Path to 100% Renewables

Chile
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Executive Summary

Chile, like many other countries across the world, is putting CO$_2$ targets in place to reduce national emissions. The country has shown an urgency and commitment to reduce its carbon footprint by setting strong targets e.g. joining the Paris Climate Agreement in 2015.

On June 4th 2019, President Piñera presented a schedule for the first stage of Coal Plant retirements from the Chilean power system. This schedule is the result of an agreement between power plant owners and the Ministry of Energy. The first stage ensures the retirement of 8 coal plants by 2025, totalling 1047 MW. These coal plants are the oldest and, therefore, produce higher amounts of CO$_2$. The next stage and target set by President Piñera is the total retirement of coal generation by the year 2040. The retirement schedule for the remaining coal plants (20) will be decided in the future taking into consideration the rate at which renewable generation is added to the power system. The President aims to negotiate and develop a detailed coal retirement plan every 5 years targeting the overall goal, which was announced as well, to reach CO$_2$ neutrality by the year 2050.

The purpose of this paper is to contribute to the discussion in Chile. Instead of presenting one solution, this study presents several scenarios and compares the results – share of renewables, CO$_2$ emissions and total national electricity generation costs. This paper is not suggesting that any scenario should have priority over the others, instead the intention is to provide solid ground for understanding the impacts of certain decisions and weather conditions (mainly hydro generation) on the cost of power, and emissions. The study also evaluates transmission expansion costs for each of the scenarios by using the cost estimation method from CEN’s decarbonization study.

This study uses globally recognized data sources for future price forecasts (learning curves) of technologies, mainly from Bloomberg New Energy Finance (BNEF), and one of the world’s top dynamic power system modelling software’s, Plexos. Inodu (a Chilean consultant) provided local investment cost forecasts and fuel price estimates. The capacity expansion model includes most of the increasingly important technology constraints for thermal power plants while the technology options for flexible thermal generation are compared in a detailed, dynamic short term dispatch model, as the last step of the study. This study does not model the electricity market and the market prices, instead it focuses on the physical power system itself, and allows Plexos software to find the optimal capacity mix for the forecasted future electricity needs, and the most effective way to dispatch the system. To reach the national generation costs, renewable share and emissions presented in the study, the electricity market and national policies need to be modified to provide adequate incentives for investors to invest in the capacity additions proposed by Plexos.

Total generation cost includes:

- Operative expenses like fuel and power plant operation and maintenance
- Fixed costs of capital, for all new plants installed after 2019
Below is a summary of the scenarios

<table>
<thead>
<tr>
<th>Name</th>
<th>Explanation</th>
<th>Coal Phase out</th>
<th>Other</th>
</tr>
</thead>
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<td>Base Case</td>
<td>Current plan with global price forecasts</td>
<td>Announced* &amp; committed schedule until 2024</td>
<td>Bloomberg and Inodu pricing and learning curves</td>
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<td>Announced coal retirement schedule until 2024 and schedule from CEN decarbonization study 2025 onwards</td>
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<tr>
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</tbody>
</table>

*Announced schedule: 1047 MW of coal is retired by the end of 2024

Table 1 Summary of studied scenarios.

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**Figure 1** Cumulative total cost difference of each scenario, compared to the Base case.
Figure 1 shows the difference in total generation costs between the scenarios. The total generation cost for the Base Case is about 88 BUSD over the 21 year period.

Due to heavy presence of coal, most scenarios show similar total costs until 2025, with the exception of Scenario 1d where annual hydro generation is lower. The total cost in most of the scenarios begins to increase due to the phasing out of coal and the resulting heavy investments in renewables. The phase out of coal also increases the investments in transmission grid. Coal is retired completely during the period in all scenarios except Base Case.

The retired coal is replaced mainly by wind and solar PV. As the share of renewables in the system’s capacity mix increases drastically, the system requires more flexibility. The lowest cost for phasing out coal is achieved when the flexibility is provided by hydro, battery storage, and flexible gas generation. This is the case in Scenarios 1, 1b, and 1c.

The most economic phase out is achieved in Scenario 1b with lower gas price after 2028. The economic gas even reduces the total costs compared to Base Case.

Scenario 1c investigates the construction of an HVDC line in 2029 to relieve transmission bottleneck between the northern solar generation and southern consumption. More solar PV capacity enters the system as a result of the new line but the competitive battery storage prices reduce the benefit from the HVDC line.

In Scenario 2 coal is phased out faster, which causes an increase in costs at the beginning of the period as earlier investments in wind power and flexibility are necessary. On the other hand, early investments in wind and solar PV reduce the system operational costs as fuel cost drops.

Investment requirements for new generation capacity in each of the scenarios are presented in Figure 2. The 21 year timeline has been divided into 4 sections to illustrate the timing of investments. For Base Case investments are equally spread over the study period as most of the coal remains in the system. In scenarios 1, 1a, 1b, 1c, and 1d, more investments are made before 2040 which is caused by the investments in new generation as the last of the coal is phased out. Generally, most investment potential appears when coal generation is phased out. This is also seen in the case of Scenario 2 where the last coal plant is closed in 2029.

Annual emissions for the total electricity generation in Chile are compared in Figure 3. Base Case shows the slowest reduction in emissions over the 21 year time frame, contrasting other scenarios where phasing out coal results in a considerably higher reduction. Scenario 2 provides a dramatically higher rate of emissions reduction when coal, which is producing the majority of the CO2, is phased out earlier. It is obvious from the graph that as long as coal remains in the system, the emissions remain higher.

Similarly, the presence of the coal generation in the system slows down the growth of renewable generation. The highest share of renewables is achieved when coal is phased out and it is replaced by solar PV, wind, battery storages, and flexible gas generation.
Table 2 summarizes the simulation results of total national generation (OPEX+FO&M+CAPEX) and transmission expansion cost, and emissions over the study period (2020-2040). (FO&M = Fixed Operation and Maintenance costs)

In conclusion, the study shows that earlier retirement of coal along with fast and early introduction of wind and solar power, storage and flexible gas generation results in relatively small impact on the generation costs, but reduce emissions dramatically.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Generation Cost BUSD</th>
<th>Transmission Cost BUSD</th>
<th>Total Cost BUSD</th>
<th>Total Emissions MtnCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>83</td>
<td>5</td>
<td>88</td>
<td>595</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>84</td>
<td>6</td>
<td>90</td>
<td>478</td>
</tr>
<tr>
<td>Scenario 1a</td>
<td>86</td>
<td>6</td>
<td>93</td>
<td>489</td>
</tr>
<tr>
<td>Scenario 1b</td>
<td>81</td>
<td>6</td>
<td>87</td>
<td>530</td>
</tr>
<tr>
<td>Scenario 1c</td>
<td>83</td>
<td>8</td>
<td>91</td>
<td>475</td>
</tr>
<tr>
<td>Scenario 1d</td>
<td>88</td>
<td>7</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>88</td>
<td>8</td>
<td>96</td>
<td>280</td>
</tr>
</tbody>
</table>

Table 2 Summary of scenario results.
Chile, like many countries across the world, is putting in place targets for reducing the country’s emissions. In 2015 Chile agreed to join the Paris Climate Agreement and in 2017 the country ratified the Nationally Determined Contribution (NDC). The NDC stated, (1) to reduce the country’s CO\textsubscript{2} emissions per GDP unit by 30% below the 2007 levels by 2030 (2) to reduce its CO\textsubscript{2} emissions per GDP unit by 35% to 45% below the 2007 levels by 2030, if international support is received.

A key factor contributing to Chile’s targets is the falling prices of renewable electricity. Countries all over the world are taking advantage of competitive wind and solar electricity prices.

A complication that Chile is facing is the large share of inflexible coal units (~39% of total energy generated in 2017), and large combined cycle gas turbines (CCGT). This type of large generation assets, which use steam boilers, are not the best match to the intermittency and variability which renewables add to the power system. Steam power plants need to operate constantly on a high load and they cannot stop and restart fast to balance the flow of renewables, and they tend to cause curtailment of the clean renewables already at relatively low shares of wind and solar. At the same time, coal power plants produce roughly double the CO\textsubscript{2} compared to gas power plants / MWh of electricity.

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The purpose of this paper is to contribute to the discussion in Chile. Instead of presenting one solution, this study presents several scenarios and compares the results – share of renewables, CO\textsubscript{2} emissions and total national electricity generation costs. This paper is not suggesting that any scenario should have priority over the others, instead the intention is to provide solid ground for understanding the impacts of certain decisions and weather conditions (mainly hydro generation) on the cost of power, and emissions. The study also evaluates transmission expansion costs for the scenarios by using cost estimation method from CEN’s decarbonization study.
Objectives and Approach for This Study

Main Objective

- To use a leading power system expansion software – Plexos - to develop an accurate long term system expansion scenarios for the Chilean power system.

- These scenarios hopefully help understand the impacts of different decisions and weather conditions of the power system optimum capacity mix, costs and emissions.

In order to reach the necessary objectivity and accuracy, the following approaches were chosen:

- Use globally recognized data sources for forecasting future price development of wind, solar PV, CSP, geothermal and battery storage investment costs.
  - Current wind and solar PV prices in Chile are provided by Inodu, a Santiago-based energy consultant
  - Future price projections are from Bloomberg New Energy Finance

- Introduce power system flexibility related parameters to the expansion model. These parameters, which mainly reflect the lack of dynamic capabilities and additional costs of the thermal power plants to support and balance the variability of wind and solar power, have an increasing impact on the system costs when the share of renewables grows.

- Compare flexibility options in the future system with highly accurate short-term dispatch model, which includes all relevant power plant technical parameters/constraints.
The Model

Plexos is the power system modelling tool used for this study. The tool is developed by Energy Exemplar. The software is widely used by system operators, utilities and consultants for power system analysis as well as system planning and dispatch optimization.

In this study, Plexos is first used to make and optimize the long-term capacity expansion for the Chilean power system. The studied time span is from 2020 to 2040. The objective of capacity expansion is to find the optimal new build generation capacity to supply the future electricity demand, with given boundaries such as future price curves for different technologies, political decisions etc. The optimal generation capacity will supply the demand at the lowest cost, over the studied period of time. The generation costs include capital expenses (CAPEX), fixed operation and maintenance (FO&M), and Operating expenses such as fuel and maintenance costs (OPEX). This optimization is solved subject to several power plant and system level constraints.

The model can choose which technologies it adds to the power system from a large number of technologies and plant sizes. For each technology, characteristics such as size of plant, minimum stable generation %, heat rate at 100% and at 50%, VO&M, FO&M, start-up cost, min up/down times, maintenance and forced outage rates, and installation cost are included. Due to the complex nature of the power system capacity optimization some simplifications and compromises are needed.

In order to capture the system inflexibility and the true costs of thermal generation, level of detail of wind and solar PV variability modelling should be high. The modelling should contain sufficient amount of sample days and high granularity in order to capture the variable nature of wind and solar PV. This ensures that the model sees days and weeks with high and low variable renewable energy (VRE) generation levels as well as their intra-daily variation. In this study, the long-term model is run with 2 hour time resolution using real whole-year wind and solar data measured in Chile.

System level constraints originate from the transmission system and security of supply. The model uses three nodes – Far North, North, and Central-South Chile - with interconnectors between them. The model also includes necessary system reserves for maintaining the balance and reliability of the system at all times and weather conditions. Primary and secondary reserves are modelled together with additional reserve requirement for wind and solar PV balancing due to weather forecast errors.

Transmission expansion is not optimized in the study. Instead, the cost of transmission line additions is evaluated based on CEN’s decarbonization study, which focused on the transmission expansion. In their analysis, scenario AM06 (a) and (b) presented future generation capacity mix with high share of solar PV and wind. The cost of transmission expansion (USD per installed MW of wind and Solar PV) was taken from those scenarios and scaled up with the share of wind and solar PV added in the scenarios of this study. This study does not address HOW to connect all the new wind and solar plants to the grid, it simply estimates the costs of such transmission lines.

The model includes potential rehabilitation of old combined cycle gas power plants. Plexos decides whether it makes economic sense to rehabilitate > 30 year old gas power plants. 30 years is the age when such plants normally require a major life time extension overhaul. Plexos may rehabilitate the old plants for a cost of 300 US$/kW. This is average, some plants may require more expensive repairs, some might be possible to rehabilitate for less.
Model Inputs

The database used by the Chilean Independent System Operator (CEN) in the Decarbonization study is used as a basis for the model. It provides current generation capacities and generator properties as well as fuel prices, electricity demand, hydro inflows, and generation profiles for wind and solar.

Price assumptions of the new build options are shown in Figure 6 and Table 3 in more detail. Fuel prices assumptions are shown in Table 4. The CAPEX and fuel price assumptions for this study are provided by local Chilean consulting company Inodu and they are combined with globally respected source Bloomberg New Energy Finance (BNEF). The present long-term expansion model also considers fixed operation and maintenance (FO&M) costs, which are assumed to be 1-2% of the technology CAPEX.

Figure 6
(Left) CAPEX of the renewable energy source technology options in the long-term model. Source Inodu & BNEF.
(Right) CAPEX of the battery energy storage systems (BESS) in the long-term model. Source BNEF.
<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Heat Rate GJ/MWh</th>
<th>VO&amp;M Charge $/MWh</th>
<th>Start Cost $/MW</th>
<th>FO&amp;M $/kW,a</th>
<th>CAPEX (EPC + owner’s cost)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Open Cycle Gas Turbine Heavy Duty) OCGT HD</td>
<td>9.47</td>
<td>3</td>
<td>70</td>
<td>15</td>
<td>800</td>
</tr>
<tr>
<td>(Open Cycle Gas Turbine Aeroderivative) OCGT AERO</td>
<td>9.0</td>
<td>4</td>
<td>&lt;1</td>
<td>15</td>
<td>900</td>
</tr>
<tr>
<td>CCGT NEW</td>
<td>6.54</td>
<td>3</td>
<td>60</td>
<td>15</td>
<td>1150</td>
</tr>
<tr>
<td>Flexible Gas Engine</td>
<td>7.82</td>
<td>5</td>
<td>0</td>
<td>15</td>
<td>900</td>
</tr>
</tbody>
</table>

Table 3: Gas-fired power plant input data used in the long-term expansion model, and in the short-term dispatch model. Source: Inodu & Wärtsilä.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>100 USD/tn</td>
</tr>
<tr>
<td>Diesel</td>
<td>700 USD/tn</td>
</tr>
<tr>
<td>Gas</td>
<td>8 USD/MMBTu</td>
</tr>
</tbody>
</table>

Table 4: Fuel prices used in the long-term and short-term dispatch models. Source: Inodu.
Summary of Scenarios

<table>
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<tr>
<th>Name</th>
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<th>Coal Phase out</th>
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*Announced schedule: 1047 MW of coal is retired by the end of 2024

Table 5 Summary of studied scenarios.

Scenario Results

This section presents the scenario simulation results. The results of each scenario are first introduced, and then each scenario is compared to the previous ones with particular focus on total power system generation costs, share of renewables, and emissions.

Base Case

Base Case investigates a potential future outcome where most of the coal generation remains in the system. Only the announced and committed 1047 MW retires by the end of 2024. The price and technology inputs are as presented in model input section.

The resulting capacity mix and annual electricity generation are presented in Figure 7. The figure on the left shows the evolution of the installed generation capacity over the study period, and the peak electricity demand (dotted line). The figure on the right illustrates the annual electricity generation by technology, and the demand (dotted line).
The results show that future capacity additions consist mostly of solar PV and wind with batteries and flexible gas generation. The new capacity additions are presented in Table 6.

Most of the flexibility that is required to balance the variable renewables is provided by reservoir hydro with some support from batteries, flexible gas generation and the remaining coal plants.

Battery capacity in the system is mostly for energy shifting purposes. As seen in Figure 7, the share of PV generation increases after 2030 due to the declining prices of energy shifting batteries. In the generation figure, the (green) energy above load line indicates the generation from storage, i.e., shifted energy. This energy is mainly excess solar PV generation that is stored at daytime and discharged at night.

As seen in the figure, some CCGT capacity is retired during the planning period - approximately 70% of the installed > 30 years old gas plant capacity is retired. The retiring CCGTs are mainly replaced by flexible gas generation which saves money and reduces emissions due to their more efficient capability to balance renewables.

Coal power plants operate in a system with a growing share of variable renewable generation. As a result, coal generation is subject to highly cyclic operation as they need to follow the highly variable net load (net load = demand minus renewable generation), and increasingly need to provide reserves (up-ramp capability) to balance weather forecast errors. The capacity factor of coal plants decreases year-by-year, making their operation steadily less economical.

**Table 6** Capacity additions in the Base Case.

For this table and others to follow BESS (Battery Energy Storage System) includes both power batteries for ancillary services, and 6 hour energy shifting batteries.
The share of renewable increase remarkably during the study period, reaching 85% in 2040 - see in Figure 8. Most of the wind and solar PV additions supply the increasing demand, which is seen as growth in the renewable share. However, coal plants are still generating in the future, which is why emissions are decreasing only by 40%.

The annual system total generation cost with its components is illustrated in Figure 9. OPEX is declining during the study period as imported fuel costs and other variable costs begin to fall. At the same time, fixed CAPEX component becomes larger as the cost of renewables is mostly CAPEX. The figure also shows the evaluated CAPEX of transmission expansion. One should note that figure includes only the CAPEX of new generation capacity and transmission additions - the capital expenses of existing assets are not presented. Therefore, the CAPEX component has quite little impact at the beginning of the study period.
Scenario 1

This scenario introduces the phasing out of coal by 2040. The first 5 years are following the announced schedule after which the retirement schedule from CEN's decarbonization study is used. In brief, older coal plants are retired first. The results – generation capacity mix and annual electricity generation by technology - are illustrated in Figure 10.

Once coal phases out, more wind and solar PV is installed into the system, compared to Base Case. Plexos also builds battery storage and flexible gas generation all through the period. The total capacity additions over the study period are shown in Table 7.

Once coal is retired the system is made up of mainly renewables: solar PV, wind, which are balanced by hydro, battery storage and flexible gas. This can be seen in Figure 11 presenting the share of renewables. As a result of the coal retirement, emissions also begin to fall faster.

The right-hand side figure shows the total cost difference between Scenario 1 and Base Case. The costs are similar until 2025, after that the cost of Scenario 1 starts to increase. The cost of phase out is 2.5 BUSD, compared to base case, including the generation cost and transmission CAPEX. This cost difference is approximately 2.8% of the total cost.
Figure 11 Share of renewables and amount of emissions over the study period (on the left) and cumulative cost total system cost compared to the Base scenario (on the right).

Scenario 1a

This scenario follows the expansion plan of Scenario 1. The only difference is that the flexible gas generation (utilizing modern gas engines) is replaced with high efficiency combined cycle gas turbines (CCGT). The capacity mix and generation is presented in Figure 12 where the new gas-fired capacity is displayed as CCGT NEW. Otherwise, the capacity additions are the same as Scenario 1.

Figure 12 Scenario 1a capacity mix (left) and annual electricity generation (right).
The results compared to the previous scenarios are studied in **Figure 13**. With the CCGTs, a high share of renewables and low emission can be achieved but not as effectively as in **Scenario 1** where the flexible gas generation is utilized more.

With a high share of renewables, high efficiency of a gas power plant is less important as the operation of the thermal fleet is more cyclic (more starts and stops and partial loading). This kind of operation is challenging for CCGTs which e.g. at every start must boil large quantities of water under high pressure and temperature. Stopping a plant takes time, and one needs to wait minimum 4 hours for the plant to cool down before it can be restarted. This leads in practice to maintaining such plants on line, on minimum stable output (which is typically about 50 % of the full output), even when they are not really needed. Thus, running these plant burns gas while it forces more renewable curtailment, increasing the cost of operation. The total cost compared to other scenarios are shown in **Figure 13**.

**Figure 13** Share of renewables, amount of emissions and cumulative total system cost compared to the Base scenario.
Scenario 1b

In this scenario, gas price is reduced from 8 USD/MMBtu to 6 USD/MMBtu from 2028 onwards, which represent an assumed gas price level from Argentina. Otherwise, the scenario is the same as Scenario 1.

The results of scenario 1b are shown in Figure 14. The share of renewables, emissions, and total cost compared to the previous scenarios are shown in Figure 15.

Lower gas prices make the phasing out of coal more affordable as the generating costs of gas fired generation would fall resulting in a generating cost that is similar to coal, and thus increase the operating hours of gas power plants. When compared to Scenario 1, the results show that a portion of solar PV, battery storage and wind power capacities are replaced by gas-fired generation. The capacity additions are displayed in Table 8.

![Figure 14](image)

**Figure 14**
Scenario 1b capacity mix (left) and annual electricity generation (right).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Solar PV</th>
<th>Wind</th>
<th>BESS</th>
<th>Flexible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity built [GW]</td>
<td>20.7</td>
<td>15.6</td>
<td>8.8</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**Table 8** Capacity additions in Scenario 1b
Figure 15 Share of renewables, emissions and cumulative cost total system cost compared to the Base Case scenario.
Scenario 1c

This scenario investigates the impacts of adding an HVDC line between Far North and Central-South. To accomplish this, a 2 GW line is added in 2029 at a price of 1.5 BUSD. The resulting capacity mix and annual generation are presented in Figure 16.

The addition of the line results in an increase of solar PV installation in the North in comparison to Scenario 1. More affordable solar PV generation begins to enter the system as in the North solar resources are more favourable than in the southern region of the country. In addition to solar the line also allows for more wind capacity installation in the north area.

The addition of the line does not have a noticeable impact on the emissions or renewable share but it does result in a reduction in the cost of generation by approximately 80 MUSD per year.

However, once the cost of adding the line is considered, this scenario becomes more expensive in relation to Scenario 1, meaning that the line addition is not reducing the total generation costs. The energy shifting batteries start to become economic in late 2020’s, reducing the benefit of the HVDC line - similarly to a HV line addition, energy shifting batteries mitigate bottlenecks and enable a higher share of renewables. One should note that the line is likely to improve system reliability and controllability - the value of which is not estimated in this study.

![Figure 16](image_url)

Scenario 1c capacity mix (left) and annual electricity generation (right).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Solar PV</th>
<th>Wind</th>
<th>BESS</th>
<th>Flexible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity built [GW]</td>
<td>22.1</td>
<td>16.4</td>
<td>9.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Table 9 Capacity additions in Scenario 1c.
Figure 17 Share of renewables, emissions and cumulative total system cost compared to the Base Case scenario.
### Scenario 1d: Dry Hydrology

Hydro power plays an important role in Chile as a highly valuable resource of flexibility for balancing wind and solar generation. However, the trend of hydro inflows has declined over the last few years.

Again, this scenario is the same as Scenario 1, but with lower availability of hydro power: 21 TWh over the study period, consistent with the level of hydro generation over recent years.

When analysing the quantity of dispatchable thermal power in the system, such a low hydro year scenario becomes the dimensioning one. It is therefore important to study such years and the impact it has on the capacity mix. The results of scenario 1d are shown in Figure 18. The share of renewables, emissions and total cost compared to the previous scenarios are shown in Figure 19.

In this scenario Plexos adds more wind power and flexibility, compared to Scenario 1. With more wind generation in the system, the hydro power is better utilized balancing wind generation instead of producing electricity on high output. Gas-fired generation is also utilized more but the installed capacity does not differ much from Scenario 1. Total generation costs increase as more wind and solar power plants are needed, and some more gas is used to produce the electricity. The capacity additions are summarized in Table 10.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Solar PV</th>
<th>Wind</th>
<th>BESS</th>
<th>Flexible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity built [GW]</td>
<td>20.6</td>
<td>21.2</td>
<td>9.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**Table 10** Capacity additions in Scenario 1d.
Figure 19 Share of renewables and amount of emissions over the study period and cumulative cost total system cost compared to the Base scenario.
Scenario 2
Phasing Out Coal by 2030

This scenario investigates what would be the optimal capacity mix for Chile, and how the system would be dispatched with a faster retirement of coal. In Scenario 2, Plexos gradually retires all coal power plants by 2030. The results are presented in Figure 20. The total cost and emission intensity compared to the previous scenarios are shown in Figure 21.

The retirement of coal creates space for the installation of more renewables, especially wind, at a much faster rate than in the previous scenarios. The capacity additions can be seen in Table 11.

Along with the wind, a greater amount of flexible gas generation is built. This type of capacity is necessary to balance the increasing wind power, to provide fast starting system reserves, and to maintain the necessary dispatchable capacity margin in the system.

An accelerated phase out of coal drastically reduces national emissions as seen in Figure 21, indicating that a majority share of the current emissions are being produced by coal. The accelerated coal phase out increases the system cost in the short term, in the 2020s, due of the early investments in the capacity to replace coal.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Solar PV</th>
<th>Wind</th>
<th>BESS</th>
<th>Flexible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity built [GW]</td>
<td>19.3</td>
<td>20.0</td>
<td>8.0</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Table 11 Capacity additions in Scenario 2.
Figure 21 Share of renewables, emissions and cumulative total system cost compared to the Base Case scenario.
**Scenario Summary**

*Table 12* summarizes the (cumulative) simulation results of total generation costs (OPEX+FO&M+CAPEX), transmission CAPEX and total cost as well as emissions over the study period (2020-2040).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Generation Cost BUSD</th>
<th>Transmission CAPEX BUSD</th>
<th>Total Cost BUSD</th>
<th>Total Emissions MtnCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>83</td>
<td>5</td>
<td>88</td>
<td>595</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>84</td>
<td>6</td>
<td>90</td>
<td>478</td>
</tr>
<tr>
<td>Scenario 1a</td>
<td>86</td>
<td>6</td>
<td>93</td>
<td>489</td>
</tr>
<tr>
<td>Scenario 1b</td>
<td>81</td>
<td>6</td>
<td>87</td>
<td>530</td>
</tr>
<tr>
<td>Scenario 1c</td>
<td>83</td>
<td>8</td>
<td>91</td>
<td>475</td>
</tr>
<tr>
<td>Scenario 1d</td>
<td>93</td>
<td>7</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>88</td>
<td>8</td>
<td>96</td>
<td>280</td>
</tr>
</tbody>
</table>

Plexos scenario simulations show that coal phase out is necessary to reach low levels of carbon emissions. The phase out brings along a total cost increase of a few % in most scenarios, but it also allows faster additions of renewables and removes most of the imported fuel cost risks. Along with the renewables, storage need to be added, but due to the steep downward learning curve of battery cost, Plexos proposes in most scenarios to start installing them after 2028, mainly for solar energy shifting.

Flexible gas generation needs to be added to balance the system, provide reserves, maintain capacity margin, and to allow for maximum utilization of renewables. As a world-wide market for synthetic will emerge - during the next decade or so - for recycled fuels (LNG, methanol etc), the flexible gas generation capacity will as the final step be converted to use those “renewable” fuels, and thereby the mission to reach 100 % decarbonized power system will be finished.

Phasing coal out at a faster rate has minimal impact on total generation costs, but reduces emissions drastically.

Investment requirements to new generation capacity for the scenarios are displayed in Figure 22. The 21 year timeline has been divided into 4 sections to illustrate the timing of investments. In Base Case is equally spread over the study period as most of the coal remains in the system. In scenarios 1, 1a, 1b, 1c, and 1d, more investments take place before 2040 which is caused by the investments in new generation as the last coal plants are phased out. Generally, most investment potential appears when coal generation is phased out. This is also seen in the case of Scenario 2 where the last coal is closed in 2029.
Figure 22 Investment needs in 5 year increments.
Dimensioning of Flexible Generation

The installed capacity in all scenarios contains a large share of renewable energy sources, most of which are weather and climate dependent. Wind, solar PV, and hydro form a good basis for carbon free generation but their generation output varies from hour to hour, seasonally and year to year. Therefore, this section investigates the worst case scenario, which dimensions firm and dispatchable thermal capacity and battery storage in the system. This scenario is built on Scenario 1 with the following dimensioning criteria:

- The uncertainty related to variable renewable generation forecasting is increased to 30% of wind generation output, plus 20% of solar PV output. The system needs to have adequate reserves to balance weather forecast errors at all times. In reality the dispatcher (in this case Plexos) must ensure that there is at all times adequate and fast dispatchable capacity to ramp up the output when weather conditions deviate from the forecast.

- Dry hydro inflow scenario is assumed, i.e., 21 TWh of annual hydro generation.

The resulting capacity additions are presented in Figure 23. Plexos adds battery storage for reserve production and flexible gas generation for balancing already in the early 2020's. Later in 2020's, energy shifting batteries are added together with additional flexible gas generation.

Figure 23 Capacity additions of flexible gas generation and battery storage to ensure security of supply while adding renewables as per scenario 1.
The path to 100% renewable system is summarized in Figure 24. The numbers are from Scenario 1 until the year 2040 and then extrapolated onwards. The remaining 4% of non-renewable generation in 2040 will use biogas or synthetic gas which results in a 100% renewable system. In 2040, “Baseload gas / Peakers” contains mostly peaking power plants that are assumed to retire by 2050 and become replaced by modern flexible units running on bio or synthetic fuels.

Figure 24 Path to 100% renewables of Chile.
Comparison of Flexibility Options

Long-term expansion optimization has computational limitations due to the size of the mathematical optimization task. Some technical details / constraints need to be left out of the model to keep the problem solvable and to avoid unrealistic computing times.

A good practice is to compare the optional flexible generation technologies with an accurate shorter term dispatch optimization model, e.g. for 1 year, picking the year in the latter part of the study period to see how they perform with the renewables. In these short term models one can include all important technical constraints and can thus more effectively display the power system inflexibilities, and calculate the costs as well. The new parameters – often called technical constraints - are included for each thermal power plant in the system: ramp rates up and down (%/min), minimum up and down times (min), and minimum stable operation levels (%). These were partly considered in the long-term expansion model but in short term model they can be defined for each generation unit. Furthermore, the best dispatch can be solved with higher 1 hour granularity.

Short-term model brings forward the challenges of balancing the variability of wind and solar PV, in real life, hour-by-hour. Inflexible power plants, which cannot be switched off and restarted again relatively fast, must remain on-line at minimum load even when they are not needed, burning fuel on poor efficiency, and producing high emissions. At the same time wind and solar power may have to be curtailed. Short-term dispatch model optimizes the system operation hour-by-hour by looking several days forward multiple times, changing parameters one by one, and finding the most cost-efficient way to operate the system. Short term model does not add or retire any plants from the system, it just finds the optimum dispatch for the given power plants.

This section compares different flexible technology options by their ability to provide cost-efficient flexibility for the power system with a high share of wind and solar PV. In order to illustrate system operation after coal, with high share of renewables, we focus on year 2035, and we study Scenario 2, where coal is phased out by 2030. The capacity mix is shown in Figure 20. Even in scenarios with a slower coal retirement timeline, a similar kind of situation is discovered, but a few years later.

Scenarios:

- Compared technologies are aeroderivative gas turbines (GT AERO), heavy duty gas turbines (GT HD), combined cycle gas turbines (CCGT NEW), and modern gas engines (ENGINE). The technical parameters of these power plants are shown above in Table 3.

- As suggested by the long-term expansion model, 3 GW of flexibility is included in the system in 2035. The short-term model is run once with each flexible generation technology - with either GT AERO, GT HD, CCGT NEW or ENGINE.

Results:

- Figure 25 illustrates the system dispatch over a week in the summer of 2035, with modern gas engines (orange colour) providing the flexibility. There is no coal generation in the system. A majorshare of the demand is supplied by wind, solar PV and hydro. Gas-fired generation is mainly dispatched at night (no solar) and when wind generation output is low. During the day, renewable generation exceeds the system demand. This excess generation is stored in energy shifting battery storage, and discharged at night. The need for flexibility is evident in the graph - engines and hydro continuously ramp up and down to balance the variability of wind and solar PV.
Figure 26 illustrates the hourly generation profiles of the compared flexible generation technologies during the same week in 2035. ENGINE is the same generation profile as above in Figure 25 whereas Figure 26 also displays the hourly profiles for the other technologies (GT AERO, GT HD, and CCGT NEW).

Engines as well as aeroderivative gas turbines are continuously balancing the system, starting and stopping multiple times per day, cycling continuously. GT AEROs get less running hours than modern gas engines due to their lower efficiency. Due to the high starting costs and considerably lower efficiency, GT HDs are running clearly less during the week. CCGT have the highest amount of running hours but at the same time, they are not able to balance the system as efficiently as modern gas engines and aeroderivative gas turbines. Some CCGTs stay online during the daytime and all through the week as they cannot otherwise be restarted fast enough for the evening ramp when the sun sets. This forces curtailment of wind and solar power, replacing them by burning fuel and producing emissions.

Note: “CCGT” in the graph above is the older combined cycles which are still in the system.
Annual capacity factors, and number of starts are presented in Figures 27 and 28. These figures are in line with the observations from Figure 26. CCGTs have the highest utilization while GT HDs show the lowest, both these technologies have the least amount of starts due to their high starting costs.

CCGTs reach a capacity factor of 40 %, which is low for a steam power plant. They start only 1-2 times per week, and do their balancing by alternating their output between minimum and full load, not by going off-line and on-line. This obviously does not reflect the solar cycle and wind variations, and is not a very efficient operation mode for CCGTs.

Aeroderivate gas turbines operate on a capacity factor of 15 %, and heavy duty gas turbines slightly below 15 %. Due to the higher electrical efficiency, and no starting costs, modern gas engines reach a capacity factor of 21 %, which is fairly typical for such machines in a high renewable power system e.g. in Texas, USA. Gas engines start more than once per day, running on the average 4 h per start, while the heavy duty gas turbines are only started 1-2 times per week and run 16 h per start.

![Figure 27 Annual capacity factors.](image1)
![Figure 28 Annual starts per unit.](image2)
Finally, the total system generation cost comparison for the flexible generation technologies is shown in Figure 29. The figure illustrates the annual system level generation cost difference compared to the lowest cost option, modern gas engines. The cost incorporates all power system operation cost (fuel cost, start-up cost, variable O&M of all the power plants in the system), fixed O&M, and the annualized CAPEX of the installed capacity.

Having flexible generation available enables the dispatcher to operate the inflexible assets in the system in a more efficient manner. Also, wind and solar curtailment is minimized as the thermal plants can rapidly go off-line. And fast starting flexible generation can provide the wind and solar forecast error reserves from stand-still, burning no fuel and producing no emissions. For the dispatcher they provide a strong tool to ensure system reliability at all circumstances, even when the weather does not follow the forecasts and large quantities of e.g. wind generation may disappear rapidly from the system. The savings caused by flexible generation take place all over the system, not only in the flexible power plant itself.

Modern gas engines provide the lowest total generation cost for the Chilean power system, compared to the other alternative flexible generation options. Traditional thinking is that CCGTs would provide the lowest cost as they offer higher efficiency than the modern gas engines, but in the future there is no base load available for thermal plants. CCGT’s cannot start and stop as frequently and fast as the weather condition changes would require and also have a higher CAPEX than the other technologies. Adding more inflexible CCGTs in power systems with high national renewable targets brings a major risk of stranded assets as has already happened in Germany and Texas, with closures of new modern CCGTs only after a few years of operation.

Figure 29 shows annual savings during 2035, which accumulate over time. Based on the long-term model, the annual capacity factors of the flexible gas technology remains fairly stable over the years i.e. the savings in Figure 29 are likely be repeated every year. Thus, in ten years, flexible gas engines would save nearly 500 million USD compared to aeroderivative turbines and 3.5 billion $ compared to combined cycle gas turbines, and enable higher utilization of renewables and faster reduction of carbon.
Conclusions

This study searched for the optimal path for developing the Chilean power system towards 100% decarbonization, using the modelling software Plexos. Several “what-if” scenarios were studied. The overall objective was to find paths providing both competitive generation costs and low emissions. The modelling inputs for expected future technology prices are from reputable sources, such as Bloomberg and Inodu.

Solar PV, wind and hydro will have a central role and generate majority of the electricity in the future. Storage, together with hydro and flexible gas generation, will balance system, maintaining stability and balancing the variability of wind and solar PV. Storage will also shift mainly solar PV generation from day to night, starting in the North as soon as battery storage capacity costs have decreased adequately.

In the early years, coal generation supplies a large share of electricity but it is also responsible for the majority of the CO₂ emissions. Provided that the emissions costs remain low, coal would remain competitive through the study period. However, increasing share of wind and solar PV generation require flexibility from the thermal power generation, which coal power plants do not provide. It is vital for the thermal fleet to be capable of shutting down and restarting rapidly when weather conditions change. For coal plants, this takes days, and they need to be phased out before one can reach truly high renewable penetration in the system.

The most economic way to replace coal is with wind and solar PV, and this also leads to dramatic CO₂ emission reduction and converts costs from fuel import Opex to highly predictable Capex. Chile fortunately has a relatively large capacity of flexible hydro, which can balance the volatility of renewables especially in Central-South regions and during wet years. Chile needs to add 4 GW of flexible thermal generation to ensure system stability and security of supply during all weather and climate conditions.

In addition to the Long Term expansion plan this study compared different flexible thermal technologies to understand their performance and impact on total generation cost. There are distinctive economic differences between the technologies.

During the path to 100 % thermal power plants need to transit from base load operation to dynamic wind and solar balancing and to providing critical power for the systems during extreme weather conditions. As tempting as it might be to try to use highly efficient CCGT-plants in this application, they would due to their inflexibility disable efficient utilization of renewables, and burn fuel and produce emissions even when it is not necessary. In Chile in 2035 the annual cost difference of using CCGTs instead the most efficient flexible generation option, modern gas engines, is $350 million. The era of large inflexible steam power plants is definitely approaching its end, and no nation with high ambitions on de-carbonization should consider adding any such power plants to the power system - risk for stranded assets is more than obvious. Gradual retirement is the way to go.

Plexos did not find a role for solar CSP and geothermal generation due to excessive cost. However, time will show what role they could play in Chile in case a strong capital costs reduction took place.
Chile is fortunate to have some of the best wind and solar resources in the world, which provides opportunity to develop a cost effective and clean power system. Chile can show the world a solid and fast path to total decarbonization. The transition is a major opportunity for utilities and investors as large quantities of new generation and storage will be needed. To enable these investments, changes to the regulatory framework are necessary - current electricity market does not provide any realistic incentives for investors to construct flexible generation and storage. Studying the electricity markets in Texas and Australia (NEM) provides one view of how the open market could be developed.

Hopefully this study helps to understand and analyze some of the options for Chile to lead the way towards the 100% renewable power system.

Chile needs to add 4 GW of flexible thermal generation to ensure system stability and security of supply during all weather and climate conditions. Later on these power plants shall be converted to recycled, synthetic fuels – this will finish the mission and path to 100 % carbon free power system in Chile.
Appendix 1

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.

A Plexos model is a combination of power system data and advanced mathematical formulation, which captures the characteristics of the studied system. Figure 1 shows the power system data used in a model. 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 the figure. 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. In a short-term model, the objective is to minimize the power system operation cost for the study period.

![Figure 1: Plexos power system model.](image)
The energy landscape is in transition towards more flexible and sustainable energy systems. We envision a 100% renewable energy future. Wärtsilä is leading the transition as the Energy System Integrator – we understand, design, build and serve optimal power systems for future generations. Engines and storage will provide the needed flexibility to integrate renewables and secure reliability.

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Path to 100% renewables
Chile