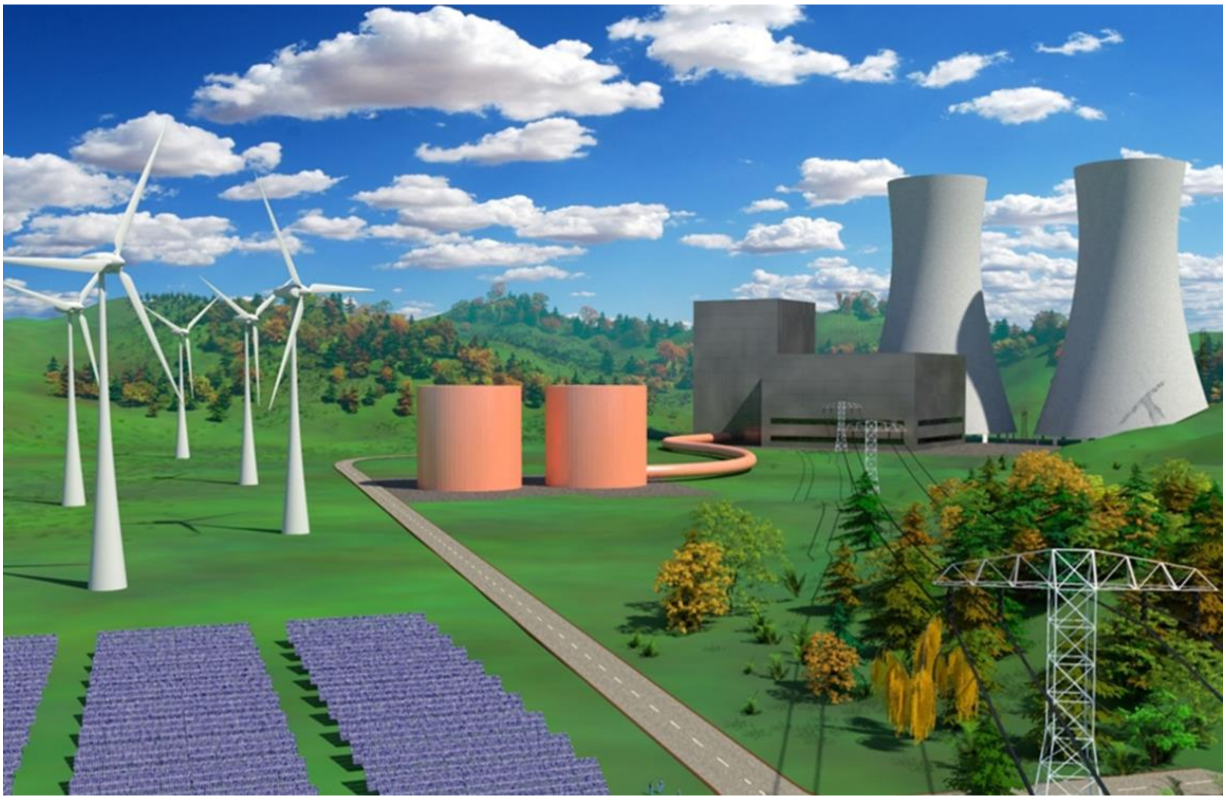
Programa de Energías Renovables y Eficiencia Energética en Chile



Repurposing of existing coal-fired power plants into Thermal Storage Plants for renewable power in Chile

Executive Summary

August 25th, 2020

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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Table of contents

1. Introduction and Background

1.1. Background – Decarbonization of Chile's Energy Sector

Chile's economic growth in recent years has led to a steady increase in the country's energy needs. To ensure energy supply after the loss of gas supply from Argentina in 2004, thermal power plants were built based on imported coal. Today, the effects on the climate can be clearly seen: in 2018 the electricity sector was responsible for 39% of GHG emissions; coal accounted for almost 80% of this percentage. In 2019, 57% of the required electrical energy is generated from fossil fuels such as coal, natural gas and diesel. (1).

On the other hand, Chile offers an enormous potential for the use of renewable energies, estimated in more than 1,800 GW. In recent years, Chile has developed a great dynamic to exploit this potential in the best way. In 2019 the installed capacity of renewable energies connected to the electrical system, such as hydroelectric, solar, wind, geothermal and biomass, amounts to about 11 GW, that is, approximately 46% of the electricity is generated in a sustainable way. As part of this development, President Sebastián Piñera announced in 2019 that Chile would become carbon neutral by 2050.

These ambitions are recognized by the intention to completely eliminate carbon from the energy matrix. In order to achieve this in the best possible way, a commission called the "table of withdrawal and/or conversion of coal-fired power plants" was formed in 2018, in which the GIZ participated. This commission developed recommendations for action by the government and analyzed various exit strategies. Among other things, GIZ prepared a study for the commission which examined possible alternatives for the conversion of coal-fired power plants using existing infrastructure. Within the framework of this development and the new project managed by GIZ "Decarbonization of the Energy Sector in Chile" commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the integration of a thermal energy storage system (based on molten salt) rechargeable with renewable energies in existing coal-fired power plants was analyzed, in order to completely replace coal combustion. This technological solution, called "Carnot Battery" or "Thermal Storage Plant (TSP)", represents a viable way to reduce GHG emissions, especially for Chile, where salts are extracted and processed to be used for thermal storage and where cheap renewable energy sources are available.

In this Executive Summary, resulting benefits of repurposing Chilean coal plants by conversion to thermal storage plants for renewable power are assessed from two perspectives

1. Assessment of the system benefits and cost of TSPs for the Chilean power sector by analyzing the impact of such converted storage plants within the scenarios A and E of the Chilean long term energy plan ("Planificación Energética de Largo Plazo" -PELP) (2).
2. Assessment of the project benefit and cost by analyzing the performance and cost of converting existing selected Chilean coal plants into storage plants

1.2. German Coal Exit and Conversion of Coal Plants into Storage Plants

The idea of converting retired coal plants into thermal storage plants was adopted by the official German government coalition program in 2018 (7), which commits the German coalition government to "examine the extent to which power plant sites no longer needed in future may be used for large thermal storage plants" (lines 3321-3322).

In June 2018, the German government established the "Commission on Growth, Structural Change and Employment" to facilitate a coal phase out and a socially balanced energy transition process. Its final report was published in January 2019 (8), (9) recommending a phase out of coal by 2038 at the latest with a review in 2032 to determine whether the exit date can be advanced to 2035. At the end of 2018, Germany had 42,6GW of active coal plants – 19,9GW lignite coal and 22,7GW hard coal – producing 38% of annual net electricity consumption in 2018. The report recommends early closures of 12GW of coal capacity by 2022 and further reduction of coal capacity to 17GW by 2030. Renewable power generation shall be increased from some 40% share of annual net electricity consumption in 2018 to 65% by 2030 and over 80% by 2050. DLR has estimated that such increase of renewable power generation will require additional 7GW of 16-hour storage capacity by 2030 and additional 25GW by 2050 in order to make the variable wind and solar renewable power fully dispatchable and guarantee the security of power supply. Retired coal plants converted into storage plants could become a very competitive storage solution for the German energy transition while conserving jobs. First demonstration projects to show the viability of using thermal storage for the German energy transition („Energiewende") were proposed by the German regional government of North Rhine Westphalia (NRW) to the German "Coal Commission" and became part of its recommendations (8), where the project proposals "Reallabor Wärmespeicher-Kraftwerk StoreToPower" (proposal 106) and "Malta-Projekt" (proposal 109) were listed.

As one support instrument for the proposed energy transition projects, the German Federal Ministry for Economic Affairs and Energy in February 2019 launched an idea competition on Real-World laboratories for energy system transformation ("Reallabore für die Energiewende") within its new energy research program (10). Under leadership of German utility RWE and with participation of DLR, a pilot conversion of a lignite coal plant in NRW into a thermal storage plant was proposed as Reallabor under the project name "StoreToPower" and selected in shortlist published in July 2019 (11).

On July 3rd 2020, the German Bundestag adopted the coal exit and coal region support laws ("Kohleausstiegsgesetz" und "Strukturstärkungsgesetz Kohleregionen") (13), which is aimed at strengthening the mining regions following the country's coal exit. It would allocate up to €40 billion euros grants until 2038, €26 billions of which are dedicated to infrastructural measures for the federal states of North Rhine-Westphalia, Brandenburg, Saxony and Saxony-Anhalt. The grants are aimed at stimulating the economy in a wide range of areas, such as business-related infrastructure, improvement of public transport, broadband and mobility infrastructure, environmental protection and landscape management. The StoreToPower project has been included in the draft project list to be funded under this draft law. Conversion of Chilean Coal Plants into Thermal Storage Plants (6).

2. Conversion of Chilean coal plants into Storage Plants

2.1. Retrofit of coal plants with proven CSP molten salt storage

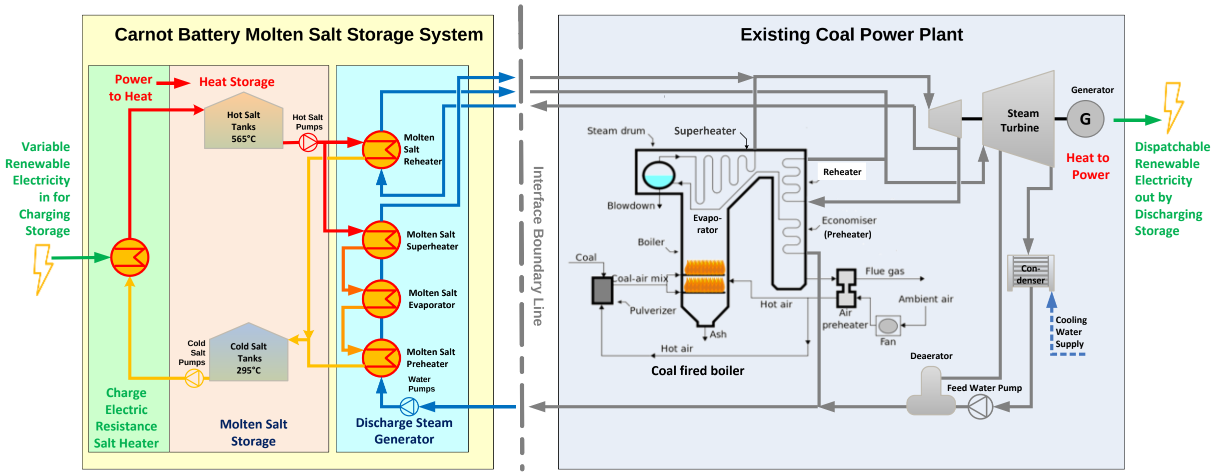


Figure 1: Integrating a high temperature molten salt storage system into an existing coal plant, making use of its existing Rankine steam cycle

Retiring coal power plants can receive a new life serving the green economy by storing renewable energy in thermal batteries, delivering the stored energy back to the grid using the former coal plant's existing power blocks and grid connections.

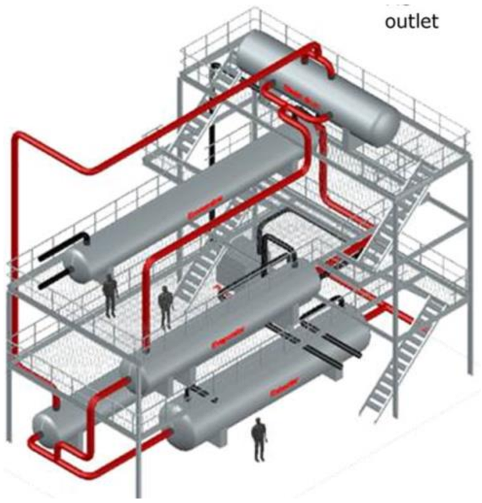
Utility scale molten salt thermal energy storage systems with several hours capacity are state-of-the-art in Concentrated Solar Power (CSP) plants and have over 10 years of commercial track record. In Chile, a 110MWe 17hour molten salt storage system is now being commissioned at the CSP project "Cerro Dominador" in Maria Elena, Atacama desert, Chile (14). It is proposed here, to use such molten salt thermal storage systems beyond CSP plants and retrofit retiring coal plants with them. The process is illustrated in Figure 1: Integrating a high temperature molten salt storage system into an existing coal plant, making use of its existing Rankine steam cycle.

Figure 2: 17hour 110MWe molten salt storage system at CSP tower project Cerro Dominador in Chile (14)

The CSP plants like Cerro Dominador collect the solar energy during the day, convert it into heat and store it in large molten salt tanks to produce electricity in the hours after sunset. There are CSP plants with up to 17 hours of storage capacity that allow for 24/7 base load operation (3), (4).

The molten salt mixture used in these storage systems is a binary mixture of Sodium Nitrate (60%) and Potassium Nitrate (40%) – they are abundant as basic components of mass used fertilizers. This molten salt mixture is nonflammable, non-toxic and non-penetrating in ground soil – it freezes at soil contact. The molten salt mixture is durable for up to 35 years lifetime of the storage system without degradation or need of refill. Its high mass specific energy density is magnitudes higher than water in pumped hydro and is technically comparable with electrochemical batteries. It is capable of achieving high temperatures up to 565°C at ambient pressure. The salt mixtures can be used as heat transfer fluid and easily exchange heat with other working fluids like water/steam (4), (5).

(a) 6.6MWe molten salt heaters of SQM at Nitrate Plant in Chile Coya Sur, Chile (Source: Vulcanic)



(b) Typical molten salt heated steam generator system (Source: Aalborg CSP)

Figure 3: Molten salt resistance heaters for charging (a) and molten salt heated steam generator (b)

In the retrofitted coal plant, the molten salt would be heated using electrical resistance heaters as shown in Figure 3a fed by renewable electricity. In this way the surplus or curtailed variable electricity available in the grid from PV and wind power plants can be stored as thermal energy. Upon later demand, this stored thermal energy will be discharged by pumping the hot salt through a turbine steam generator system as shown in Figure 3b, where it transfers its heat to the turbine steam and returns so cooled down to the cold tank. This turbine steam is then used by the existing steam cycle of the former coal plant and generates electricity. With such thermal storage plant the variable intermittent renewable electricity is converted in firm and dispatchable power. This will decarbonize the coal plant while granting 100% dispatch ability utilizing most of the existing equipment in the plants and saving jobs. Furthermore, this will make perfect use of existing power plant infrastructure and grid connection as well as proven operational power plant procedures. All the components are mature technologies; only the combination of technologies is new.

2.2. Case study Chile of a coal plant retrofit with molten salt storage

2.2.1. Technical Assumptions

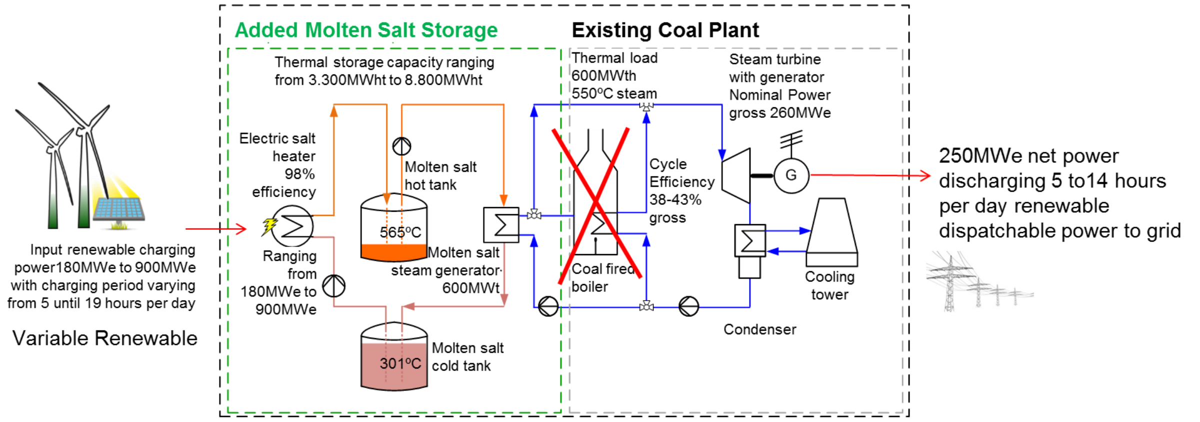


Figure 4: Retrofit of a 3.300-8.800MWht thermal capacity molten salt storage system to an existing coal plant of 250MWe class (net) in Chile – example configuration used in the techno economic analysis

In this part of the study a preliminary techno economic analysis was conducted on the performance and cost of retrofitting an existing Chilean coal plant with a CSP molten salt storage, resistance heater and molten salt steam generator as presented in Figure 4. In the selected 250MWe (net) coal plant, the coal fired boiler was substituted by a molten salt steam generator to run the turbine generator with the discharge heat stored in the molten tank storage. Therefore in all following analysis variants the capacity of the molten salt steam generator is constant 600MWt. To charge the molten salt storage, molten salt from the cold tank(s) is pumped through electrical salt heaters powered by renewable electricity, heated there to its hot temperature and stored in the hot tank (s). For the technical performance analysis and the calculation of the annual energy yield this configuration was modeled with the power cycle modeling tool Ebsilon (21).

Sensitivity Variant	Unit	V1-O1	V1-O2	V1-03	V1-O10	V1-O11	V1-O12
Discharging Duration	[hours]	5,00	5,00	5,00	8,00	12,00	14,00
Thermal storage capacity	[GWht]	3,33	3,33	3,33	5,15	7,57	8,79
Charging Duration	[hours]	5,00	10,00	19,00	11,00	11,00	10,00
Charging electric salt heater capacity	[MWe]	680	340	179	478	703	897

Table 1: Sensitivity variants of discharging duration (full load hours), thermal storage capacity, charging duration and capacity of electric salt heaters

To analyze the sensitivity of annual energy yield, load factor, total investment cost and Levelized Cost of Electricity the discharging duration, storage capacity and charging duration were varied as follows:

- Discharging duration
  was varied from 5 to 14 full load hours, varying the corresponding thermal storage capacity from 3.300 to 8.800 MWht and the corresponding plant load factor from 20,8% (5 hours) to 58,3% (14 hours).
- Charging duration
  the charging duration is directly proportional to the installed capacity of the electric salt heaters and the thermal storage capacity. The charging duration was varied from 5 to 19 hours, varying the corresponding electric salt heater capacity from 180MWe to 900MWe.

The corresponding sensitivity variants are summarized in Table 1. The detailed technical assumptions are described in the Final Report of Subtask:"Techno-economic analysis for the transformation of a coal fired power plant to a heat storage power plant (Carnot Battery)" of this project.

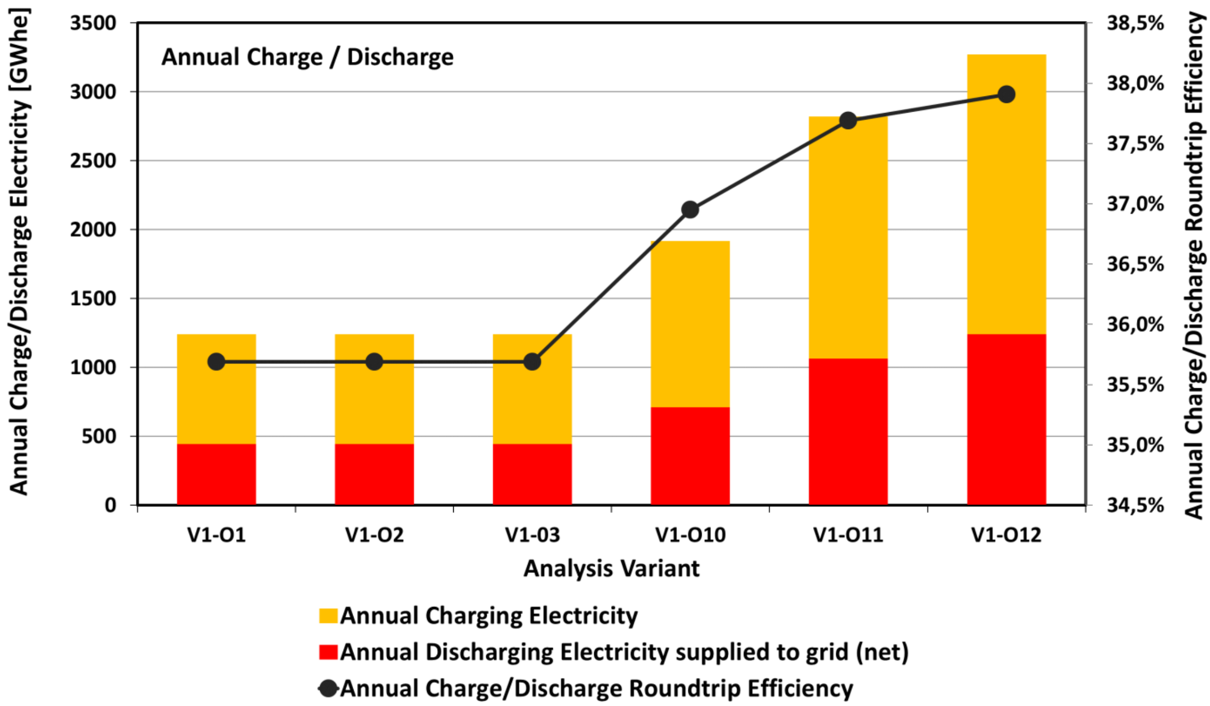


Figure 5: Annual charging/discharging electricity and annual roundtrip charging/discharging efficiency for the analysis variants

The resulting annual charging and discharging net electricity amounts together with the corresponding annual round-trip charging/discharging efficiencies are illustrated in Figure 5. It shows that highest annual round trip charging/discharging efficiencies are obtained with the longest discharging duration of 14 hours and a corresponding charging duration of 10hours (Analysis Variant V1-O12).

2.2.2. Investment Cost (CAPEX) and Operation Cost (OPEX) Assumptions

For this study the specific economic parameters (investment and operational costs) were taken from the Final Report of subtask "Estimation of Investment and Operation Cost for Chile´s "Long Term Energy Planning 2020" from this project. The key financing and cost parameters are listed in Table 3 and Table 2. With the molten salt steam generator capacity constant for all analysis variants, its investment cost is also constant for all analysis variants.

For the analysis variant cases V1-O1. V1-O2 and V1-O3 the storage discharge duration is kept constant at 5 hours while the charging duration is varied to be 5, 10 and 19 hours. This keeps the capacity of the molten salt storage capacity constant at 5 equivalent full load hours requiring 3,33 GWhe thermal capacity while the capacity of the electrical salt heaters vary to be 680, 340 and 179 MWe. Figure 6 shows the resulting total investment cost (CAPEX) for the 5 discharge hour analysis variants V1-O1. V1-O2 and V1-O3 ranging from some 200 to 250 million USD.

In analysis variants V1-O10, V1-O11 and V1-O12 the full load discharge duration is varied to be 8, 12 and 14 full load hours respectively – varying accordingly the full load hour storage capacity and the corresponding thermal capacity to become 5,15, 7,57 and 8,79 GWht respectively. Charging duration is varied to be 11 hours for analysis variants V1-O10 and V1-O11 and 10 hours for analysis variant V1-O12. Correspondingly to the varying storage capacity and charging duration, the capacity of the electrical salt heaters becomes 478 MWe for V1-O10, 703 MWe for V1-O11 and 897 MWe for V1-O12. Figure 6 shows the resulting total investment cost (CAPEX) for the 8, 12 and 14 full load discharge hour analysis variants V1-O10. V1-O11 and V1-O12 ranging from some 300, 400 to 450 million USD.

Specific investment cost	**unit**	**value**
Electric heater	[$/kW$_{el}$]	100
Storage system	[$/kWh$_{th}$]	23
Solar salt	[$/t]	incl. in storage
HTF System		
…Hot and Cold salt pumps	[$/kW$_{th}$]	incl. in storage
…HTF piping system	[$/kW$_{th}$]	incl. in storage
…Heat tracing system	[$/kW$_{th}$]	incl. in storage
Molten Salt Steam Generator	[$/kW$_{th}$]	90
Power block including BOP (existing unit)	[$/kW$_{th}$]	0
Integration cost to existing PB	[$/kW$_{th}$]	10
Modification cost of grid connection*	[$/kW$_{el}$]	0
Total surcharges (engineering, risk, management)	[%] of DC	30
Specific O&M		
O&M incl. insurance	% of DC/y	3
Fuel costs**	[$/MWh]	Not used
Electricity cost for charging***	[$/MWh$_{el}$]	20

* For this study it is assumed that no modification of the grid connection is necessary.

** For this study the power plant is not operated on fossil fuel therefore the fuel cost are not specified.

*** For this study it was defined that the charging power from the grid is constant at 20 $/MWh$_{el}$ without considering the origin of it. However, in reality the source for this would be most likely from a PV power plant.

Table 2: Assumed specific investment cost (CAPEX) for the retrofit of a first existing Chilean coal plant of 250MWe class with state of the art CSP molten salt storage technology

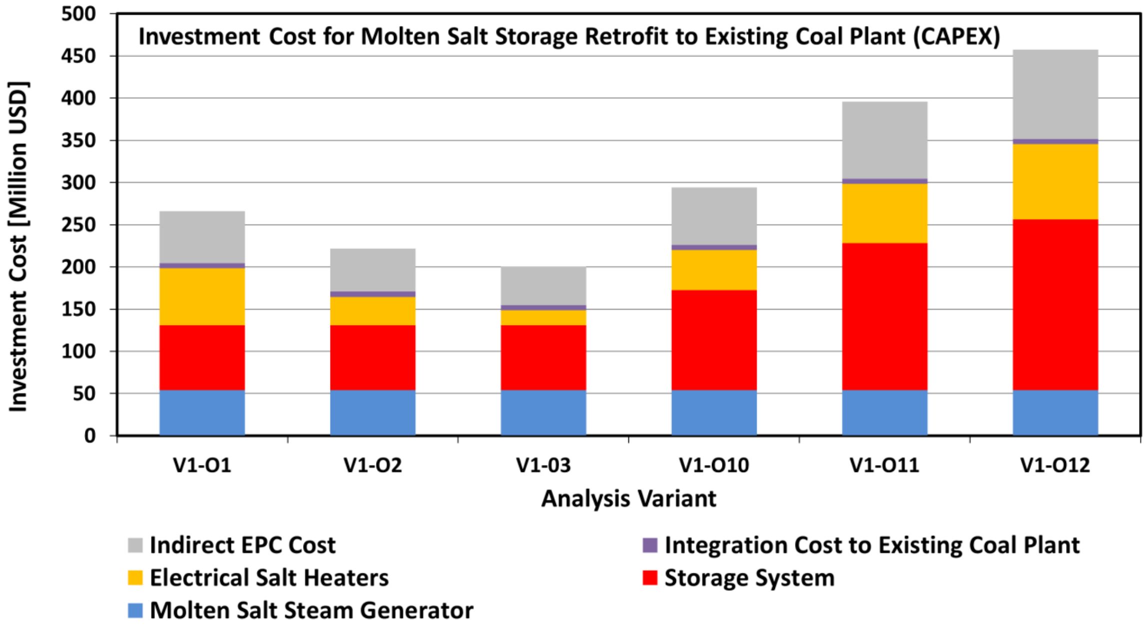


Figure 6: Total investment cost (CAPEX) estimate for the retrofit of a molten salt storage system with electrical resistance heaters and molten salt steam generator to selected Chilean coal plant for the analysis variants

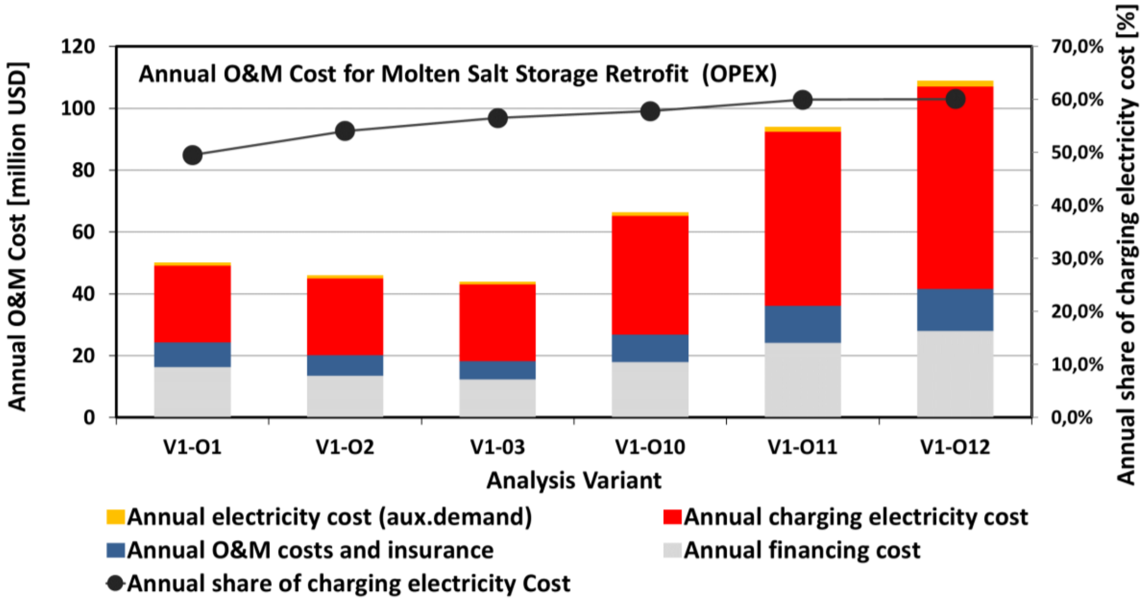


Figure 7: Annual operation cost (OPEX) estimate for the retrofit of a molten salt storage system with electrical resistance heaters and molten salt steam generator to selected Chilean coal plant for the analysis variants

For the computation of the annual Operation cost shown in Figure 7, the following preliminary simplified cost have been assumed:

- constant cost of charging electricity of 20USD/MWhe (this may be reduced in future with consideration of specially dedicated large PV systems for storage charging)

- annual O&M cost including insurance estimated at 3% per year of the respective CAPEX (this needs to be verified against real O&M service offers)
- financing cost determined by simplified Levelized Cost of Electricity analysis based on 100% financing over a debt period of 35 years with constant real discount rate of 5% as summarized in Table 3 (to be validated against real project finance offers)

Figure 7 shows that the share of the charging electricity cost in the total annual O&M increases with full load discharging hours – from some 50% at 5 hour discharge duration to some 60% at 12-14 hour discharge duration.

2.2.3. Levelized Cost of Discharge Electricity

The main benchmark used here for ranking the various analysis variants is their levelized cost of electricity (LCOE). In this ranking other economic parameters are neglected, such as taxes, project financing concepts, etc. The financing assumptions for this ranking analysis are summarized in Table 3.

Financing Data for LCOE	unit	value
Debt Period	years	35
Discount rate	%	5,0
Annuity	%	6,11

Table 3: Financing assumptions for calculating Levelized Cost of Discharge Electricity

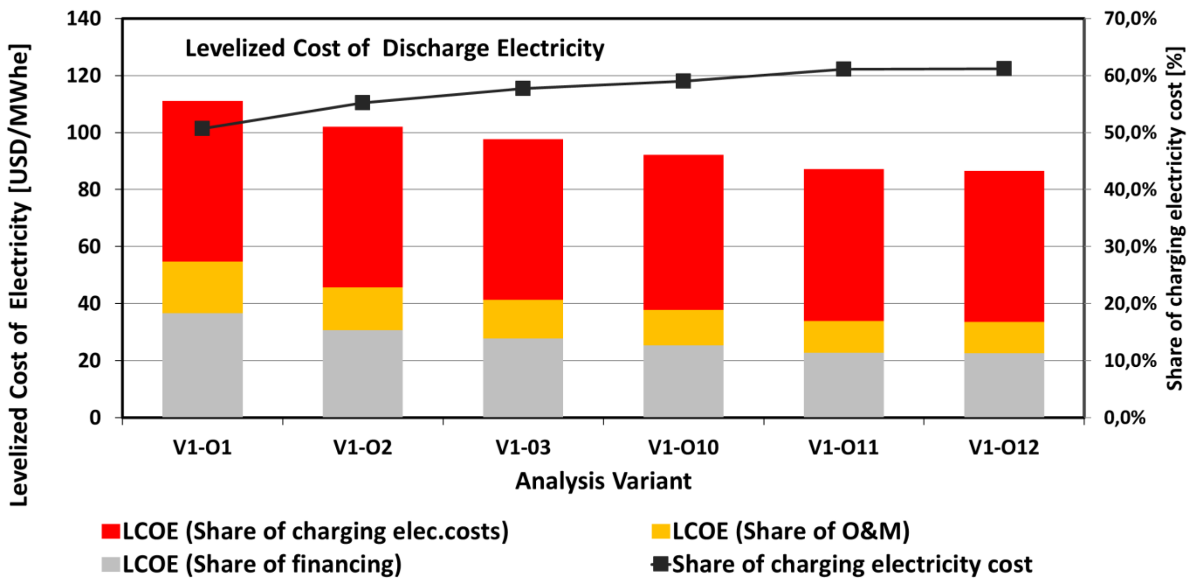


Figure 8: Levelized cost of discharge electricity for the retrofit of a molten salt storage system with electrical resistance heaters and molten salt steam generator to selected Chilean coal plant for the analysis variants

Figure 8 shows the resulting ranking of such analysis of levelized discharge electricity cost (LCOE) for the various analysis variants of the selected Chilean coal plant converted into a thermal storage plant and the percentual share of charging electricity in such LCOE. For the 5 full load hour discharge duration the LCOE is in the range of 100-110USD/MWhe, while for the longer discharge durations the LCOE drops well below 100USD/MWhe, decreasing to 92,2USD/MWhe for the 8 hours (V1-O10), 87,2USD/MWhe for the 12 hours (V1-O11) and 86,5USD/MWhe for the 14 hour (V1-O12) discharge duration.

3. Thermal storage plants for covering Chile's future residual load

A key challenge of transforming the Chilean power sector from fossil fuel based to renewable energy based generation is the residual load curve, which is basically the result of subtracting intermitting variable renewable power production from power demand curve. This residual load curve can vary greatly over time between a maximum, when no renewables are available, and zero, when there is excess of renewables. Up to now, fossil thermal power plants have been in Chile the main option to securely cover the residual load curve - in 2019, 57 % of the electrical energy, required was generated from fossil fuels such as coal, natural gas and diesel (1).

While thermal power plants will still be needed in the future to guarantee security of supply and coverage of the residual load peaks, they need to become adapted to the future challenges:

- growing limitations of GHG emissions
- falling cost of solar and wind generation
- reduction of required operating hours with evolving future residual load curve
- falling prices

To cope with these energy transition challenges, the Chilean power system will need in future flexible thermal power plants that are able to

- deliver of guaranteed power capacity (firm capacity) at any time,
- follow flexibly the ramp ups and downs of the residual load demand curve
- minimize GHG emissions by maximum use of renewable energy sources
- be economically affordable and financially bankable

The here proposed Thermal Storage Plants (TSP) are an innovative thermal power plant concept that could become a key to a fast transition towards renewable electricity supply world wide, as it solves the a.m. challenges related to the residual load curve (15). The TSP configuration used for the analysis of the long term Chilean power sector energy transition PELP is presented in Figure 9 and consists of the following elements:

1. Steam (Rankine) cycle of an existing coal plant including steam turbine, condenser, feed pump and steam generator for intermediate and base load supply with typically 4000 and more full load hours per year. The

original coal boiler may be partially used with solid coal or where possible with biomass for backup over a transition period until substituted by a gas fired back up boiler or the peak gas turbine waste heat recovery boiler.

2. Optional retrofit with gas turbine (Brayton) cycle with gas turbine, compressor and combustion chamber used to cover short-term peak load – on top of the Rankine cycle – with 1000 or less full load hours per year. Its exhaust heat may be recovered in a waste heat recovery boiler to generate steam for the existing steam turbine.

3. Retrofit of thermal energy storage system consisting of cold and hot tanks for molten salts as used in the concentrated solar power plants. At storage charge, the molten salt is pumped from the cold tanks through salt heaters to the hot tanks, raising its temperature from some 280°C in the cold tanks to some 565°C in the hot tanks. At storage discharge, the molten salt is pumped from the hot tanks through steam generators, where its heat is used to generate, superheat and reheat turbine steam. The cooled molten salt returns from the steam generators to the cold tanks. The electric salt heaters are fed by large scale dedicated photovoltaic generators directly connected to the thermal plant or interconnected via the grid to supply their daily electricity generation to charge the molten salt storage

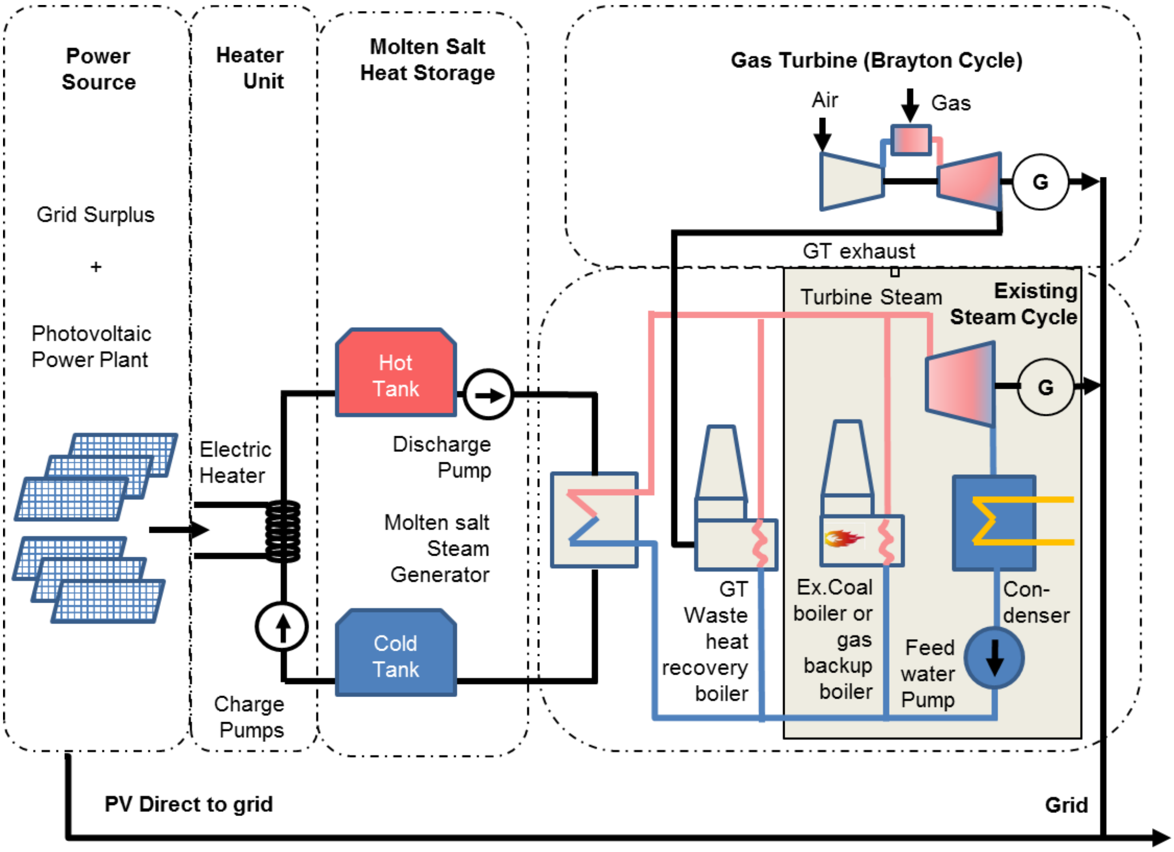


Figure 9: Configuration of thermal storage plant for analysis of impact, benefit and cost of a generalized use of thermal storage plants in the long term energy transition of the Chilean power sector in accordance with PELP

The TSP have different operation modes to cover the dynamic residual load transients:

1. Part of the electricity generated from the connected photovoltaic generators is injected directly into the grid, while its excess is fed to the electric salt heater of the TSP, converted to heat and stored. During charging the steam cycle may be operating or be in standby.
2. If direct power from the PV plant does not suffice to cover the load, the steam turbine goes online, in the first instance powered by the heat storage.
3. If the energy contained in the heat storage sinks to a critical level, backup co-firing of solid biomass (if possible), coal or gas is used to secure capacity for firm power generation.
4. If the load exceeds the maximum capacity of the steam turbine, a peaking gas turbine fired by natural gas, biogas or synthetic natural gas is added and its waste heat used for generating further turbine steam.

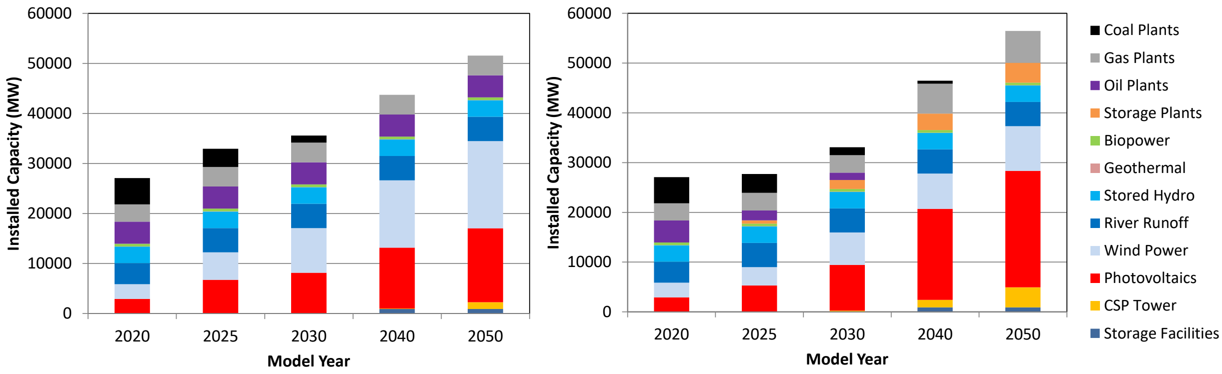
Due to the use of fuels, the full capacity of the power plant (steam turbine plus gas turbine) can be guaranteed at any time, and supply can be flexibly adapted to any load situation. At the same time, significant amounts of biomass, biogas or natural gas are saved by photovoltaic electricity either injected directly into the grid or stored in the heat storage and delivered later.

Former base load supply of coal steam cycle or gas fired combined cycle power plants (5000-7000 h/a) is subsequently substituted by interrupted medium load supply (3000-4000 h/a) alternating with direct supply from variable renewables like PV.

In the course of the transition of the Chilean power sector towards renewables, all kinds of conventional thermal power plants like coal steam cycles, combined cycle gas turbines, wood pellet biomass plants or biogas plants can be substituted by or modified to become highly flexible Thermal Storage Plants, particularly if the former conventional power plants are not longer competitive or flexible enough to cope with the new requirements of the residual load curve. In some cases, conventional power plants may be modified and transformed to Thermal Storage Plants by introducing a thermal energy storage system for higher flexibility rather than being decommissioned.

Storage plants can include peaking gas turbines for few operating hours with peak residual demand that cannot be economically covered by steam cycles. If connected to the steam cycle, their waste heat can be recovered leading to high efficiency during peak load supply. In this case, peaking gas turbines will have a similar efficiency as combined cycle power plants. This option has been assessed in Scenario A-SP. Nevertheless, steam cycles can also be operated as Storage Plants without gas turbines.

3.1. Thermal storage plants for PELP Scenario A



(a) Scenario A (b) Scenario A-SP

Figure 10: Development of installed capacity according to (a) Scenario A of "Planificación Energética de Largo Plazo (PELP)" (16) and (b) alternate Scenario A-SP with Concentrated Solar Power plants and Thermal Storage Plants

PELP Scenario A foresees an increase of Chilean annual electricity consumption from a total of 78.7 TWh/a in the year 2020 to around 130 TWh/a in 2050. As a first guess, it was assumed that peak load would increase proportionally, from about 11.6 GW in the year 2020 to 19.2 GW in 2050. To cover this consumption, increase PELP Scenario A considers a significant increase of installed capacity from 27.1 GW in 2020 to 51.6 GW in 2050, mainly adding wind power and photovoltaic power capacities, while coal power plant capacities are completely decommissioned after 2030 (Figure 10a). In this analysis, the DLR simulation tool ELCALC (17) has been used to model Chile's hourly balance of power demand and supply and to identify possible surplus and deficits that usually are not detected when only making an annual electricity balance. An hourly load curve of the year 2019 was provided by GIZ for time series modelling (18). The hourly load values are scaled up for each model year in proportion to the growing annual demand, while the aspect of the curve remains constant. Gross consumption including supply system internal demand and transmission losses was considered with 6% added to net demand

This analysis revealed some shortcomings of the **Scenario A** related to considerable surplus and curtailment of renewable power supply on one hand and a critical reduction of redundancy caused by the decommissioning of coal plants in front of strongly growing demand.

An alternative **Scenario A-SP** was developed here including Concentrating Solar Power Plants and Thermal Storage Plants with increased flexibility, backup fuel for firm capacity and making use of renewable power surplus saved in thermal energy storage. This alternative Scenario A-SP makes the following changes to Scenario A (Figure 10b):

1. Reduction of PV and wind power capacity in 2025 in order to reduce curtailment.

2. Reduction of wind power capacity and increase of PV capacity in all other model years in order to foster regular cycles for heat storage and pump storage.
3. Introduction and expansion of Storage Plants of with peaking gas turbines and hybrid operation with natural gas in all model years. Storage plants are configured with a Heater Multiple of 3.3 and a thermal energy storage capacity of 12 hours of full load operation.
4. Earlier introduction and stronger expansion of Concentrating Solar Thermal Power Plants in hybrid operation with natural gas backup with a Solar Multiple 3 and 12 hour thermal energy storage capacity.
5. Subsequent decommissioning or transformation of all conventional power plants except peaking gas turbines (that are connected to the Storage Plants). In the long run, fossil fuels are only used as backup in Storage Plants and CSP Plants.

In the last two decades Scenario A-SP foresees installation of some 5 GW more capacity than in the original Scenario A, and maintains some coal plants still operating in 2040. On the other hand, expensive Oil & Gas plants are decommissioned completely. After 2040 all gas turbine capacity is (optionally) connected to Storage Plants.

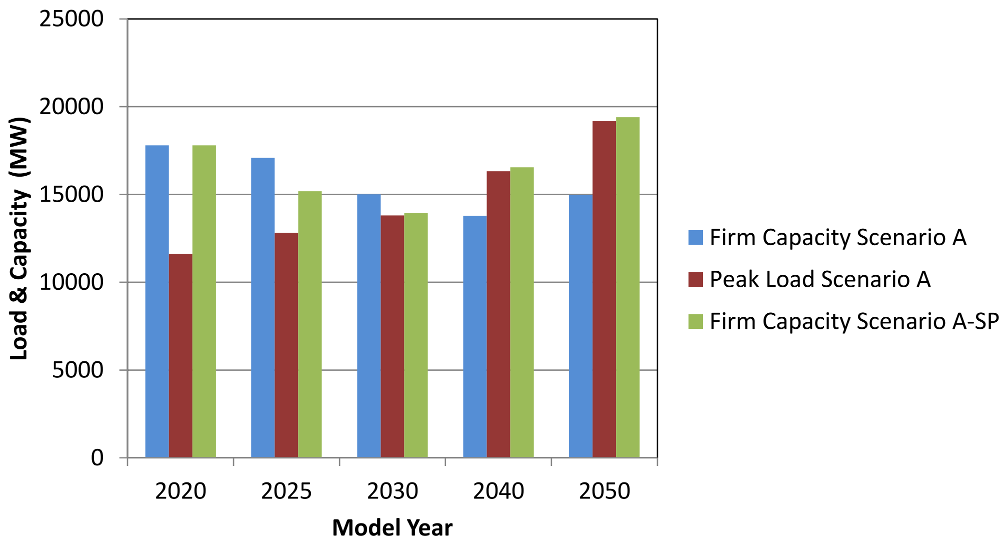
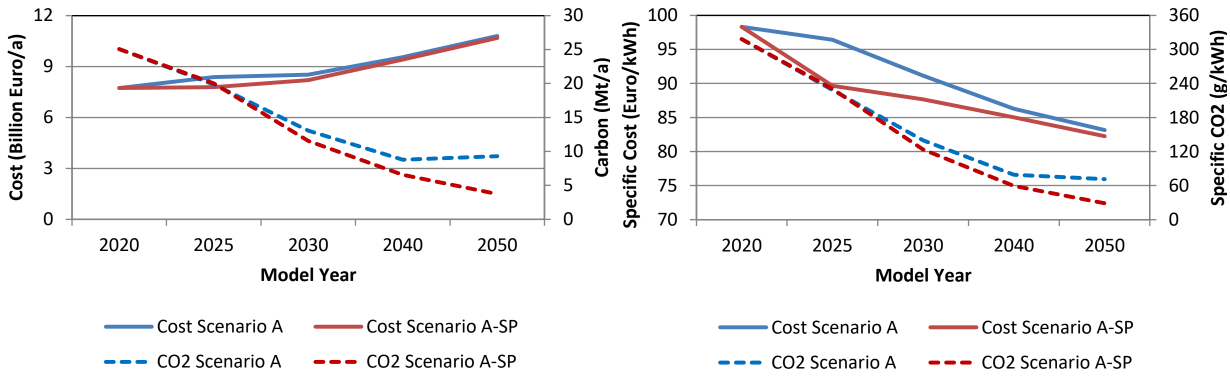


Figure 11: Firm power capacity versus peak load in Scenarios A and A-SP. Redundancy is not secured in Scenario A beyond 2040; Scenario A-SP secures such firm capacity for peak loads

Figure 11 shows the development of annual peak load as modelled with ECALC for Scenarios A and A-SP. According to ECALC the decommissioning schedule of fossil fuel based thermal power generation capacity foreseen in Scenario A may lead to a lack of reserve capacity and to electricity supply gaps from 2040 onward.

This situation has been avoided in Scenario A-SP by strongly expanding the capacity of Thermal Storage Plants (4 GW) and also Concentrating Solar Thermal Power Plants (4 GW) until 2050, both with natural gas backup for firm capacity, showing many advantages but no drawbacks compared to Scenario A. It might be a good strategy to convert conventional power plants into Thermal Storage Plants as far as possible and add significant solar thermal power capacity to cope with growing demand.



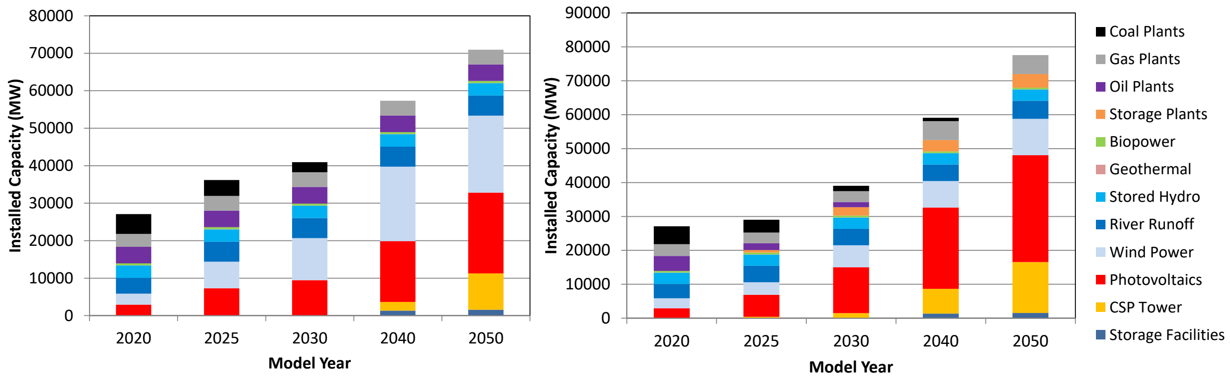
a. Total annual Chilean power generation cost versus total annual carbon emissions

b. Specific Chilean cost of electricity versus its specific carbon emissions per kWhe

Figure 12: Chilean generation cost and carbon emissions for Scenario A and alternative Scenario A-SP that includes Storage Plants and Concentrating Solar Power Plants

Figure 12a show the development of total annual generation cost (B€/a) and CO2-emissions (Mt/a) of Chilean power system under the high growth assumptions of Scenario A and reveals a stagnation of carbon emission reductions in the last decade that is due to demand growing faster than renewable shares. There is also a strong increase of annual generation due to the growing demand. Looking however at specific cost and emissions per consumed net electricity unit in €/MWh and g/kWh in Figure 12b, both scenarios A and A-SP reveal steadily decreasing values both for specific electricity cost and specific electricity emissions per kWhe generated.

3.2. Thermal storage plants for PELP Scenario E



(a) Scenario E

(b) Scenario E-SP

Figure 13: Development of installed capacity according to (a) Scenario E of "Planificación Energética de Largo Plazo (PELP)" (16) and (b) alternate Scenario E-SP with Concentrated Solar Power plants and Thermal Storage Plants

According to the assumptions related to Scenario E following "Planificación Energética de Largo Plazo" (PELP) of the Chilean government, annual electricity consumption may increase from a total of 78.7 TWh/a in the year 2020 to around 200

TWh/a in 2050. It was assumed that peak load will increase proportionally, from about 11.6 GW in the year 2020 to 29.3 GW in 2050. In order to cover the increasing electricity demand mainly by renewable electricity, PELP Scenario E considers a significant increase of installed capacity from 27.1 GW in 2020 to 71 GW in 2050, mainly adding wind power, photovoltaic and concentrating solar thermal power capacities, while coal power plant capacities are completely decommissioned after 2030 (Figure 13a). Like in section 3.1 for the Scenario A analysis, 2019 hourly load values are scaled up for each model year in proportion to the growing annual demand, while the aspect of the curve remains constant. Gross consumption including supply system internal demand and transmission losses was also considered here with 6% added to net demand.

In order to reproduce PELP Scenario E by hourly time series modelling with ELCALC, the installed capacities according to Figure 5a were implemented for each plant category and model year. Electricity yield from wind power and photovoltaics was calculated from hourly time series stemming from global renewable energy resource assessment tools like ENDAT (19) and Meteonorm (20), electricity output being scaled to the installed capacities given by each scenario. For photovoltaics a 50:50 mix of fixed and two-axis tracking PV capacity was assumed, with most tracking capacities installed in Northern Chile. For onshore wind power the electricity yield was calibrated to the average capacity factors of wind power in Chile assumed in Scenario E.

Also Scenario E leads to a significant increase in renewable energy shares and to a related decrease of carbon emissions, but on the other hand, firm capacity is critically reduced while peak load demand strongly increases, which may lead to a loss of system supply security. In 2020 firm capacity from thermal and hydropower plants is much higher than peak load, but in the course of Scenario E system transformation this relation changes after 2030 to a situation where peak load is higher than firm capacity, increasing the risk of system failure.

An alternative **Scenario E-SP** was developed here including Concentrating Solar Power Plants and Thermal Storage Plants with increased flexibility, backup fuel for firm capacity and making use of renewable power surplus saved in thermal energy storage – with the following changes (Figure 13b):

1. Reduction of PV and wind power capacity in 2025 in order to reduce curtailment.
2. Reduction of wind power capacity and increase of PV capacity in all other model years in order to foster regular charge/discharge cycles for thermal storage and pump storage.
3. Introduction and expansion of Storage Plants of with peaking gas turbines and hybrid operation with natural gas in all model years. Storage plants are configured with a Heater Multiple of 3.3 and a thermal energy storage capacity of 12 hours of full load operation.
4. Earlier introduction and stronger expansion of Concentrating Solar Power Plants with hybrid operation with natural gas backup with a Solar Multiple 3.5 and 12 hour capacity.
5. Subsequent decommissioning or transformation of all conventional power plants into thermal storage plants except peaking gas turbines. In the long run,

fossil fuels (mainly LNG) are only used as backup in Storage Plants, CSP Plants and for peaking Gas Turbines.

In the last decades about 7 GW more capacity is installed in E-SP than in the original Scenario E, and some coal plants are still operating in 2040. On the other hand, expensive Oil & Gas plants are decommissioned completely. After 2040 all gas turbine capacity may optionally be connected to Storage Plants for waste heat recovery. However, utilization of gas turbines is very low. They are mainly used as reserve capacity for emergencies in only a few hours per year.

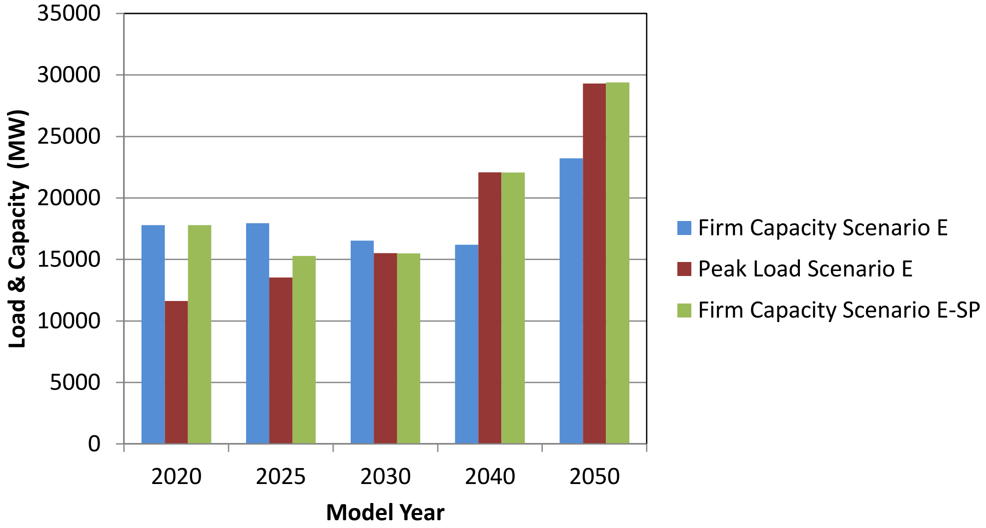
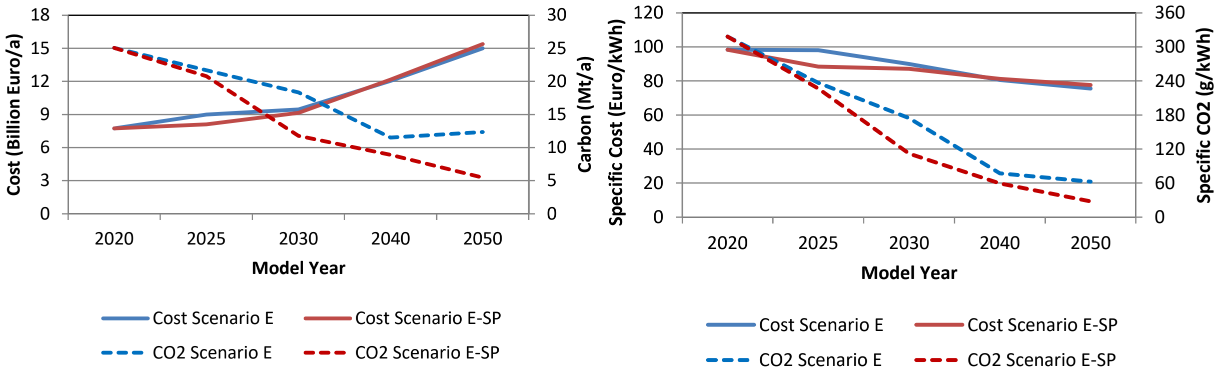


Figure 14: Firm power capacity versus peak load in Scenarios E and E-SP. Redundancy is not secured in Scenario E beyond 2040; Scenario E-SP secures such firm capacity for peak loads

Figure 14 shows the development of annual peak load as modelled with ECALC for Scenarios E and E-SP. According to ECALC the decommissioning schedule of fossil fuel based thermal power generation capacity foreseen in Scenario E may lead to a lack of reserve capacity and to electricity supply gaps from 2040 onward. Firm power capacity in Scenario E-SP is maintained sufficiently high all over the complete transformation pathway and there is no risk of capacity deficits during any model year.

Fast reduction of fossil fuels especially by a fast introduction of solar thermal power plants allows for longer operation of few coal plants up to 2040 without causing higher carbon emissions. In the long term only natural gas is used in gas turbines, CSP and Storage Plants. The consumption of gas does not increase during this transformation pathway. The consumption of biomass is slightly reduced.



a. Total annual Chilean power generation cost versus total annual carbon emissions

b. Specific Chilean cost of electricity versus its specific carbon emissions per kWhe

Figure 15: Chilean generation cost and carbon emissions for Scenario E and alternative Scenario E-SP that includes Storage Plants and Concentrating Solar Power Plants

Figure 15a show the development of total annual generation cost (B€/a) and CO2-emissions (Mt/a) of Chilean power system under the high growth assumptions of Scenario E and reveals a stagnation of carbon emission reductions in the last decade that is due to demand growing faster than renewable shares. There is also a strong increase of annual generation due to the growing demand. Looking however at specific cost and emissions per consumed net electricity unit in €/MWh and g/kWh in Figure 15b, both scenarios E and E-SP reveal steadily decreasing values both for specific electricity cost and specific electricity emissions per kWhe generated. Already in the short, medium and long term, electricity production by renewable sources in Chile is cheaper than conventional power generation based on fossil fuels.

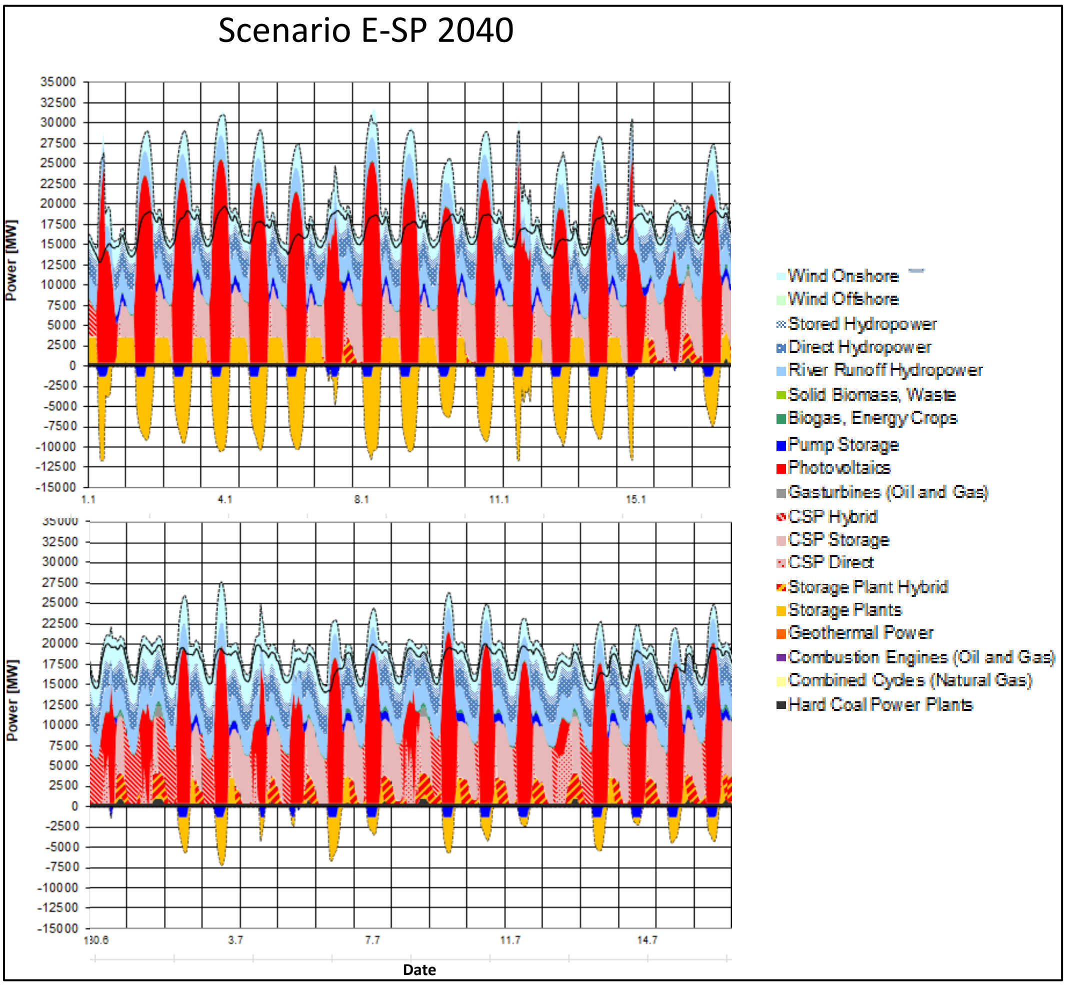


Figure 16: Hourly Time series of electricity consumption and production for the model year 2040 of Scenario E-SP. Negative values indicate electricity sent to storage, positive values indicate electricity production and net demand (solid black line). Dashed line: gross consumption including stored electricity. Production surpassing dashed line indicates curtailed surplus. Top: high solar radiation period in January. Bottom: low solar radiation period in July.

Figure 16 shows the hourly generation break down for two weeks in summer (January) and in winter (July) for Scenario E-SP. Its demand is being fully covered by Thermal Storage Plants charged by extended PV capacity and a large share of concentrating solar thermal power plant capacity (7.3 GW of CSP by 2040) to fill the appearing supply gaps. CSP plants can easily fill the gap by direct supply, through their thermal storage and by co-firing with natural gas (or alternatively biomass).

This co-firing measure perfectly solves the problem at particularly low cost and fully complying with the needs of system redundancy concerning firm power capacity, as has been discussed before. At the same time, this measure avoids increasing consumption of natural gas that otherwise would be needed in view of the strongly growing demand and at the same time decommissioning Chile`s coal plants (or better modifying them to Thermal Storage Plants).

4. Conclusions, Recommendations and Next Steps

Figure 17: Model of future CSP, PV, wind, biomass, hydro, converted coal into storage and combined cycle gas plants to cover Chile's power demand (https://4echile.cl/maqueta/)

In section 3 of this study it was shown both for Chilean Scenarios "Planificación Energética de Largo Plazo (PELP)" A and E, that with the addition of further CSP plants with storage and the conversion of existing coal plants into thermal storage plants, the growing peak load in Chile can be covered with renewable sources and maintaining Chile's security of supply while significantly reducing carbon emissions and reducing Chile's levelized cost of electricity generation with renewable sources. The various elements of such future power park in Chile are illustrated in the model of Figure 17.

In section 0 the performance and cost of retrofitting state of the art molten salt storage technology to a selected existing Chilean coal plant of 250MWe class (net) were determined. Best annual round trip efficiencies around 38% and lowest levelized cost of discharge electricity below 90USD/MWhe were obtained for long duration discharge periods of 12-14 hours. With such conversion, existing Chilean coal plants can be fully decarbonized while conserving most of their power plant jobs.

As next steps it is recommended, to carry out a detailed engineering study of the proposed retrofit of molten salt storage with electrical salt heaters and molten salt steam generators in an existing Chilean coal plant in order to obtain commercial offers and explore the funding and financing options for such measure.

In parallel, Chilean power market regulation should be revised and its competitive remuneration mechanisms be adapted to incentivize with respective bankable storage energy and/or capacity long term off take arrangements such decarbonization and conversion of existing Chilean coal plants into thermal storage plants. To make such conversion competitive and economic, the permitted discharge duration should be extended from 5 full load hours per day to 14 full load hours per day without elimination of the respective plant capacity payment.

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