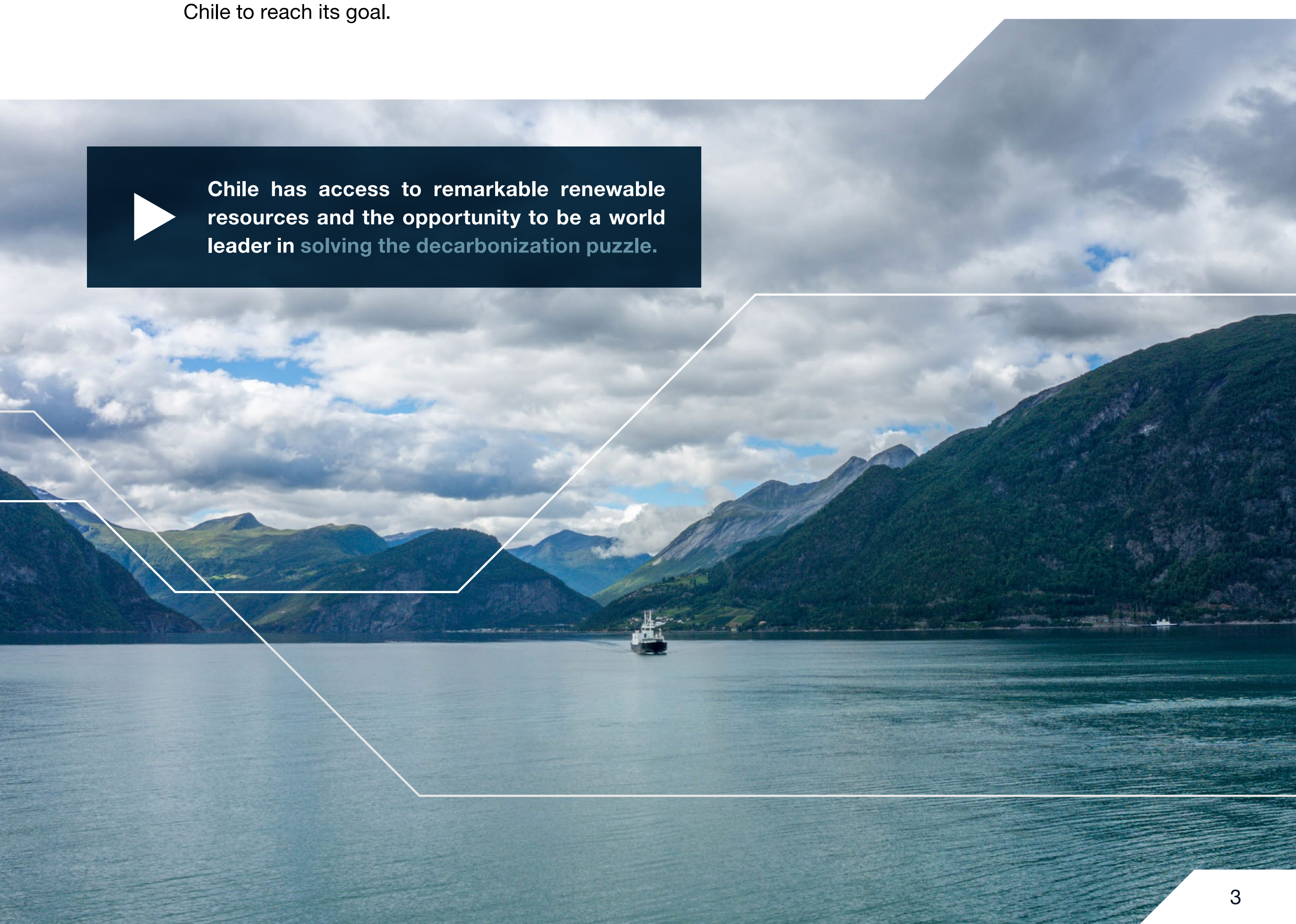
**Chile has set an ambitious goal to decarbonize the country's electricity generation by 2050.**

This study presents the optimal path for decarbonization established by leading power system expansion modelling software Plexos, using inputs and a modelling approach defined in the appendixes. This study also presents the optimal power system capacity mix to develop year-by-year, reaching the decarbonization targets and providing security of supply for lowest generation costs. While this study answers the question WHAT needs to happen and WHY, it does not attempt to provide actual policies or regulatory changes i.e. HOW to make the things happen.

The utilization of already proven power generation and storage technologies coupled with a well-structured and realistic plan will enable Chile to reach its goal.

**FIGURE 1**
**Components of 100% carbon neutral power system**



**Chile has access to remarkable renewable resources and the opportunity to be a world leader in solving the decarbonization puzzle.**

STAGE 1

# COMPREHENSIVE PLANNING

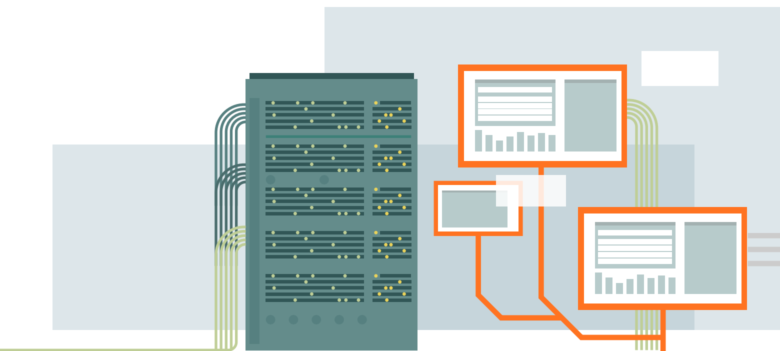
**Planning is the key for a successful decarbonization strategy to avoid incurring similar mistakes made by early-mover countries with ambitious decarbonization targets.**

A comprehensive long-term plan is necessary before actions are taken and investments are made. In the past, countries like Germany have made the mistake of moving forward without such a plan. Germany attempted to decarbonize as quickly as possible by adding more and more renewables on to the grid through incentives and subsidies. However, there was no plan in place to build a power system to adapt and fully utilize the variable renewables added to the system. Instead, they left the existing highly inflexible power system more or less “as is” and even added more coal-based power.

The result of that inflexibility causes renewable curtailment and consequently the cost of electricity in Germany has more than doubled over the past 20 years while the share of renewables was still only 46% of the total generated electricity in 2020. Naturally the high cost is partly a result of Germany introducing large quantities of wind and solar power while the price was still higher than today.

Chile can avoid these issues by engineering a proper power system transition plan, utilizing available modern power system expansion software and supercomputers, something that did not exist 20 years ago for Germany. Sophisticated power system expansion modelling will reveal how to:

- Reach the targets set for carbon reduction & renewable share
- Ensure system reliability and capability to serve the load at any hour during the 29 years
- Get the lowest generation costs = lowest cost of electricity for households and industries

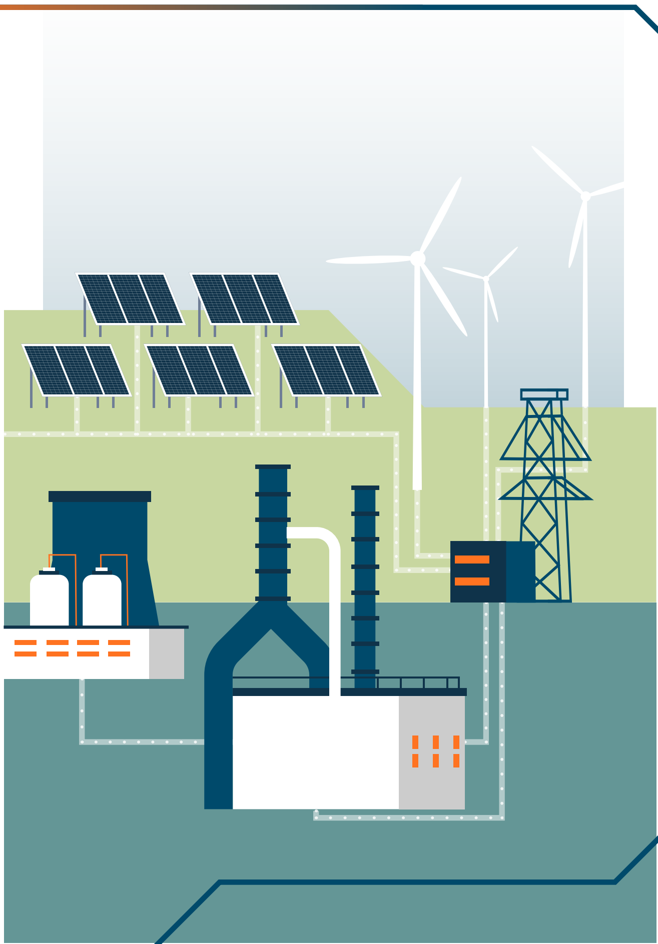


**The software will select what technologies you need to add and retire in the system, year by year during the transition period. However, it will not propose any policies or regulatory changes. Developing a comprehensive decarbonization plan with a strong modelling foundation is a vital piece of the puzzle to enable Chile to achieve an efficient zero-carbon power system.**

STAGE 2

# BUILDING THE FOUNDATION FOR DECARBONIZATION BY 2030

**A major step for Chile to achieve the 100% carbon neutral power system is to enable the retirement of the high carbon emitting sources of coal and diesel oil fired generation. In order to retire all legacy coal and diesel plants by 2030, 29 GW of new capacity needs to be added.**



### Between now and 2025

By 2025 Chile needs to add 4.8 GW of wind and solar PV generation to its power system and as a consequence coal and oil-fired generation can start to gradually retire, creating space for more renewable generation. Throughout this period, carbon emissions are declining slightly as fossil fuel fired power plants are still providing a large share of the electricity (Fig. 3).

The generation cost of electricity will not decline considerably during this period as the country is investing heavily in new renewable generation. It is important to note that during this period, due to new investments, the generation costs start to gradually move from operational expenditures (OpEx) (mainly fuel) to capital expenditures (CapEx).

## 2026–2029

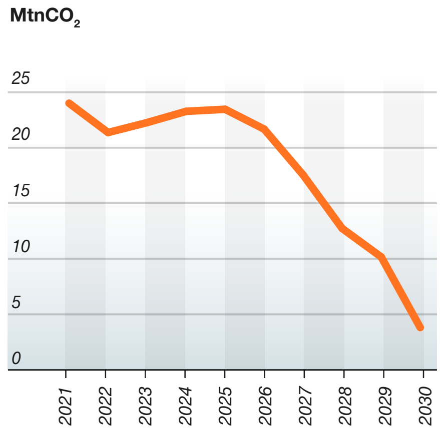
By 2026 the prices of solar and battery storage technologies have declined to a point where shifting solar power from day to night becomes economically viable. Consequently, more and more energy shifting batteries are installed into the power system. These additions enable the power system to avoid curtailment of wind and solar power while improving system efficiency. Excess energy will be stored in the batteries and shifted to be used at night. The model knows the learning curves of battery storage, solar and wind power plants, and optimizes the timing of investments for lowest generation costs.

Prior to the retirement of coal power plants, firm and highly flexible gas generating capacity must be added to "fill gaps" and ensure system reliability in times when solar, wind, and storage are not generating enough power to serve the load. These flexible gas power plants will not operate as base load but instead only come on-line as needed, producing minimal carbon emissions. The system will require frequent starts and stops from these flexible gas power plants with the model showing the plants starting and stopping several hundred times every year. These power plants need to be capable of operating in irregular short patterns to respond to renewable volatility and to ensure system reliability.

To minimize the use of fossil fuels, it is important that these plants can come on and off-line rapidly and produce electricity with high efficiency. Key operational features of the flexible gas-fired power plants - high efficiency and no starting costs - demonstrate major value in a high-renewable power system. Such plants must also have the capability to convert to sustainable fuels in the future.

During this period the incorporation of storage and flexible gas generation into the Chilean system enables further retirements of coal and diesel oil plants, and greater additions of wind and solar PV. Thereby decarbonization can continue, less coal is burned, and carbon levels begin to fall drastically. By year 2030, the total carbon level will have decreased by 84% from year 2021. Figure 2 depicts the decrease in carbon emissions from 2021 and 2030.

**FIGURE 2 Annual carbon emissions during the decarbonization**



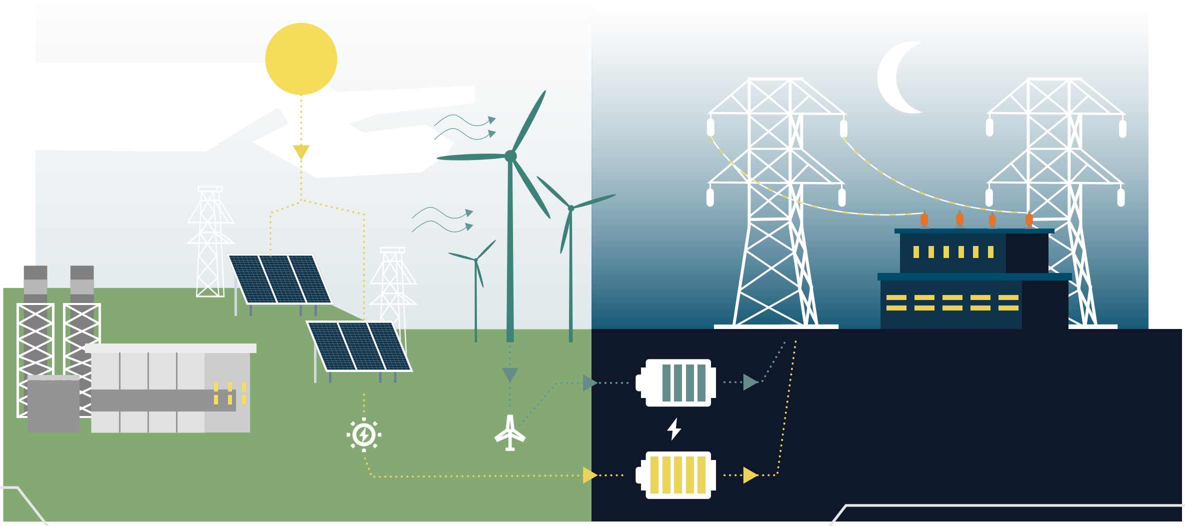
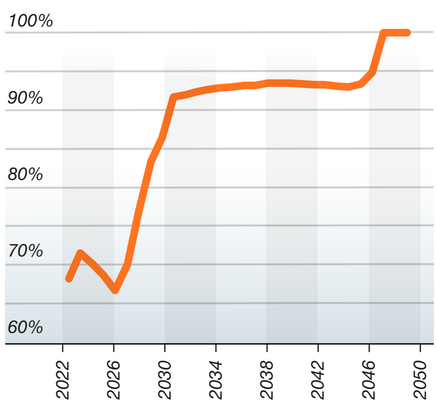



**FIGURE 3 Share of renewables during the decarbonization**

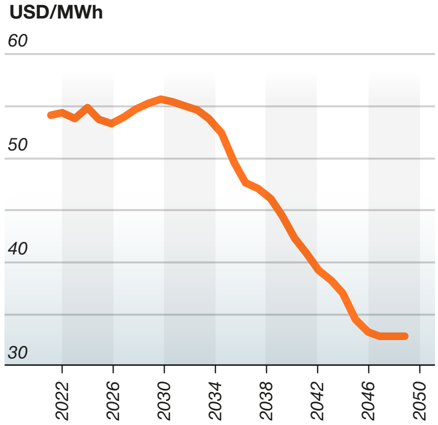
Note: Hydro is considered renewable




The full retirement of coal generation is evident in the reduction of carbon emission from 2020-2030. The next 20 years the model continues to operate the system economically. The renewable share remains relativity stagnant until the system is forced to reach Chiles target of 100 percent by 2050. This goal of zero carbon could be reached even sooner if there is a will to do so.

**FIGURE 4 Annual electricity generation costs during the decarbonization**

Note: Does not include either transmission or distribution costs




## 2030

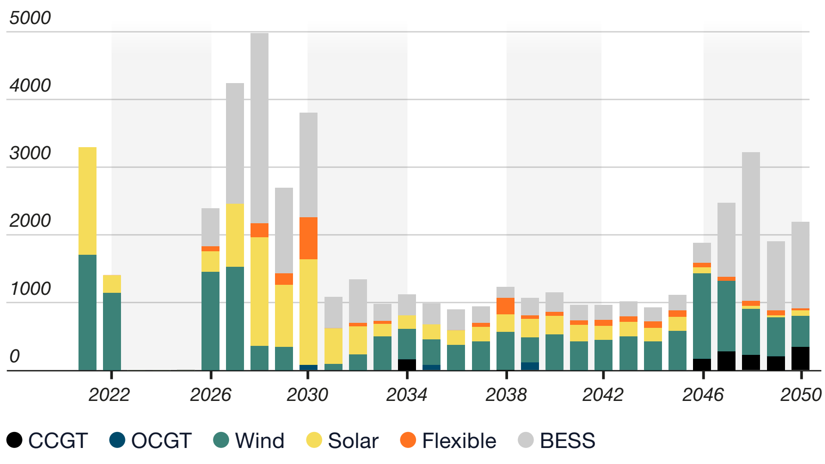
By 2030 the Chilean power system is ready to retire the last coal and diesel oil plants. This is a major step in the decarbonization process.

It is important to realize that closing the coal plants, which provide a large share of the electricity today, is not possible without constructing a robust high-renewable power system capable of providing all the electricity and maintaining system reliability. Closing coal fired assets earlier than 2030 would require even earlier construction of the mentioned 29 GW of new flexible and renewable generating capacity, and due to solar and battery storage learning curves, would cause an increase in generation cost.

By 2030, when coal has fully retired, the carbon emissions will have fallen drastically, and the share of renewables will have climbed to over 90%. Electricity generation costs will remain constant during this stage due to the heavy investments in renewables, storage, and flexible power plants as seen in Fig. 4.

Although generation costs have remained relatively similar, the cost profile has shifted. The majority of the costs in 2030 are fixed, and the variable fuel costs have gone down dramatically compared to the cost levels in 2021. After closing coal and diesel oil fired plants, only the new flexible gas power plants and the few remaining legacy gas-fired power plants will still use some fuel.

**FIGURE 5 Annual investments in power generation and storage technologies during the decarbonization**



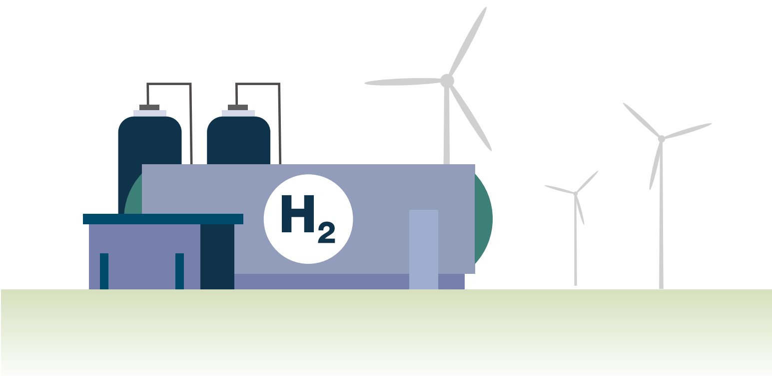

**The period between 2021 to 2030 is crucial for decarbonization as this is the period where most of the investments need to take place. One could say that this decade is there to build the foundation for complete and successful decarbonization of Chilean electricity.**

STAGE 3

# FINAL STEPS TO 100% RENEWABLE ELECTRICITY

**After retiring all coal and diesel oil plants in 2030 the carbon level has declined dramatically from 24 MT/year to 4 MT/year, over 80 %, as seen in Fig 2.**

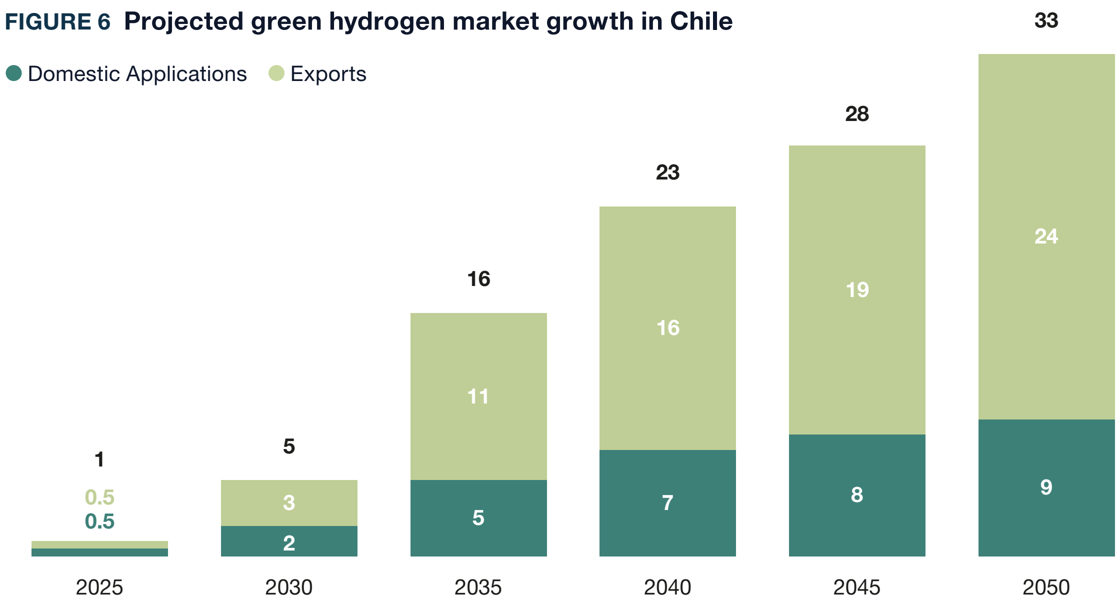
By 2030, the Chilean power system has reached over 90% renewable share. Remaining actions for achieving the 100% renewable power system include increasing the quantity of renewables and battery storage to cover the expected load growth, and converting the flexible gas power plants to operate on green hydrogen based sustainable fuels (e.g., Hydrogen, Ammonia, Methane or Methanol). These fuels are anticipated to become more competitive and available by the year 2030.



After 2030, the energy end-use, such as industry and transportation, will use less fuels and consume more clean electricity and thus lead to load growth. This load growth is mainly covered by adding more solar PV and wind.

By 2035, the Chilean green hydrogen market will pick up. Aligning the power system development with the National Green Hydrogen Strategy, which includes the hydrogen-derived sustainable fuels mentioned previously, will contribute to the country's decarbonization plan and enable the country to become fully self-sufficient in electricity generation. Green hydrogen and its derivatives provide the last piece to the power system decarbonization puzzle – the long-term energy storage to manage any unusual weather patterns.

**FIGURE 6 Projected green hydrogen market growth in Chile**




Source: https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf

# LONG-TERM ENERGY STORAGE FOR 100% RENEWABLE POWER SYSTEM

**In addition to renewable energy sources and short-term storage from batteries, a form of long-term energy storage is necessary to reach a reliable high-renewable power system. This storage is necessary during unusual weather patterns such as long cloudy or rainy periods, drought, low wind periods, heat and cold waves, and during extreme seasonal variations.**

Optimal long-term energy storage consists of three main components:

1. Production of sustainable fuels using mainly excess - otherwise curtailed - wind and solar PV generation (Power-to-X)

2. Transporting and storing these fuels on the grid or at the power plants sites (liquid fuels)

3. Using the fuels in flexible power plants (X-to-Power) to produce firm power when wind, solar PV and hydro generation are not generating enough power for extended periods of time and battery storage becomes drained

The last step in decarbonizing Chile's electricity is to convert the flexible gas power plants to operate on these sustainable fuels. The decision to convert can be made even prior to 2050 when fuels become available and there is political will to do so. These power plants operate with low capacity factors, running only a few hundred hours a year depending on hydro availability, so the fuel cost is not excessive while providing firm and reliable capacity throughout any and all-weather conditions.

Attempting to use battery storage to provide long term energy storage will lead to excessive, linearly increasing costs and still includes a bigger risk for the reliability of the system. Scalability is a key feature of long-term energy storage, making sustainable fuels the most competitive solution.

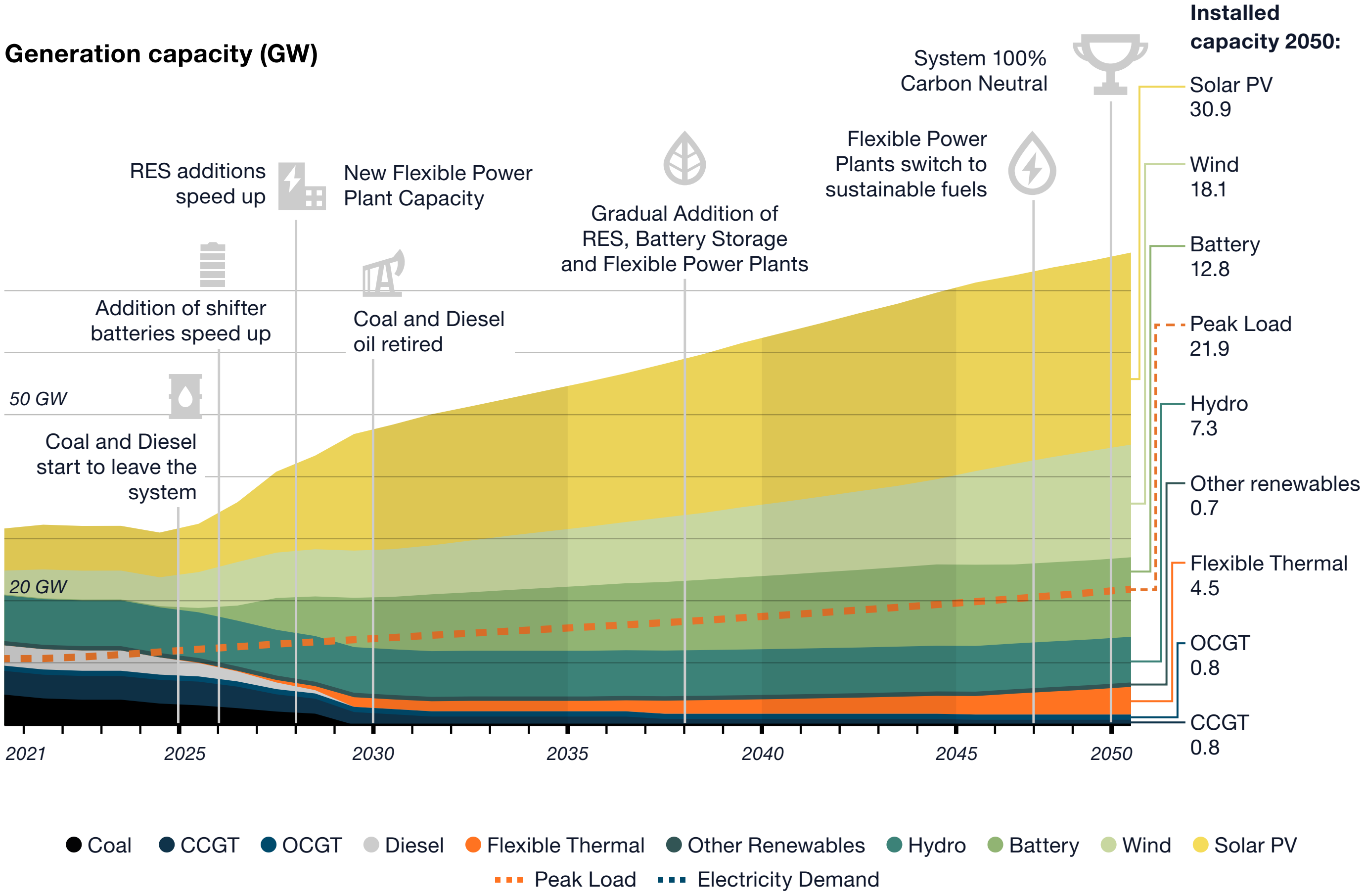
In this study, the transition from natural gas to sustainable fuels takes place in 2047, but there is really no reason why it could not be done earlier. The last old "legacy" natural gas fired power plants retire by 2050 when the system becomes fully carbon neutral.

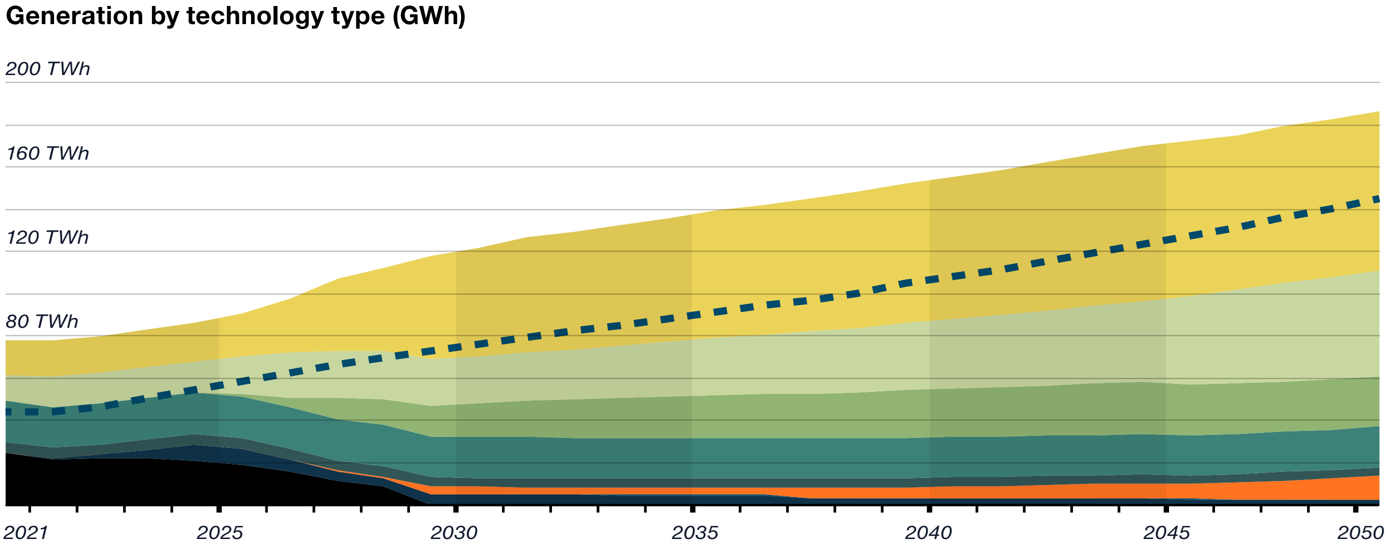
Green hydrogen derived sustainable fuels used in flexible power plants provide the final missing piece of the decarbonization puzzle.

# THE FULL PATH TO 100% RENEWABLES

**Figure 7 outlines the power system capacity expansion during the decarbonization path. Major expansion of wind, solar and battery storage capacities is necessary to enable retirement of the high carbon emitting technologies (coal and diesel oil fired plants) by 2030. In 2050 this power system provides clean, 100% carbon neutral, reliable and affordable electricity.**

**FIGURE 7** **Chilean power system path to 100-expansion 2021-2050**



# KEY TAKEAWAYS

**A 100% carbon neutral power system is realistically achievable for Chile by 2050, or even sooner.**

The technologies that will play a major part in reaching that goal are available today. This study outlines the changes that need to occur in the Chilean power system to achieve cost-efficient decarbonization.

In order to continue the incorporation of renewable energy, it is vital that Chile develops the policy and regulatory framework to incentivize the necessary investments in storage and gas-fired flexible generation during the early parts of this decade. Adding renewables, storage and flexible gas generation according to this study enables the retirement of the high-emitting coal and diesel oil power plants and a dramatic reduction in carbon emissions.

The optimal clean power system consists of 3 pillars:

1. **Renewables** - wind, solar PV and hydro - generation, producing all the energy
2. **Short-term energy storage** to manage frequency, cloud cover and daily solar shifting
3. **Long-term energy storage** —based on sustainable fuels and flexible power plants—to manage unusual and seasonal weather patterns

The cost of electricity generation will remain steady throughout this decade due to heavy investment costs, but contrary to many beliefs, the electricity costs for the rate payers will not increase – they will remain stable during the next 10 years and after 2030 they will be gradually reduced by 39%. Clean power does not have to be expensive!

**Chile is presented with an opportunity to be a world leader and showcase to other countries how to obtain reliable, sustainable, and affordable 100% renewable electricity.**

# APPENDIX

## THE MODELLING SOFTWARE

**Plexos is a simulation software for studying and dispatching of a power system. The software uses mathematically based optimization techniques to realistically represent the operation of a real-life power system.**

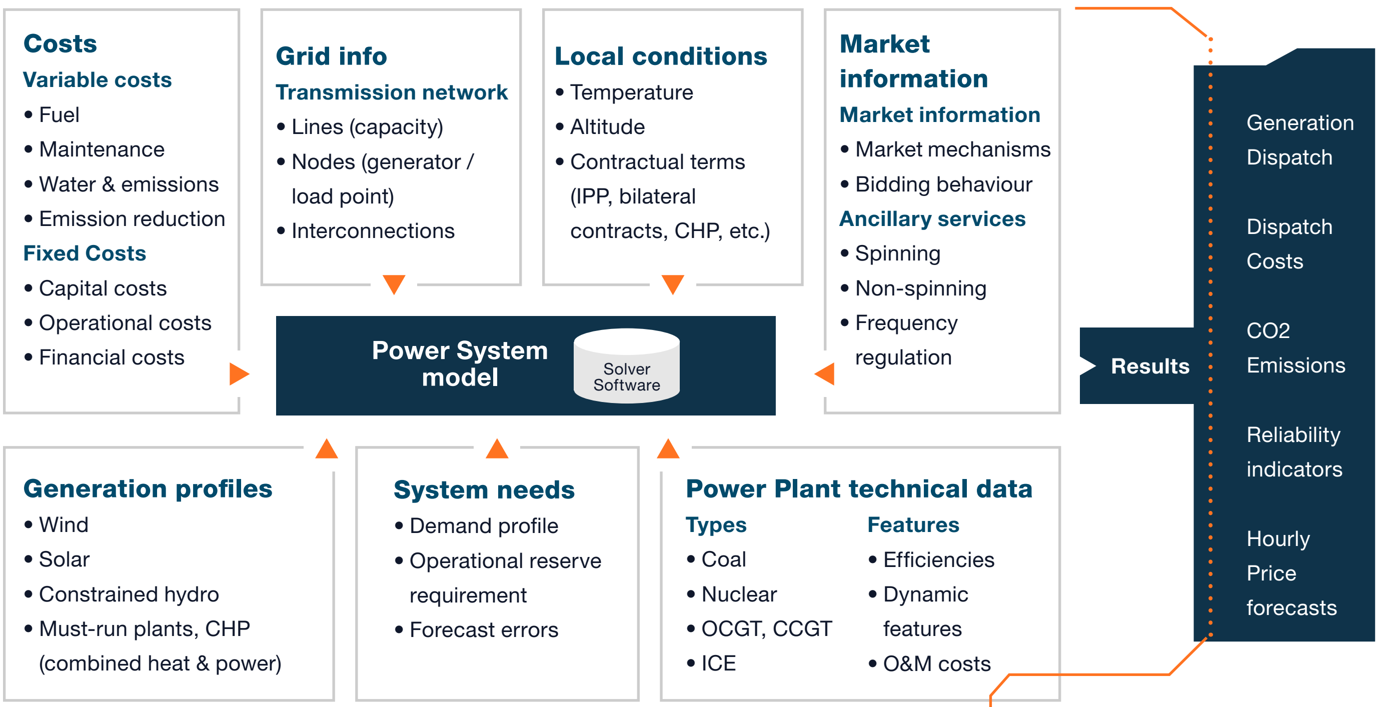
Plexos is an optimal tool for the capacity expansion studies of high variable renewable generation system because it is able to:

- Model the variability of wind and solar in detail is important for representing the low solar and wind periods required to properly model the system reliability
- Include the technical parameters needed to capture the inflexibilities of thermal generation. Such parameters include ramp rates, starts costs and profiles, minimum stable generation and minimum up and down times.
- Allow the representation of weather forecast uncertainty in operational reserve provision

A Plexos model is a combination of power system data and advanced mathematical formulation, which captures the characteristics of the studied system. This data, combined with the mathematical formulation, is a Plexos model, representing the power system with each of its techno-economic detail. The formulation basically models system features, such as the characteristics of power plants (e.g. efficiencies, dynamic features), the nodes and lines in the electrical grid, ancillary service requirements, and supply-demand balance.

The model is fed to a solver that produces the results shown in figure 8. The solver optimizes the power system. In a long-term expansion model, the optimization objective is to find the optimal (lowest cost) generation capacity additions to supply the future electricity demand. Due to the complex nature of the power system capacity optimization modelling some simplifications and compromises are typically needed. But it is noteworthy to mention that these simplifications should not severely impact the end results, which means that all compromises need to be carefully investigated and chosen.

**FIGURE 8** **Plexos power system model (requires major computing power)**




For more information on Plexos visit https://www.energyexemplar.com/plexos

**TABLE 1** **Cumulative capacity additions in Chile throughout decarbonization in different zones**

| | SING | | | | SIC-N | | | | SIC-C | | | | SIC-CS/S | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wind | Solar PV | Battery Storage | Flexible Thermal | Wind | Solar PV | Battery Storage | Flexible Thermal | Wind | Solar PV | Battery Storage | Flexible Thermal | Wind | Solar PV | Battery Storage | Flexible Thermal |
| 2021 | - | 1,556 | 140 | - | 18 | 533 | + | - | - | 871 | + | - | 1,424 | - | - | - |
| 2022 | - | 1,651 | 140 | - | 577 | 533 | - | - | - | 1,197 | - | - | 1,663 | - | - | - |
| 2023 | - | 1,651 | 149 | - | 577 | 533 | - | - | - | 1,197 | - | - | 1,663 | - | - | - |
| 2024 | - | 1,651 | 162 | - | 577 | 533 | - | - | - | 1,197 | - | - | 1,663 | - | - | - |
| 2025 | - | 1,651 | 197 | - | 577 | 533 | - | - | - | 1,197 | - | - | 1,663 | - | - | - |
| 2026 | - | 2,223 | 649 | - | 1,329 | 533 | - | 108 | - | 1,197 | - | - | 2,048 | - | - | - |
| 2027 | - | 3,786 | 2,432 | - | 2,460 | 533 | - | 108 | - | 1,492 | - | - | 2,149 | - | - | - |
| 2028 | - | 6,358 | 5,049 | - | 2,723 | 672 | 74 | 408 | - | 2,187 | - | - | 2,180 | - | - | - |
| 2029 | - | 7,629 | 5,820 | - | 2,977 | 983 | 559 | 654 | - | 2,649 | - | - | 2,222 | - | - | - |
| 2030 | - | 11,329 | 7,291 | 398 | 2,977 | 983 | 559 | 1,159 | - | 2,649 | - | - | 2,222 | - | 97 | - |
| 2031 | - | 12,624 | 7,803 | 398 | 3,055 | 983 | 559 | 1,159 | - | 2,649 | - | - | 2,222 | - | 97 | - |
| 2032 | - | 13,672 | 8,505 | 398 | 3,263 | 983 | 559 | 1,226 | - | 2,649 | - | - | 2,222 | - | 97 | - |
| 2033 | - | 14,160 | 8,772 | 398 | 3,714 | 983 | 559 | 1,287 | - | 2,649 | - | - | 2,222 | - | 97 | - |
| 2034 | - | 14,682 | 9,144 | 398 | 4,130 | 983 | 559 | 1,287 | - | 2,649 | - | - | 2,222 | - | 97 | - |
| 2035 | - | 15,234 | 9,491 | 398 | 4,457 | 1,049 | 559 | 1,287 | - | 2,649 | - | - | 2,249 | - | 97 | - |
| 2036 | - | 15,657 | 9,852 | 398 | 4,718 | 1,231 | 559 | 1,287 | - | 2,649 | - | - | 2,341 | - | 97 | - |
| 2037 | - | 15,921 | 10,049 | 398 | 5,063 | 1,323 | 635 | 1,287 | - | 2,909 | 18 | 46 | 2,401 | - | 97 | 40 |
| 2038 | - | 16,125 | 10,082 | 398 | 5,503 | 1,350 | 794 | 1,287 | - | 3,466 | 78 | 215 | 2,504 | - | 101 | 214 |
| 2039 | - | 16,446 | 10,243 | 398 | 5,675 | 1,415 | 829 | 1,287 | - | 3,919 | 78 | 254 | 2,695 | - | 189 | 255 |
| 2040 | - | 16,719 | 10,359 | 398 | 5,918 | 1,424 | 849 | 1,287 | - | 4,512 | 125 | 298 | 2,970 | - | 328 | 295 |
| 2041 | - | 16,970 | 10,443 | 398 | 6,161 | 1,424 | 895 | 1,287 | - | 5,034 | 211 | 321 | 3,154 | - | 380 | 371 |
| 2042 | - | 17,225 | 10,601 | 398 | 6,401 | 1,424 | 897 | 1,287 | - | 5,469 | 323 | 439 | 3,365 | - | 412 | 371 |
| 2043 | - | 17,453 | 10,745 | 398 | 6,667 | 1,424 | 897 | 1,287 | - | 5,979 | 407 | 549 | 3,609 | - | 469 | 371 |
| 2044 | - | 17,694 | 10,905 | 398 | 6,872 | 1,424 | 897 | 1,287 | - | 6,419 | 485 | 692 | 3,844 | - | 515 | 371 |
| 2045 | - | 17,999 | 11,093 | 398 | 7,118 | 1,424 | 897 | 1,287 | - | 6,832 | 605 | 833 | 4,208 | - | 515 | 371 |
| 2046 | - | 17,999 | 10,948 | 398 | 7,834 | 1,424 | 897 | 1,287 | - | 7,137 | 742 | 924 | 4,851 | - | 515 | 371 |
| 2047 | - | 17,999 | 10,588 | 398 | 8,256 | 1,424 | 897 | 1,378 | - | 7,137 | 742 | 1,228 | 5,561 | - | 515 | 371 |
| 2048 | - | 17,999 | 10,674 | 398 | 8,478 | 1,424 | 823 | 1,482 | 172 | 7,307 | 742 | 1,470 | 5,924 | - | 515 | 371 |
| 2049 | - | 17,999 | 10,887 | 414 | 8,631 | 1,424 | 625 | 1,569 | 440 | 7,414 | 742 | 1,695 | 6,151 | - | 515 | 371 |
| 2050 | - | 17,999 | 10,856 | 457 | 8,905 | 1,424 | 796 | 1,569 | 493 | 7,712 | 742 | 2,068 | 6,352 | - | 418 | 371 |

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## WÄRTSILÄ ENERGY IN BRIEF

Wärtsilä Energy leads the transition towards a 100% renewable energy future. We help our customers unlock the value of the energy transition by optimising their energy systems and future-proofing their assets. Our offering comprises flexible power plants, energy management systems and storage, as well as lifecycle services that ensure increased efficiency and guaranteed performance. Wärtsilä has delivered 72 GW of power plant capacity in 180 countries around the world.