PATHWAY TO 100 % CARBON NEUTRAL POWER SYSTEM – CASE CHILE

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PURPOSE OF THE STUDY

Study seeks the optimal way to decarbonize electricity in Chile by 2050

PRESENTATION

- Modelling the Chilean power system
  - Approach
  - Scenarios
- Results:
  - Path to 100% carbon neutral electricity
  - Role of long-term energy storage in managing the weather
  - Optimal features of flexible power plant capacity for the transition
- Key takeaways

MODELLING THE CHILEAN POWER SYSTEM EXPANSION UNTIL 2050

Modelling approach

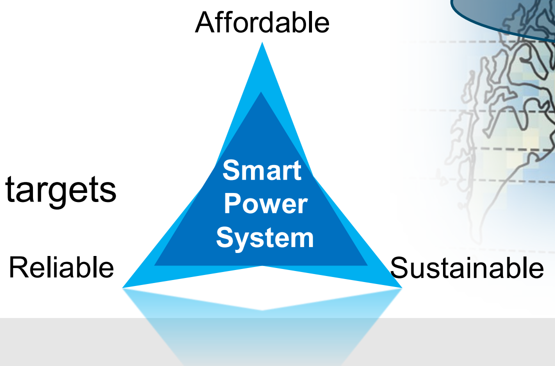
Wärtsilä has focused on modelling power systems with high share of renewables for > 10 years

Wärtsilä's second study on the Chilean power system

PLEXOS BY ENERGY EXEMPLAR — High-performance energy system simulation software

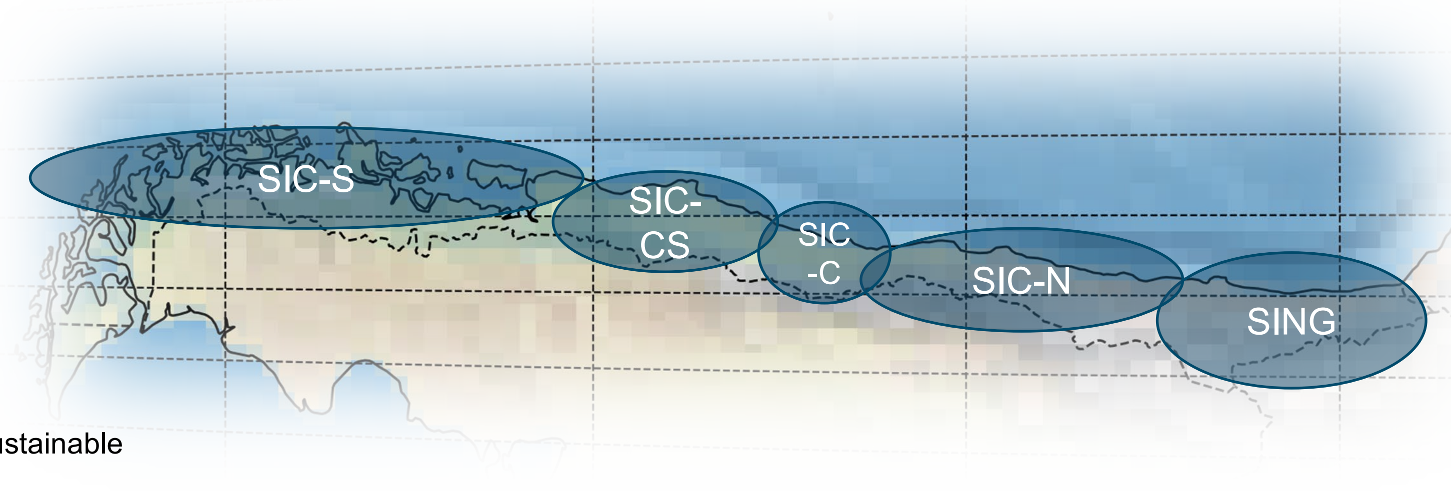
PLEXOS engineers the cost optimum Path to 100 % decarbonized power system for Chile!

1. Optimizes capacity mix
2. Serve the load, every hour
3. Balance renewables
4. Maintain reserve margin
5. Meet ramping requirements
6. Reach the carbon reduction targets



PLEXOS(TM) Inputs

- Five zones: SING, SIC-North, Central, Central-South, and South
- Power plants in SING and SIC with full parameterization
- Hourly solar and wind generation profiles for different zones
- Main transmission interconnectors, including new HVDC line in 2030
- Hourly electricity load in 5 zones (moderate load growth)
- All potential technologies included as new-build candidates
- Political decisions (Carbon neutral target, Coal phase-out)
- Model input sources: Inodu, CEN, McKinsey, Lazard



SCENARIOS

Path to 100% Scenarios:

	Retirement by Year		
Scenario	Coal	Diesel oil	CO_2 Price
S1 Coal	2030	2050	5 $/tnCO2
S2 Coal+Diesel	**2030**	**2030**	**5 $/tnCO2**
S3 Coal+Diesel Higher CO2 Price	2030	2030	30 $/tnCO2 By 2030

System technologies deep-dives:

Role of long-term energy storage in managing the weather:

- Include days with low wind and solar generation
- Compare two technology mixes to provide adequacy
  - Battery storage and renewables
  - Battery storage, renewables, and long-term storage provided by thermal capacity running on renewable fuels (PtXtP)

Optimal features of flexible power plant capacity for the transition:

- Compare flexible gas-fired technologies for x-to-Power
  - Medium speed engine
  - High speed engine
  - Aeroderivative gas turbine
  - Heavy duty gas turbine

RESULTS – PATH TO 100% CARBON NEUTRAL ELECTRICITY

STAGES OF PATH TO 100% CARBON NEUTRAL

LOCATION OF NEW ASSETS

CO_2 EMISSIONS AND RENEWABLE SHARE DURING THE PATH TO 100%

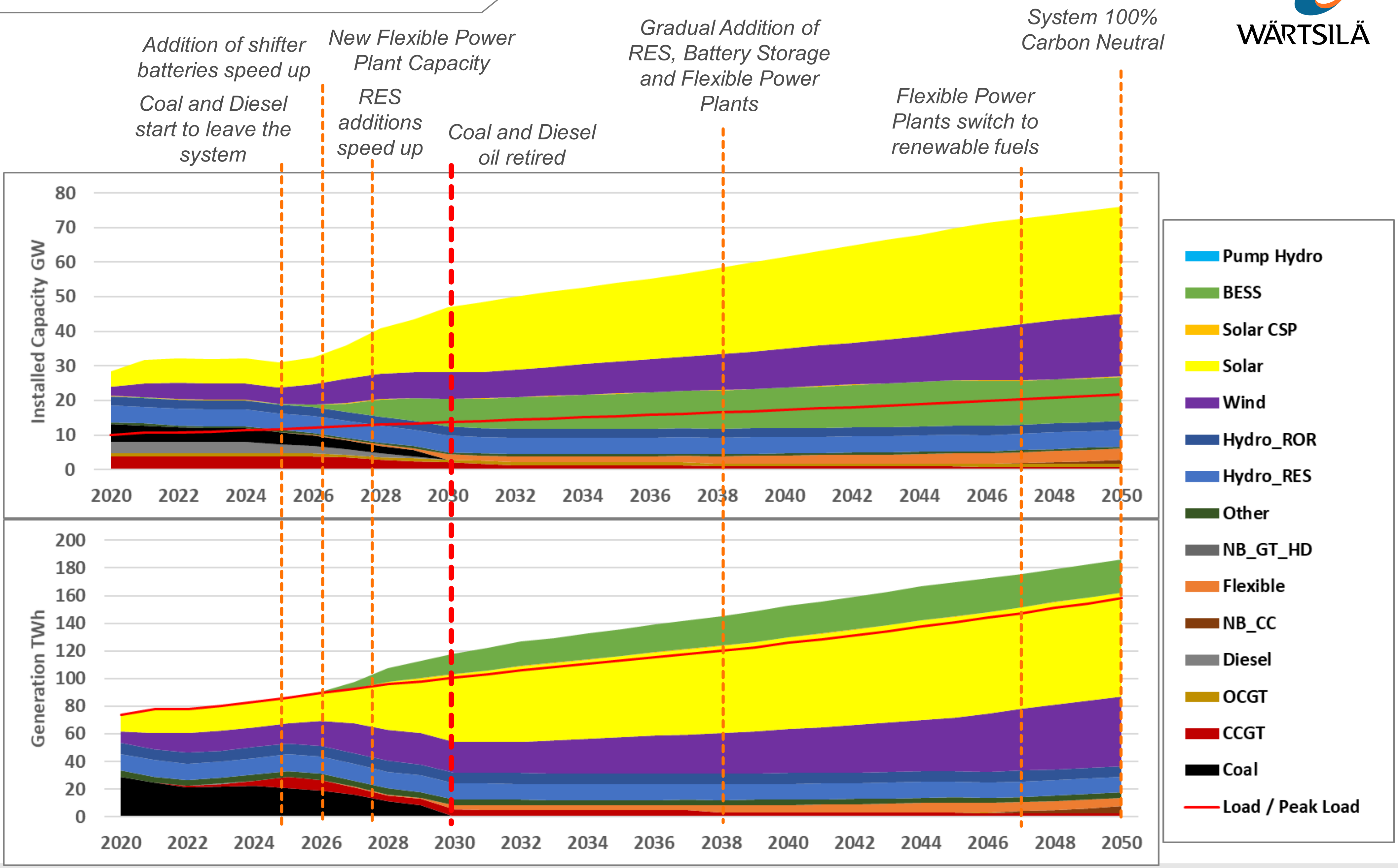
COST OF ELECTRICITY AND INVESTMENTS DURING THE PATH TO 100%

RETIRING DIESEL OIL-FIRED CAPACITY

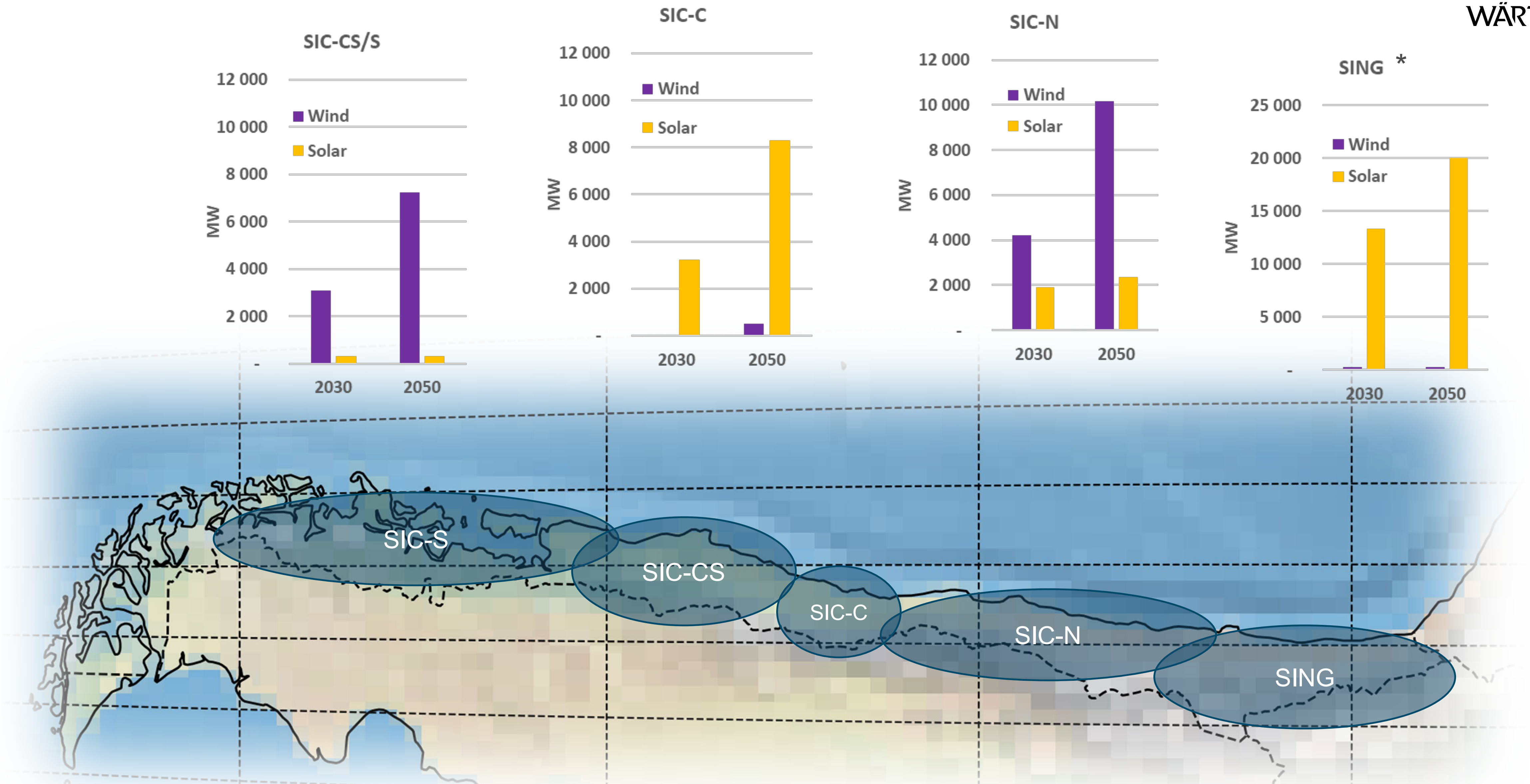
STAGES OF PATH TO 100% CARBON NEUTRAL – SCENARIO S2

High carbon emitting technologies retired by 2030

By 2030 the power system is fully capable of serving the load without coal and diesel oil

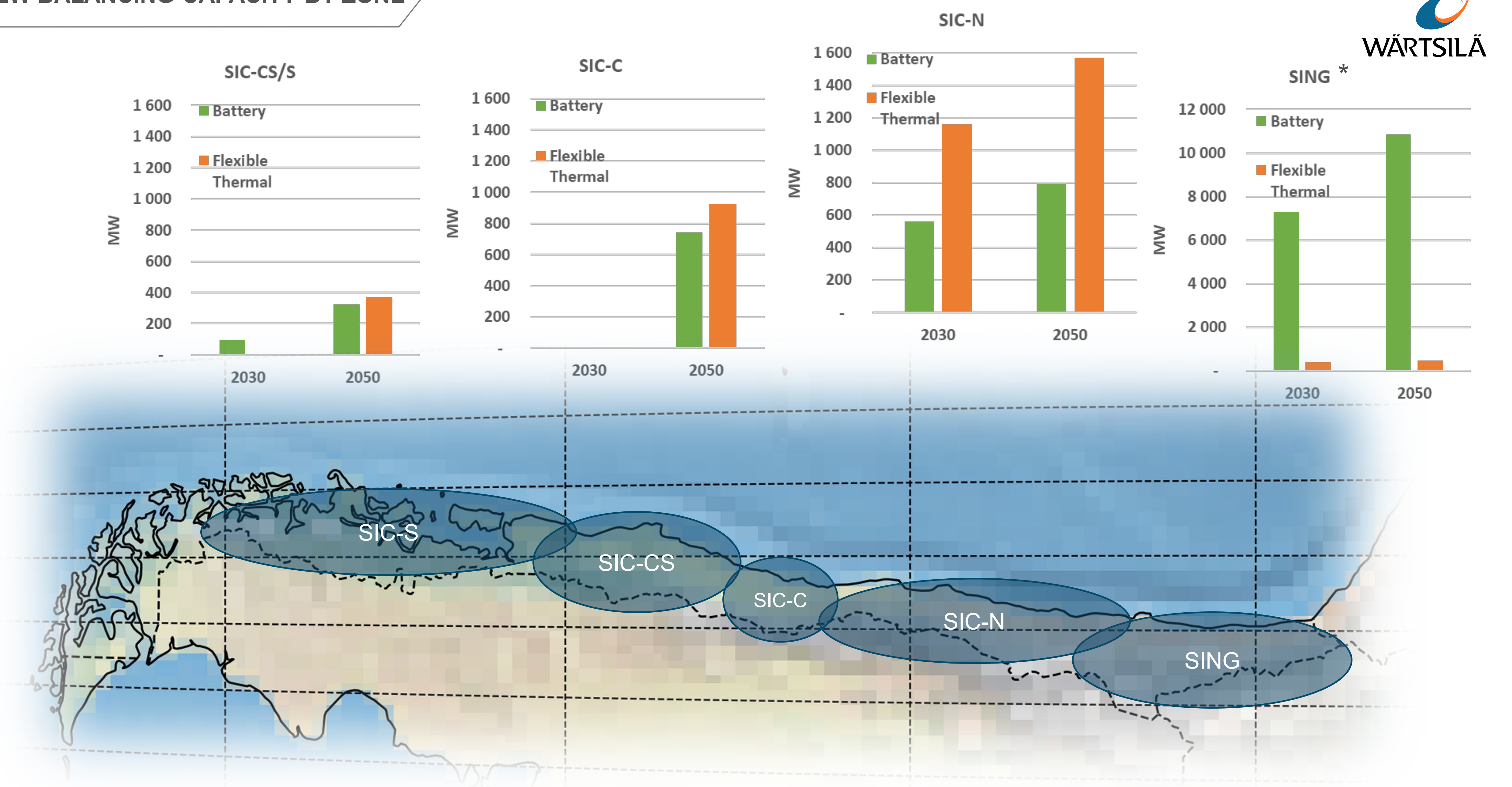


RENEWABLE CAPACITY BY ZONE



**Note difference y-axis scale*
Solar = solar photovoltaic

NEW BALANCING CAPACITY BY ZONE



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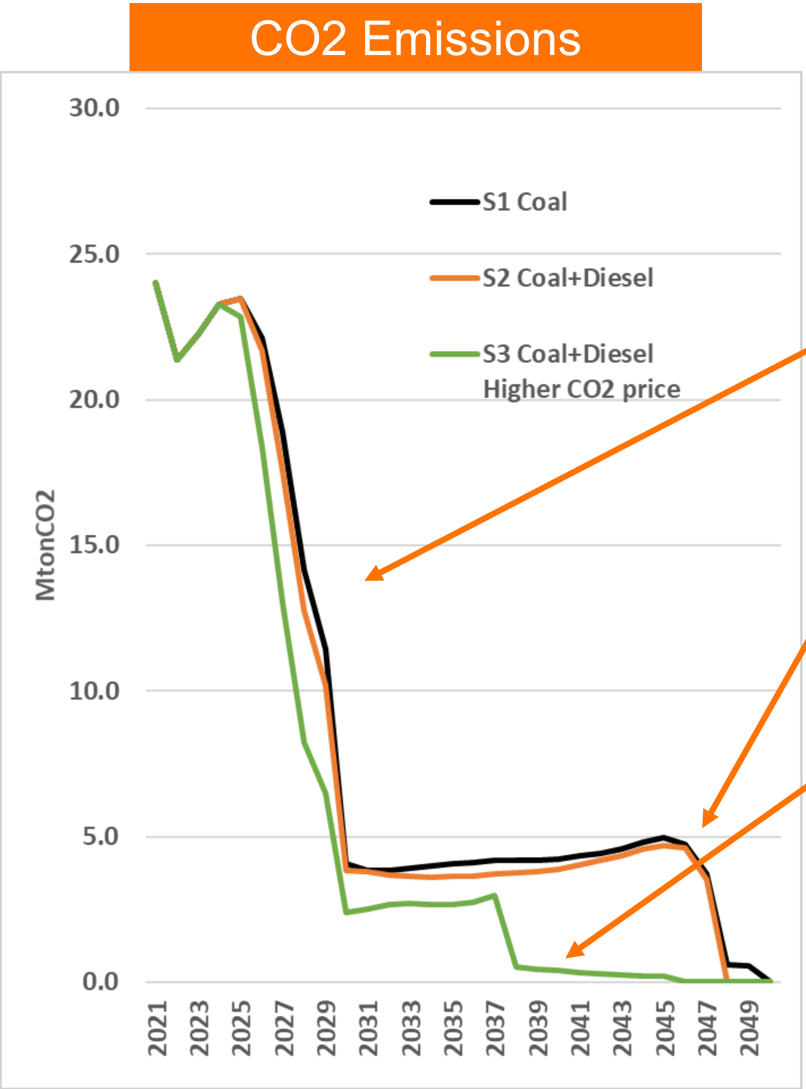
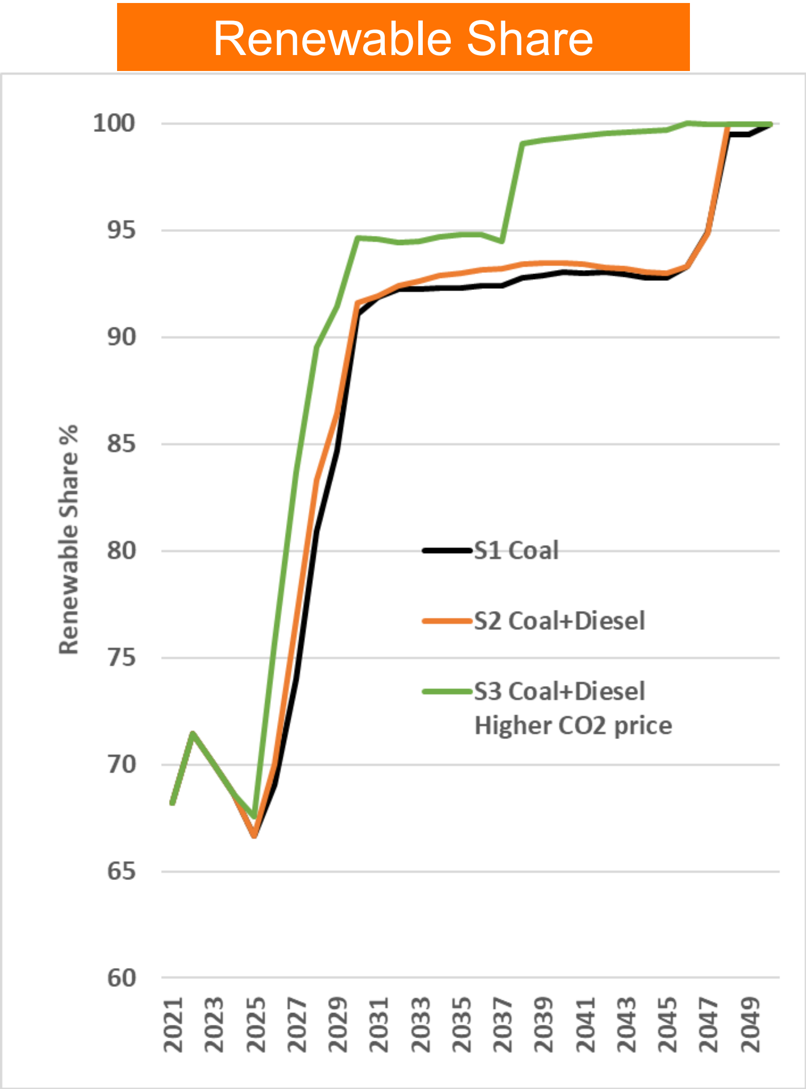


Retirement of coal and diesel-oil will have the greatest impact on the emissions and renewable share

Gas-fired thermal will switch to renewable fuels

Higher carbon tax makes fuel conversion feasible in 2038.

The conversion to renewable fuels can be done any time between 2030 and 2050



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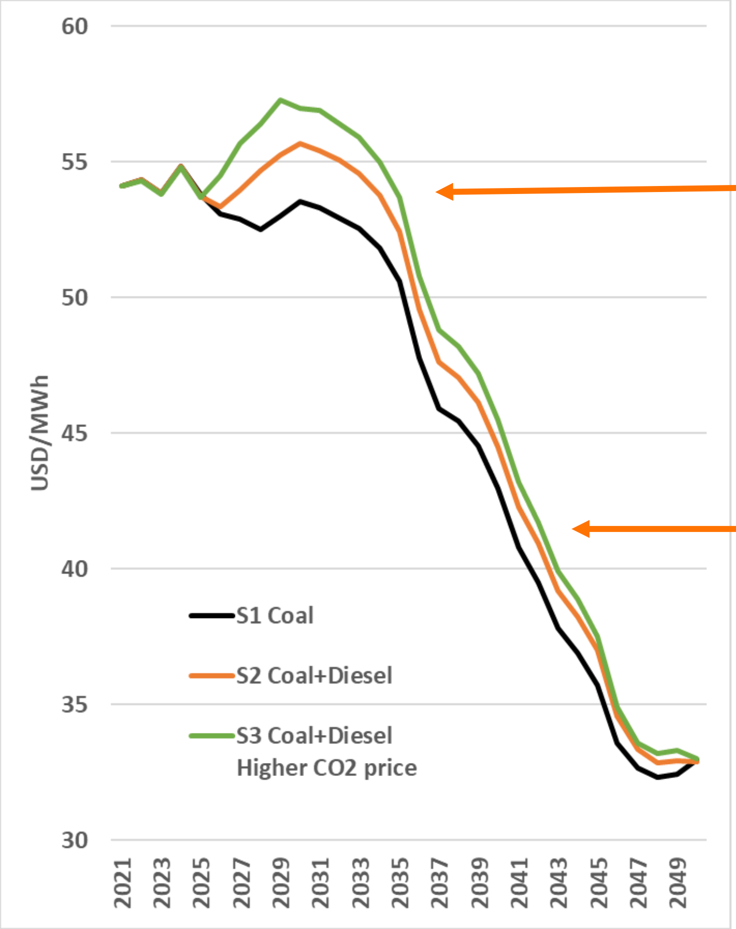
LCOE*

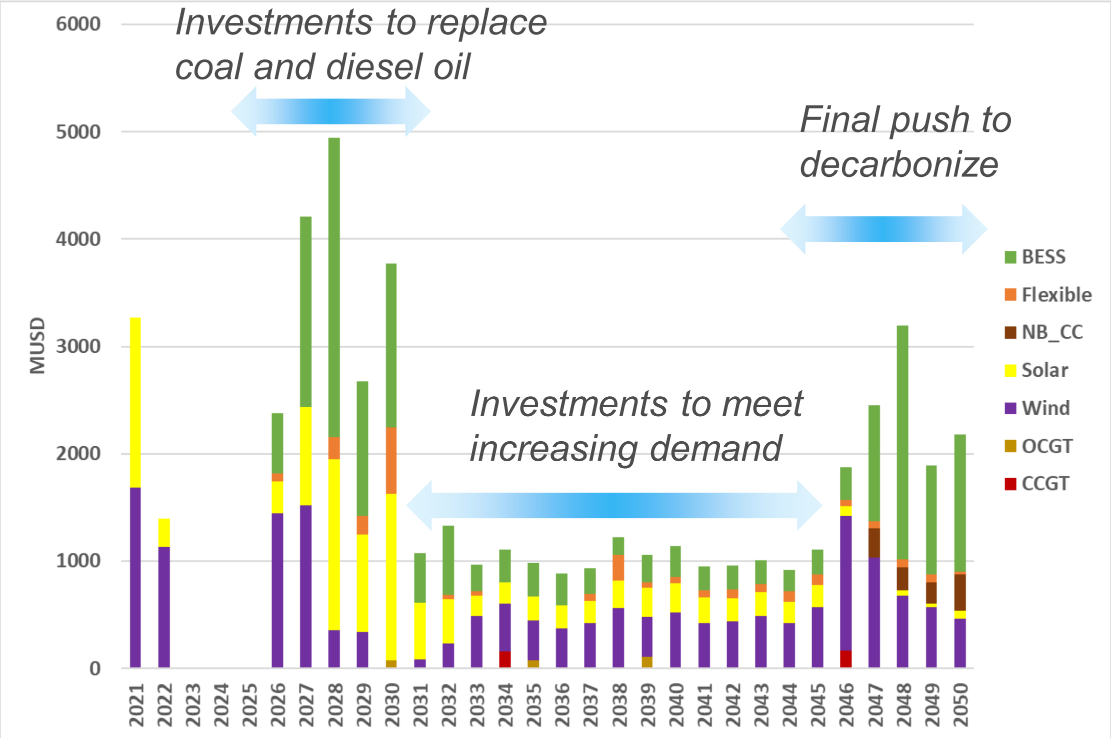


*Include generation and storage OpEx and CapEx. Wind and solar PV CapEx also includes power line to nearest substation. Cost of renewable fuel from 2 to 0.8 $/kg.

Near-term investments in clean sources enable dramatic reduction in carbon

Installation of wind and solar PV reduces the cost of electricity

Annual investments during the Path



S2 Coal+Diesel = coal and diesel retired by 2030

Total investments over the Path: 49 B$

Diesel oil-fired capacity

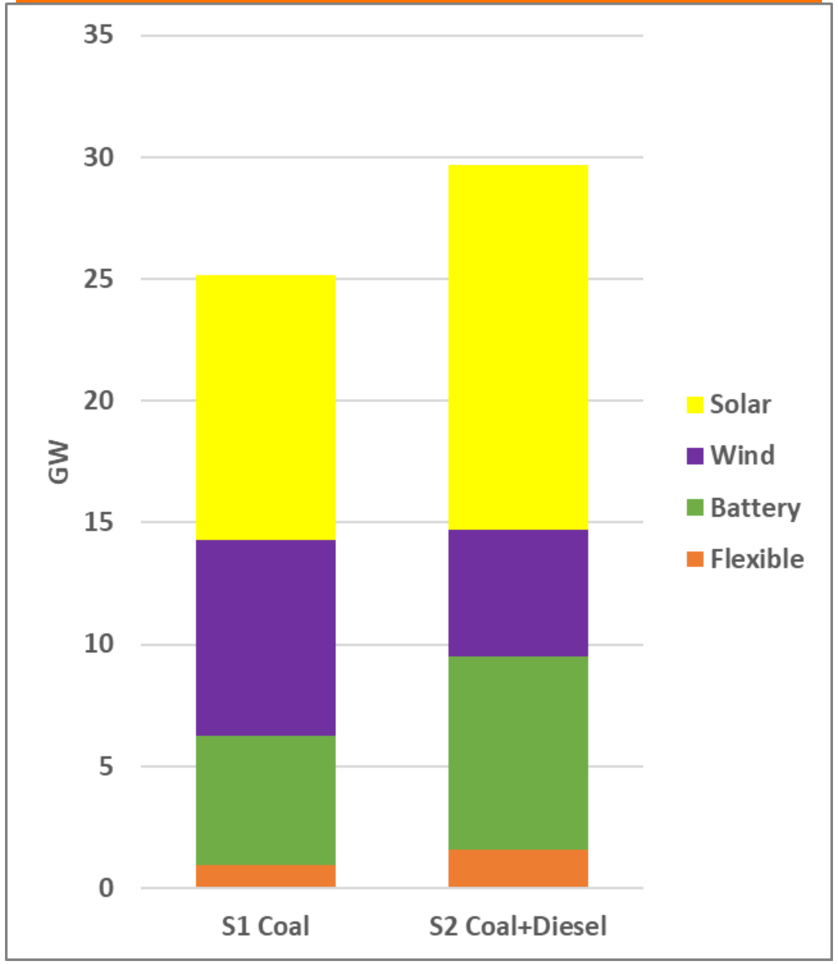
- receives capacity payments
- is expensive to dispatch
- has high carbon emissions

Retiring diesel-oil makes sense

- Is not part of carbon neutral system
- Expensive to keep and use
- Becomes replaced by
  - Clean renewables
  - Battery storage
  - Flexible power plant capacity using domestic hydrogen

  Which are part of carbon neutral system

Capacity Additions by 2030



S1 Coal = coal retired by 2030
S2 Coal+Diesel = coal and diesel retired by 2030

PATH TO 100% SUMMARY

- The cost of power during decarbonization will be drastically reduced
- Chile can reach over 90% renewable share by 2030
- Carbon neutral power system in Chile is realistic before 2050

ROLE OF LONG-TERM ENERGY STORAGE IN MANAGING THE WEATHER

Purpose

- To dimension the power system to serve the load even during extreme weather conditions

Motivation

- Path to 100% results are based on one realization of hourly wind and solar profiles

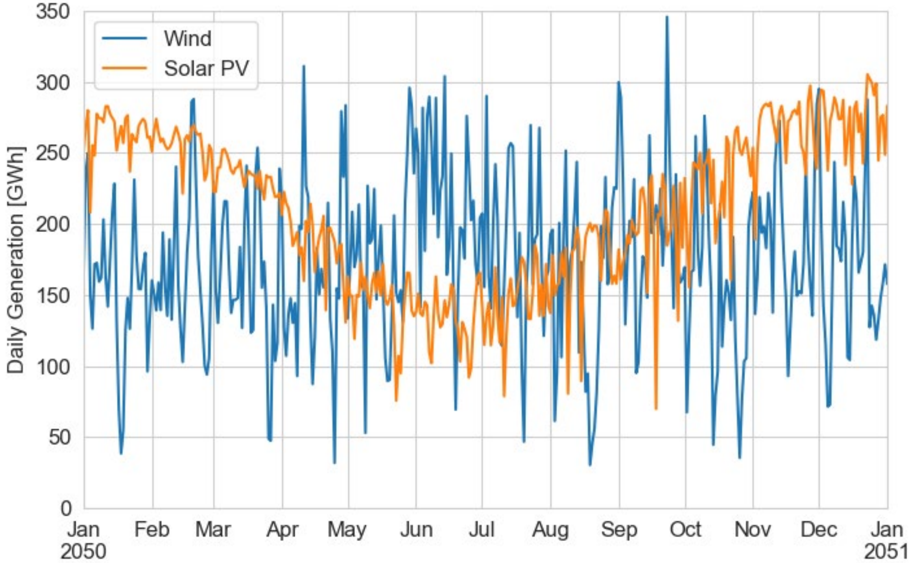
Weather in modelling for extreme days

- Low wind and solar generation days shifted on time scale to coincide

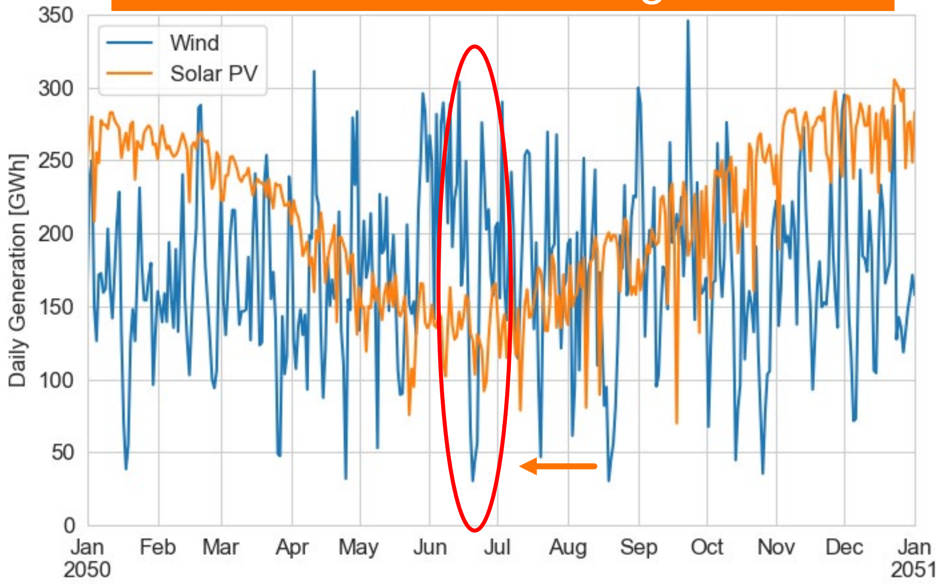
Two approaches to design the power system

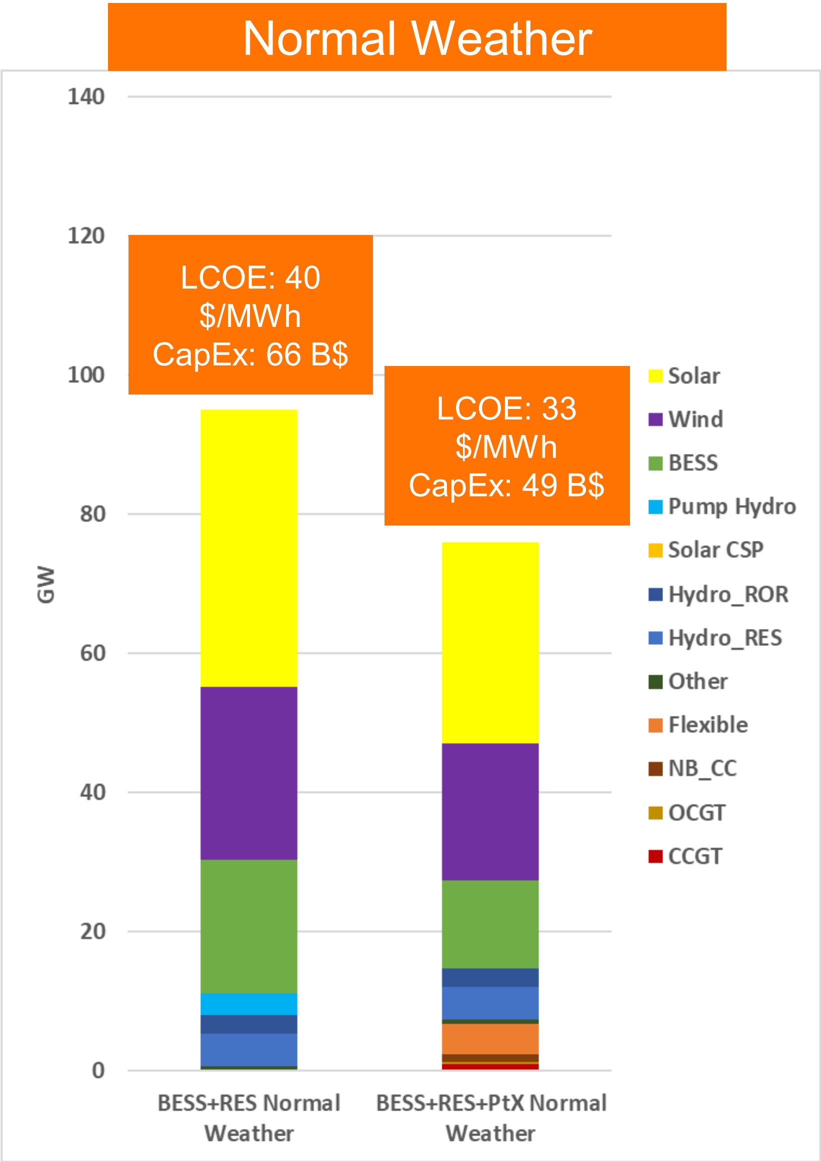
- Wind, solar and battery storage
- Wind, solar, battery storage and Power-to-X-to-Power

Normal wind and solar PV generation



Low wind and solar PV generation





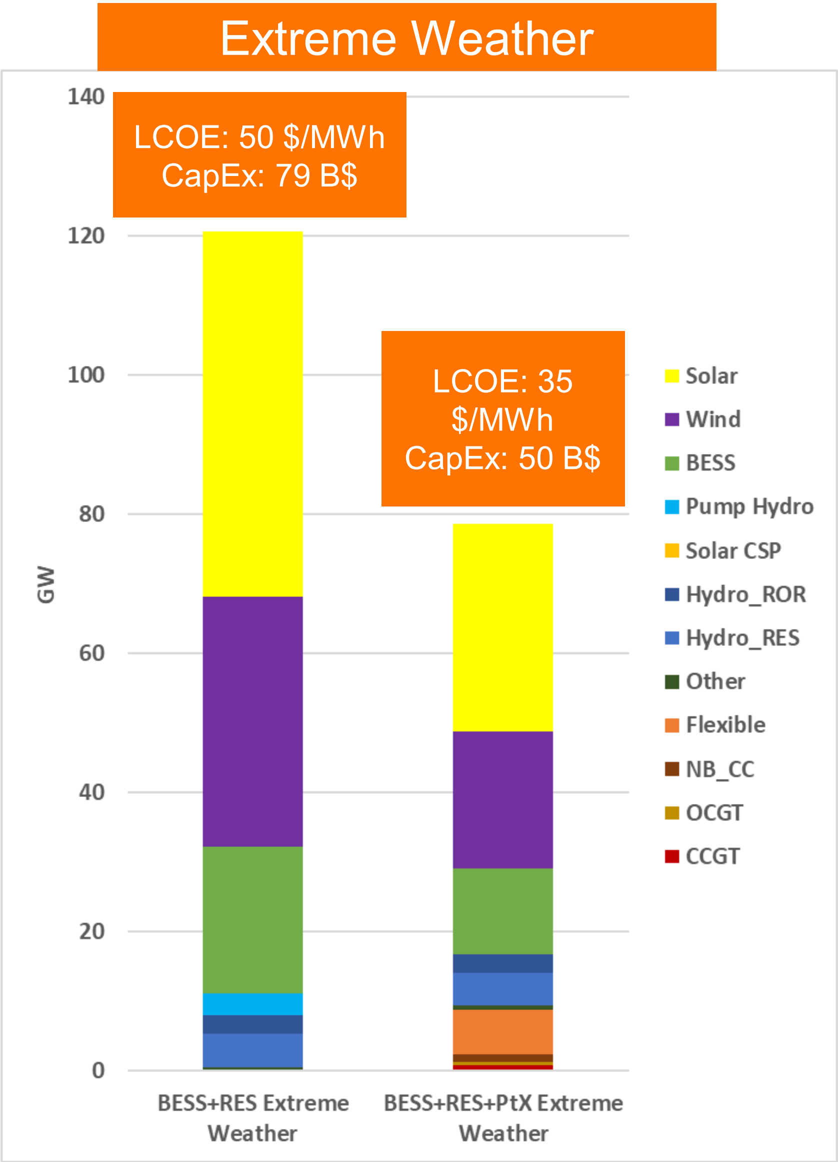
PtXtP in the system

- Reduces system size by 20 GW
- Saves in investment 17 BUSD
- Reduces generation cost by 18%
- Provides highly economical long-term energy storage

Designing for extreme weather with PtXtP

- Minimal overbuild with 45 GW less capacity
- 29 BUSD savings in investments
- 30% lower generation cost
- Owing to firm, dispatchable capacity, system less sensitive to weather

Both systems are carbon neutral



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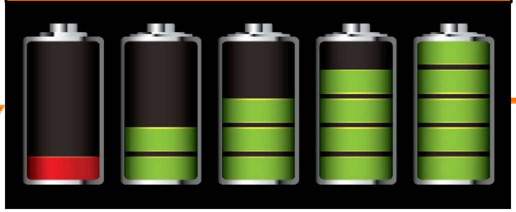
Excess Renewable Electricity

Short Term Storage



Conversion Inverter

- Ancillary services
- Minute-to-hour-to-daily balancing
- Daily shifting of solar

Long Term Storage

Carbon neutral Fuel

Conversion Gas Power Plant

Balancing Power for the Grid

- Unusual weather management
- Seasonal system balancing
- Economical to scale by expanding fuel storage

OPTIMAL FEATURES OF FLEXIBLE POWER PLANT CAPACITY FOR THE TRANSITION

Conversion Gas Power Plant

Purpose

- To understand what are the important features of flexible and dispatchable power plants during the transition to 100%

Motivation

- High renewables system needs a firm, dispatchable and flexible power plant capacity to
  - Support storage in RES balancing
  - Provide ancillary services
  - Provide firm capacity
  - Produce energy

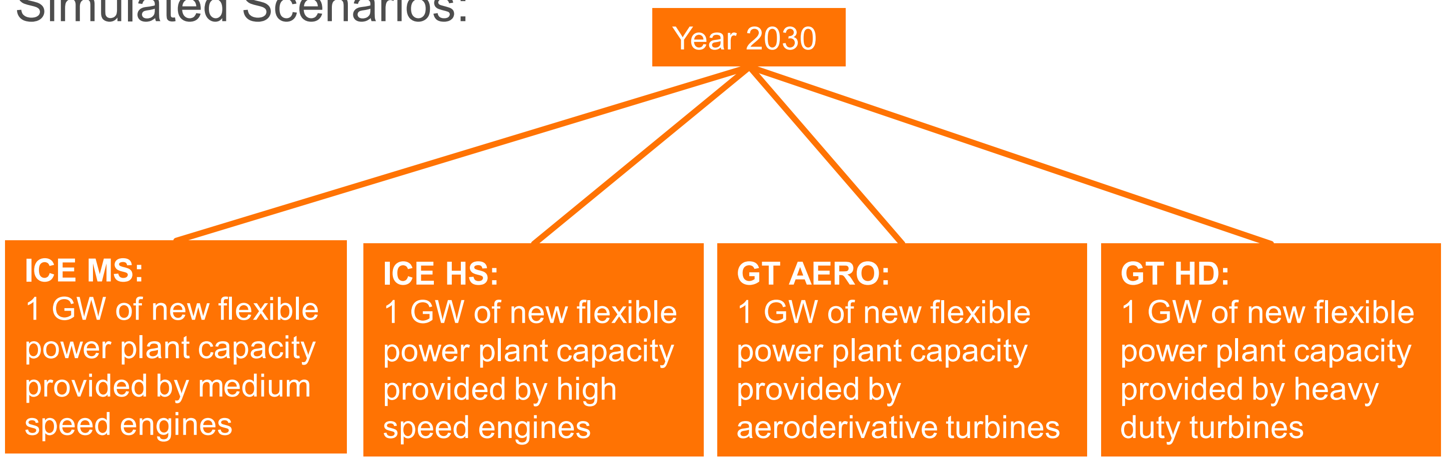
Approach

- Plexos short-term dispatch model to optimize system operation in 2030
- One flexible gas-fired power plant technology at a time

Compared gas-fired technologies:

Technology	Unit Size MW	Heat Rate GJ/MWh	VO&M $/MWh	Start Cost $/MW	Start Time min	Min Stable Level %	Full CAPEX $/kW
Open Cycle Gas Turbine Heavy Duty	100	9.47 (37)	3	70	15	30	675
Open Cycle Gas Turbine Aeroderivative	50	9.0 (40)	4	33	8	40	850
High Speed Engine	5	9.0 (40)	10	0.3	2	10	650
Medium Speed Engine	10	7.89 (45.6)	5	0.3	2	10	689

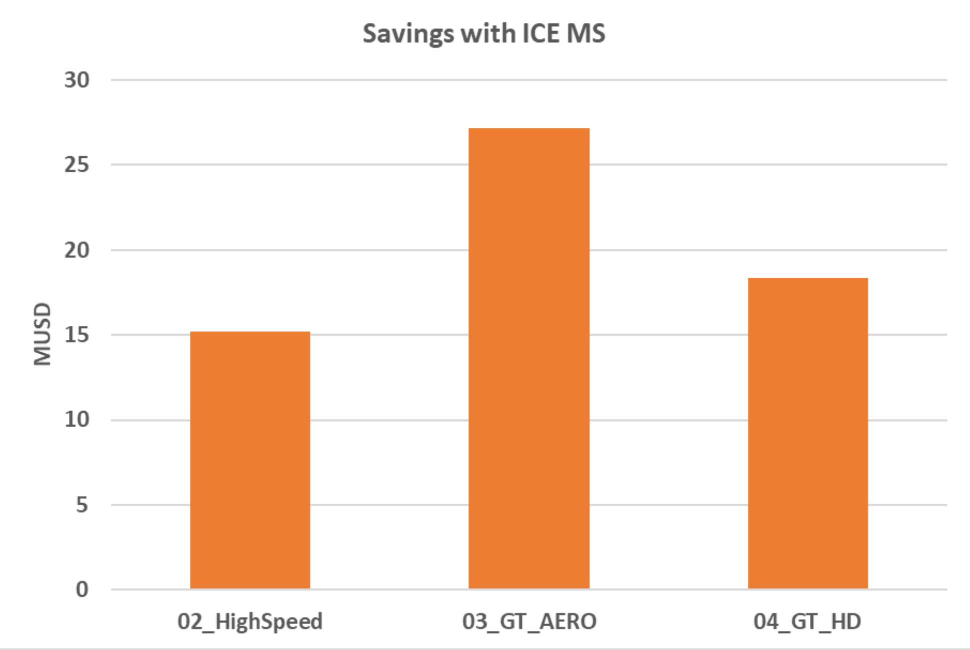
Simulated Scenarios:

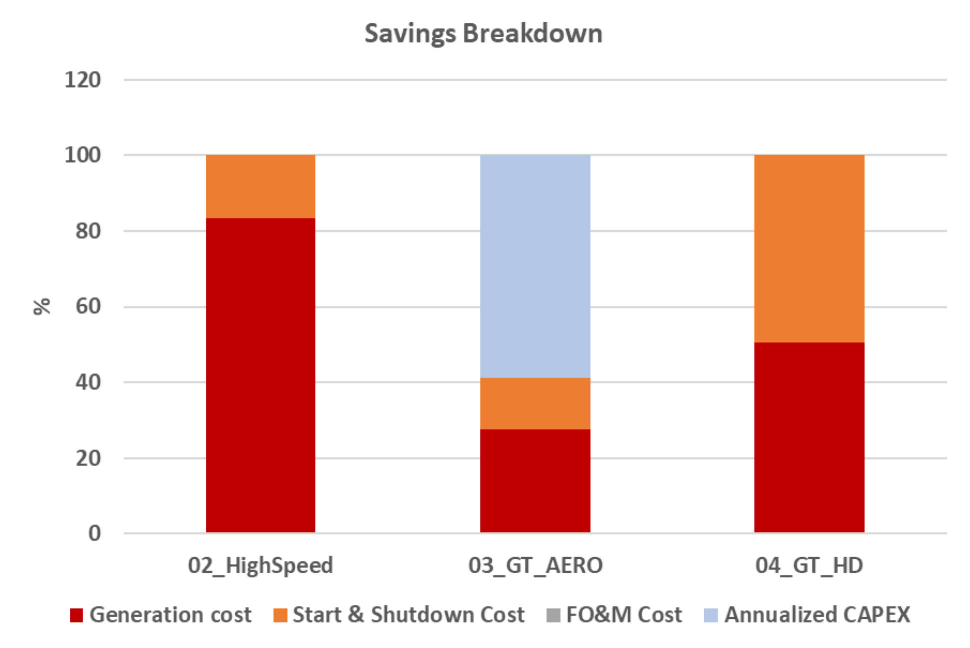


IMPORTANT FEATURES FOR FLEXIBLE POWER PLANT CAPACITY

- Annual system generation cost* differences between the flexible power plant technologies
- Medium speed engines provide the lowest cost option for the flexible power plant capacity, saving 15-25 MUSD annually
- Difference comes from
  - Fuel cost savings due to higher **efficiency**
  - **Start Cost** savings since plant maintenance not affected by frequent starting and stopping
  - Moderate investment cost (**CAPEX**)
  - **Operational flexibility** allows the plant to operate only when it is needed, maximizing RES generation
- Technology capable of conversion to renewable fuels (hydrogen, synthetic methane, ammonia, methanol), enabling X-to-Power

*Total system costs for the compared technology options include
- CAPEX + FO&M of the flexible power plant capacity
- System OPEX (Fuel, VOM, and Start Cost)





Compared against the least-cost scenario with ICE MS

MODELLING SUMMARY

- 100% carbon neutral power system is fully realistic even before 2050 with current technologies
  - Energy from solar PV, wind and hydro
  - Short-term storage with batteries
  - Long-term storage with renewable fuels used in flexible power plants
- Electricity generation costs during the transition will be greatly reduced
- PtXtP provides highly economical long-term energy storage = missing piece of the puzzle. Provides 18% reduction in electricity generation cost compared to battery storage
- Key features of flexible gas-fired power plants are efficiency, low/no starting cost, high operational flexibility and capability to convert to renewable fuels

TAKE-AWAY POINTS

- Chile has one of the most ambitious and economical decarbonization plans in the world
- The decarbonization path is very realistic and enables cost savings and lower carbon emissions
- As per Wärtsilä´s Plexos analysis, the optimal path to decarbonization of Chilean electricity includes:

1. Retiring coal and diesel-oil power plants as soon as possible
2. Constructing the power system capable of serving the load after coal and diesel-oil retirements
   - Wind and solar power to produce adequate amounts of energy
   - Battery storage for ancillary services and daily shifting of solar
   - Flexible gas-fired power plants in adequate quantity to ensure security of supply
3. Adding wind, solar, battery storage and flexible gas-fired power plants
4. Converting the flexible gas-fired power plants to renewable fuels
   - Aligning the power system development with the National Green Hydrogen Strategy (including hydrogen-derived carbon neutral fuels such as ammonia and methanol) will truly have a positive impact in the Country's decarbonization plan as it enables construction of the most economical long term energy storage based on PtXtP

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