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Assessing flexibility for integrating renewable energies into carbon neutral multi-regional systems: The case of the Chilean power system

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ABSTRACT

Reducing emissions from power systems requires enhancing the penetration of non-conventional renewable energy sources (NCRE) in the generation mix. However, such penetration requires high levels of operational flexibility in order to ensure an adequate balance between generation and demand. Concentrating solar power plants with thermal storage (CSP-TES) and battery energy storage systems (BESS) have shown to possess technical characteristics compatible with such high flexibility requirements. However, due to the high capital costs of these technologies, decision-makers must seek for cost-effective configurations and operation modes. This study presents the development of a methodological framework for designing the long-term transition of a multi-regional energy system towards a low carbon emission system. The sought system is characterized by a high penetration of NCRE, and the use of CSP-TES, BESS and electricity transmission settings for providing effective levels of operational flexibility. For this, the transformation of the Chilean electricity system between the years 2018–2050 is studied, using a tailored modification of the well-known OSeMOSYS optimization tool for energy systems planning. The main results indicate that by 2050, and considering a baseline scenario defined for 2016, for most of the scenarios studied the renewable electricity generation would be at least a 90 % and CO_2 emissions would be 75 % lower. Furthermore, it is shown that providing operational flexibility to the system requires a mixed generation from hydroelectric reservoirs, CSP-TES plants, BESS, pumped-storage hydropower and natural gas generators. The obtained results allow planning the capacity and operation of CSP and BESS plants, which are adapted to the future flexibility requirements of the Chilean electric power system. Incentive policies like stimuli to growth BESS, would favor primarily the photovoltaic growth of the system at the expense of CSP-TES capacity, while CSP-TES growth incentives would maintain photovoltaic generation levels, but would decrease Wind and natural gas generation.

Introduction and motivation

The energy systems from several developing countries are in a crucial period, featured by many related aspects such as the dynamism of energy markets due to the rapid evolution of renewable generation technologies on the one hand; and the need to reduce greenhouse gas (GHG) emissions, enhance energy access, improve the power systems reliability, and lower energy costs on the other hand. To face this reality, several countries have set goals in terms of increasing generation through renewable sources, which would allow them to exploit the large amount of resources available in regions such as Africa, South America and Asia (Afful-Dadzie et al., 2020). This, in turn, would also aid in avoiding local health problems associated with large industrial facilities such as coal fired power plants (Ruiz-Rudolph et al., 2016), thus improving family economy (Wassie & Adaramola, 2021) and promoting a better life quality (Ortega et al., 2021) overall.

However, this energy transition is not without its challenges, since it is pointed out that different elements could limit the insertion of these technologies, such as lack of access to project financing, little competitiveness with respect to the production costs of technologies based on

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fossil fuels, and technical challenges associated with the planning-operation of systems with high renewable penetration, among others (Vanegas Cantarero, 2020).

An important component of the technical complexity associated with planning-operation is related to the fact that for many of these systems this transformation initiates with an infrastructure characterized by high levels of generation through fossil fuels, which are characterized by providing a dispatchable generation source. Replacing these technologies with others whose behavior is intrinsically variable represents a challenge for the system's planning and operation (Tsai et al., 2020). Therefore, this transition will only be achieved safely if power systems have sufficient flexibility to guarantee the balance between generation and demand (IEA, 2019), which is only possible through proper planning.

For this reason, a large number of studies have been carried out to guarantee the transition towards systems with greater renewable participation. One of the approaches is to use hybrid technological configurations that allow integrating variable renewable generation sources such as wind (WI) and photovoltaic (PV), with technologies that allow managing the hourly load such as concentrated solar power with thermal energy storage (CSP-TES) and battery energy storage system (BESS). In this way, variability in renewable generation could be mitigated.

For example, in Zurita et al. (2018), a methodology for sizing a hybrid CSP + PV plant with TES and BESS for base generation is presented. The authors showed that technology configurations based on renewable sources can be used for base load supply. However, only under BESS cost reduction scenarios the hybrid plant operation with both types of storage led to a synergistic performance. The proposed configurations reached a levelized cost of electricity (LCOE) of between 75 and 95 $/MWh. In isolated systems, such as an autonomous rural system (Chennaif et al., 2021), it was found that the proposed CSP-PV-WI with TES and BESS configurations were sensitive to the desired value of loss of power supply probability. In general, the higher the system's reliability sought, the higher the obtained LCOE. Although the use of hybrid technologies would allow for a stable supply of energy through renewable sources, one of its main challenges is associated with its high costs, which is particularly critical in the context of developing countries.

Another approach is based on building electrical systems flexible enough to allow for high levels of renewable generation. In this sense, energy planning models (EPM) are useful tools to assess the effects of long-term and large-scale integration of variable renewable generation technologies, and to find cost-effective transition pathways that enable such integration (Pfenninger et al., 2014). Their use allows for the integration of variable generation technologies (PV + WI), dispatchable generation technologies, transmission, and storage capacities, while incorporating long-term planning with short-term operating restrictions (Poncelet et al., 2020). Based on these tools, different ways of configuring electrical systems for safe operation have been analyzed in previous works, some of which have focused their analysis on the role that the different elements of the system could play. For example, in relation to the transmission system, in Taliotis et al. (2016), an energy planning model was developed in the Open Source Energy Modeling System (OSeMOSYS) for Africa, between 2020 and 2040, including 47 countries. Some of the most important results indicate that transmission between regions could help to complement the renewable generation among them, inducing a drop in electricity costs. This effect could be greater as electricity demand increases (Valickova & Elms, 2021).

Authors such as English et al. (2020) have highlighted the importance of representing the flexibility requirements of the systems within energy planning models, since this impacts on the predicted generation mix and transmission capacities. They used OSeMOSYS for modeling the power system of two western Canadian provinces. The obtained results indicate that transmission can extend the flexibility provided by technologies such as hydro-dams, to regions where their potential is limited.

Other studies use energy systems models to explicitly account for cost-effective technologies that provide flexibility for large-scale renewable integration, such as CSP-TES or BESS. For example, in Fichter et al. (2017), the long-term power sector capacity expansion in Northeast Brazil was studied using the REMix-CEM model, to understand the role of CSP-TES and backup systems in providing flexibility to highly variable renewable power systems. The authors found that the least-cost alternative for capacity expansion resulted in hybrid CSP and biomass plants, which were shown able to provide flexibility, increase frequency response, and provide operational reserve services in future renewable systems.

In a similar study presented by Soria et al. (2016), also for the Brazilian case, the energy system was modeled by linking three energy systems models (MESSAGE-BRAZIL, TIMES-TiPs-B, and REMix-CEM), in order to assess the role of CSP in supplying increasing electricity demands and in providing flexibility for high-share renewable power systems. According to the obtained results, CSP was proven to be cost-effective under strict carbon reduction scenarios, showing good complementarity with PV and WI generation in the regions with the highest solar radiation. CSP could offer additional flexibility to the system, especially during dryer hydrological periods.

Authors such as Mena et al. (2019), found that if the evolution of capital costs for CSPs are not favorable by 2040, additional policies such as an increase in the CO_2 emissions tax may be necessary to make CSP-TES technologies more competitive against generation technologies based on coal and natural gas, even in regions with high solar radiation such as northern Chile. Others have highlighted that the insertion of CSP-TES could positively impact the variable cost component of the system. For example, in Du et al. (2018) it is pointed out that the substitution of PV + WI capacity for CSP capacity could reduce variable costs of thermal power plants, such as fuel, ramping and start-stop costs. This impact would be greater in systems with deficiencies in their operational flexibility, but the marginal benefit would decrease with the increasing proportion of substituting VRE with CSP.

In relation to power storage, probably its greatest challenge is associated with its high capital costs (Solomon et al., 2014), so optimal configurations are necessary to make it economically competitive (Weitemeyer et al., 2015). However, various authors have shown the benefits of its use in systems with high renewable penetration. In (Reyseliani & Purwanto, 2021) 100 % renewable scenarios were evaluated for the Indonesian electricity system to 2050. It was found that the large-scale deployment of BESS could support a system based primarily on photovoltaic generation, although with significant impacts on electricity production costs. When studying the relationship between transmission and storage capacities, Laha and Chakraborty (2021) found that unconstrained growth in transmission capacity in India's power system would decrease BESS storage requirements. They also noted that when the level of variable renewable generation increases, the marginal requirements for storage capacity become even greater.

As explained above, along with an ad-hoc transmission infrastructure and operation, one of the main sources of flexibility compatible with an expansion on renewable generation corresponds to energy storage and dispatchable generation technologies such as hydro-dam plants and CSP-TES (Huertas-Hernando et al., 2017; Zhang et al., 2021). Although hydro-dam technologies have been an important source of flexibility, the potential for the installation of these type of plants is limited in many power systems. Fortunately, over the last decades the production and operation costs of storage technologies have decreased steadily (Schmidt et al., 2017); therefore, the combined operation of BESS and CSP-TES seems to be a promising alternative to address the operative high levels of variable renewable generation.

The literature discussed previously reveals that planning long-term transitions of energy systems towards systems with a higher renewable presence requires not only to select cost-effective renewable generation technologies. It also requires to incorporate infrastructure and plan operation that is capable of ensuring enough flexibility in order to deal with operational challenges produced by the variable nature of renewable sources such as PV and WI.

Notwithstanding, to the best of our knowledge, no previous work has presented an energy system modeling approach for simultaneously characterizing the role of CSP-TES, BESS, and transmission expansion, in the transition towards more renewable systems that are able to guarantee the required flexibility.

Our contribution and paper outline: Our main contribution corresponds to the development of a methodological framework, using a customized adaptation of the OSeMOSYS energy systems model (Howells et al., 2011) for designing the long-term transition of a multi-regional energy system towards a low carbon emission system, characterized by high penetration of NCRE, and with special emphasis on effectively addressing the requirements of operational flexibility. For the development of our approach, we consider the Chilean power system as case study, whose features are particularly challenging for the considered decision-making setting and can be described as a case with: (i) high potential for variable renewable generation (solar and wind), (ii) high potential for generation through CSP-TES, (iii) a limited capacity for reservoir hydroelectric plants (so that the sources of flexibility in renewable generation would potentially be CSP-TES and BESS), and (iv) a recent governmental directive for closing all coal generators by 2040. The OSeMOSYS system is customized by adding short-term operating constraints and new restrictions to represent technological mix within the energy system, as well as the seasonal behavior of technologies such as hydroelectric reservoir plants. The resulting framework is used, on the one hand, to design transition pathways towards power systems with high levels of renewable generation; and on the other, to characterize the role of CSP-TES and BESS technologies, inter-regional transmission expansion, and energy curtailment, in ensuring flexibility and operability in such large-scale power systems.

The obtained results demonstrate that high levels of variable renewable generation, such as photovoltaic and wind, require a planned growth of dispatchable generation technologies, such as CSP-TES, hydro-dam and gas-fired power plants, along with an adequate transmission capacity. The proposed framework is capable of designing a transition path, for a real power system, that not only ensures a generation mix that accomplishes emission reduction goals but also ensures effective flexibility mechanisms (such as energy storage systems and inter-regional transmission) to endure the variability of NCRE technologies.

The paper is organized as follows. In Energy system modeling: methodology and case study section we present the methodological details of the proposed approach; the energy system modeling using OSeMOSYS framework (Energy system modeling for long term planning section) and the case study description (The Chilean power system: description and decision scenarios section). In Results and discussion section we describe and discuss the obtained results, highlighting the structure and operation of the obtained transition pathway and the influence of the different considered scenarios. Finally, in Conclusions and policy implications section we draw conclusions and set out avenues for future work.

Energy system modeling: methodology and case study

As previously mentioned, the proposed methodological planning framework features OSeMOSYS as a modeling and optimization tool for planning the expansion of the power system. In this section, a general description of the OSeMOSYS structure (Energy system modeling for long term planning section), flexibility representation and new functionalities (Flexibility representation and new functionalities section), and Chilean system planning scenarios (The Chilean power system: description and decision scenarios section), are presented.

Energy system modeling for long term planning

In this work, the configuration and operation of the power system is represented through the OSeMOSYS (Howells et al., 2011) model for planning energy systems, which determines the expansion and operation of the system that minimizes the total updated cost, satisfying the energy demand requirements. In this model, the objective function aims at minimizing the total discounted cost of the expanding and operating system and is accompanied by a group of constraints. In the same way as other long-term planning tools, OSeMOSYS is based on general assumptions such as single-decision makers, perfectly competitive markets, and inelastic and known demand (Howells et al., 2011).

The mathematical programming model embedded within OSeMOSYS involves an important number of variables and parameters. For the specific case of a power system, the model optimizes the new capacities of each generation and transmission technology (whose corresponding decision variables are encoded by vector $\mathbf{x}$) and their activity levels (whose corresponding decision variables are encoded by vector $\mathbf{y}$). When capacities correspond to electricity generation technologies, the activity levels are closely related to the corresponding dispatching schedules. Additionally, vector $\mathbf{z}$ encodes all the auxiliary variables required for adequately modeling energy balances and other technological and operational boundary conditions. Conceptually, the structure of the mathematical optimization model that encodes the underlying energy system planning problem can be expressed as follows:

$$
\begin{aligned}
z^* = \min \quad & \text{Total Discounted Cost}(\mathbf{x},\mathbf{y},\mathbf{z}) & \\
\text{s.t.} \quad & \mathcal{A}(\mathbf{x},\mathbf{y},\mathbf{z}) \geq 0 & \text{(Capacity adequacy)} \\
& \mathrm{E}(\mathbf{x},\mathbf{y},\mathbf{z}) \geq 0 & \text{(Energy balance)} \\
& \mathrm{R}(\mathbf{x},\mathbf{y},\mathbf{z}) \geq 0 & \text{(Renewable target)} \\
& \mathcal{C}(\mathbf{x},\mathbf{y},\mathbf{z}) \geq 0 & \text{(Cost)} \\
& \mathcal{N}(\mathbf{x},\mathbf{y},\mathbf{z}) \geq 0 & \text{(New capacities)} \\
& \mathcal{S}(\mathbf{x},\mathbf{y},\mathbf{z}) \geq 0 & \text{(Storage)} \\
& \mathcal{U}(\mathbf{x},\mathbf{y},\mathbf{z}) \geq 0 & \text{(Unit commitment)} \\
& \mathcal{K}(\mathbf{x},\mathbf{y},\mathbf{z}) \geq 0. & \text{(Additional constraints)}
\end{aligned}
$$

The model describes the behavior of an electrical system that can be divided into several regions, according to characteristics such as: geographic location, generation potentials and electricity transmission systems. The representation of the considered technologies and of the energy carriers that relate them is shown in the reference energy system (RES), presented in Fig. 1. The rectangles represent the technologies considered, the connecting lines represent the carriers of energy or fuels, and the ovals represent the energy storage. Next, the components considered to represent the behavior of the power system are described, which range from the system's energy inputs to the final distribution of electrical energy.

1. **Energy resources:** Four sources of fuel entry into the system are considered: Coal, diesel, natural gas and biomass. These energy sources can be imported or produced within the system.

2. **Power generation technologies:** The electricity generation technologies considered are coal-fired power plants, natural gas open-cycle power plants, natural gas combined-cycle power plants, diesel power plants, photovoltaic solar plants, concentrating solar power plants with thermal energy storage, onshore wind turbines, biomass-fired steam power plants and geothermal power plants. The hydroelectric plants were grouped as diversion (run-of-the-river) facilities and hydro dam facilities. Variable renewable generation technologies such as wind, photovoltaic, geothermal, solar field and hydro river, are restricted according to the hourly availability of the resource. On the other hand, hydroelectric reservoir plants are limited according to the availability for each season of the year, and biomass is constrained to the annual fuel availability.

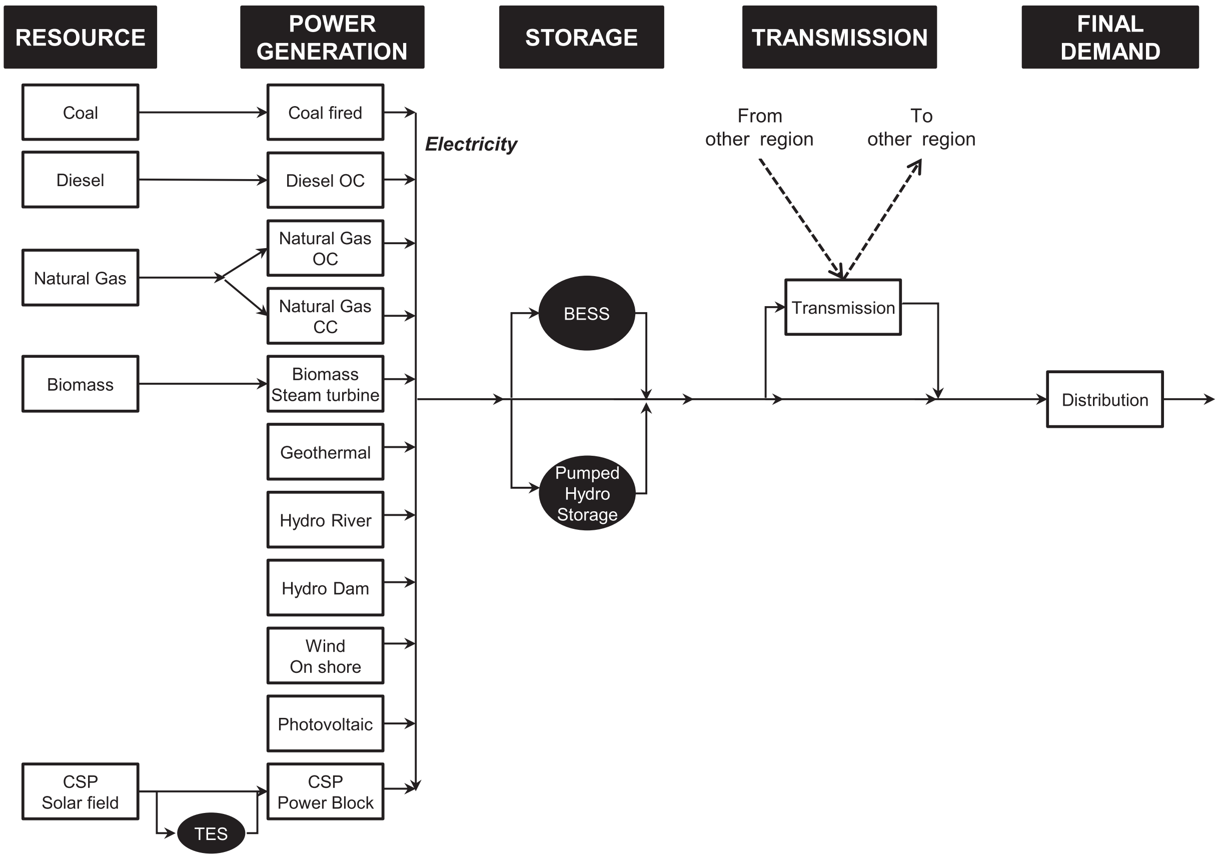

Fig. 1. Reference energy system for a characteristic region of the model. (CSP) Concentrated solar power, (TES) Thermal energy storage, (OC) Open cycle, (CC) Combined cycle & (BESS) Battery energy storage system.

3. **Storage:** Within the model, three energy storage alternatives are considered. The first is the thermal energy storage associated with CSP-TES, the second is the storage of electricity by lithium-ion batteries and, finally, pumped-storage hydropower.
4. **Transmission:** The representation of the transmission system is encompassed by two components. The first component is associated with electricity transfer between the place where the energy is generated and the main node to which it is sent (typically substation). The second component represents the electrical exchange between regions, which corresponds to the high voltage lines between substations.
5. **Distribution:** The distribution system corresponds to the infrastructure between the substations (which are fed by transmission system) and the final consumers.

The decision-making model whose main elements are described above, considers a planning horizon comprised by three-year investment periods, within which the new generation-transmission capacities are selected. Additionally, each period is divided into 96 time slices, corresponding to the representation of 4 typical days with a 1-hour resolution. The operation associated to these typical days is encoded by the constraint $\mathcal{U}(\mathbf{x},\mathbf{y},\mathbf{z})\geq 0$, which corresponds to a proxy of the underlying Unit Commitment problem, and it features the extensions to the OSeMOSYS code proposed by Gardumi et al. (2019) and Welsch et al. (2015). In particular, $\mathcal{U}(\mathbf{x},\mathbf{y},\mathbf{z})\geq 0$ allows including ramp-rates, start-up rates, minimum stable operation levels, ramp costs and – when operating at partial load – additional fuel consumption levels. It is important to point out that due to the functional and mathematical nature of the Unit Commitment problem, its explicit formulation is generally either excluded, or simplified, in long-term energy planning models (see, e.g., Koltsaklis & Dagoumas, 2018).

Flexibility representation and new functionalities

The operational flexibility of the system represents its ability to modify its production or consumption of electricity in response to variability, expected or otherwise (IEA, 2012). When the system experiences a higher level of variable renewable generation, the flexibility requirements will be greater, being able to be provided by different sources such as demand, generation, storage, curtailment or transmission (Poncelet et al., 2020).

The dispatchable generation technologies responsible for providing flexibility to the system that are represented within the model are: Hydro-dam, CSP-TES, BESS, Natural Gas, Diesel and Coal-fired.

The fundamental parameters that these technologies represent are shown in Table 1.

Table 1
Ramping characteristics as capacity percent (AG, 2018; CNE, 2020a, 2020b, 2020c; Coordinador Eléctrico Nacional, 2020a, 2020b, 2020c).

Technology	Minimum stable operation [%]	Ramping up [%/min]	Ramping down [%/min]	Ramping Costs [$/MW]	Start-up rate [%/h]
CSP-TES	30	20	20	15	50
Natural gas CC	40	25	25	30	35
Natural gas OC	40	25	25	30	40
Diesel OC	30	30	30	50	100
Coal fired	40	10	10	50	15
BESS	0	100	100	–	100
Hydro dam	10	25	25	50	100

The second component of system flexibility represented within the model is the operating reserve requirements. Depending on the time scale in which they should be delivered, they can be classified as (NREL, 2015; Palmintier et al., 2015): Regulation reserves, which must be delivered in less than 1 min and can be estimated as 1 % of the estimated instantaneous electricity demand; spinning contingency reserves, which must be delivered in less than 10 min and can be estimated as 3 % of the instantaneous demand plus a contingency reserve associated with the largest unit in the system; and flexibility reserves, which must be delivered in less than an hour and can be estimated as 7.5 % of the PV generation and 10 % of the WI generation planned for each time slice.

Operating reserves constraints were represented in OSeMOSYS as proposed by Welsch et al. (2015). Regulation and spinning reserves are grouped as primary reserves, and flexibility reserves as secondary. To achieve this representation within the model, a first run is performed for each scenario in which no reserve requirements are specified. Once a first value is obtained for the estimated generation of PV and WI, the secondary reserve requirements can be estimated for each case. The maximum contributions by technology to each type of reserves will depend primarily on parameters such as minimum stable operation and ramp rates. The values used in this work are shown in Table 2.

Additionally, to achieve a more detailed representation of the technologies in OSeMOSYS, a set of additional restrictions were proposed. Frequently, some technologies can be represented by combining different components. For example, CSP-TES can be modeled as the combination of a technology that is responsible for capturing heat from the sun (Solar field), a thermal energy storage system (TES), and a power generator. The specific proportions in which these elements are dimensioned, give rise to the different CSP-TES configurations. In OSeMOSYS these proportions cannot be explicitly specified, so in order to fix them, two additional restrictions were included. Their detailed description is shown in the supplementary material (Conclusions and policy implications section).

The first, Eq. (1), allows to regulate the proportion between the total capacities of two technologies. For example, in the case of CSP-TES technology, it could express the ratio between the capacity of the solar field and the capacity of the generator, typically expressed as the *solar multiple* factor. The second, Eq. (2), allows to regulate the ratio between the total capacity of a technology and the total capacity of a storage unit. For example, in the case of a BESS plant, it could represent the ratio of the energy storage capacity to the capacity of the Power Conversion System (PCS), frequently expressed as the E/P ratio.

Finally, the availability of resources in OSeMOSYS can be represented for the investment periods (typically years) and for the hourly blocks (from minutes to hours). However, there are certain resources whose availability depends rather on the seasons of the year. This is the case of technologies such as hydroelectric reservoir plants. In practice, these technologies can manage the availability of a resource (in this case water), over periods that can range from hours to months. To include this modeling possibility within OSeMOSYS, an additional restriction was included, Eq. (3), through which the maximum average activity that a technology can experience within a season of the year can be limited. A detailed description is shown in the supplementary material (Conclusions and policy implications section).

Table 2
Maximum contributions to operating reserve requirements by technology (AG, 2018; CNE, 2020a, 2020b, 2020c; Coordinador Eléctrico Nacional, 2020a, 2020b, 2020c).

Technology	Primary Up [%]	Primary Down [%]	Secondary Up [%]	Secondary Down [%]
CSP-TES	5	5	35	35
Natural gas CC	10	10	50	50
Natural gas OC	10	10	50	50
Diesel OC	10	10	50	50
Coal fired	5	5	35	35
BESS	30	30	100	100
Hydro dam	15	15	50	50

The Chilean power system: description and decision scenarios

This section details the case study built on the Chilean power system between 2018 and 2050, which involves the decommissioning of all coal-fired thermal power plants by 2040 (Ministerio de Energía de Chile, 2020a, 2020b, 2020c, 2020d) and reaching carbon neutrality for the energy system by 2050 (Ministerio del Ambiente de Chile, 2019). The data sources used to build the model and the definition of scenarios are detailed in the following sections.

Chilean National Electric System

The proposed model was used to find cost-effective transitions of the Chilean National Electric System (CNES) between 2018 and 2050. To express the future costs in the present 2018 value, a discount rate of 6 % according to what is indicated in the general law of electrical services was used (Ministerio de Economía, Fomento y Reconstrucción de Chile, 2006; Ministerio de Desarrollo Social y Familia de Chile, 2021).

The group of technologies available to the CNES is constructed based on those that are in operation at the beginning of the modeled period (Coordinador Eléctrico Nacional, 2020a, 2020b, 2020c), and those that could be operational during the study horizon (Ministerio de Energía de Chile, 2018a).

In relation to the spatial domain, the model covers the territory corresponding to the CNES, divided into four regions, which group the following Chilean administrative units:

- Region I: Arica y Parinacota, Tarapacá and Antofagasta.
- Region II: Atacama and Coquimbo.
- Region III: Valparaíso, Metropolitana, O'Higgins and Maule.
- Region IV: Ñuble, Bío-Bío, Araucanía, Los Ríos and Los Lagos.

Fig. 2 shows the geographic distribution of these four regions, along with the annual demands and generation capacities in the CNES by 2018.

The potential associated with the renewable generation sources, for each modeled region, are shown in Table 3, the entries in this table are obtained from the official sources (Ministerio de Energía de Chile, 2018a, 2018b; Ministerio de Energía de Chile, 2020a, 2020b), which incorporate some of the modeling techniques presented in Santana et al. (2014). With the historical CNES generation records from the period 2016–2020 (available in Coordinador Eléctrico Nacional, 2020a, 2020b, 2020c), we are capable of estimating the hourly capacity factor for each typical day and for each region. For this process, we only considered the data associated with renewable plants with at least one year of continuous operation and none energy curtailment events. In this deterministic model we used these profiles and, as well as Mena et al. (2019) and Jayadev et al. (2020), we did not consider the variations in the hourly renewables' generation profiles among years.

The technical economic parameters such as CAPEX, OPEX, fuel costs, electricity demand, installed capacity and short-term operating restrictions were obtained from different sources and are summarized in Supplementary Material (Conclusions and policy implications section).

The supply of natural gas as an energy resource is determined by the capacity of Mejillones and Quintero regasification terminals, located in regions I and III, respectively. These terminals import liquefied natural gas within the framework of take or pay contracts signed by the generating companies (Coordinador Eléctrico Nacional, 2019). In this model, the imports of natural gas from Argentina are not considered, because its current penetration in the generation mix is low and the Chilean government is not considering to increase its participation in the midterm (see, e.g., Ministerio de Energía de Chile, 2020a, 2020b, 2020c, 2020d, for further details).

Coal and diesel imports are made available for the 4 modeled regions. Biomass as fuel for generation technologies is mainly associated with the use of forest residues located towards the south of the country,

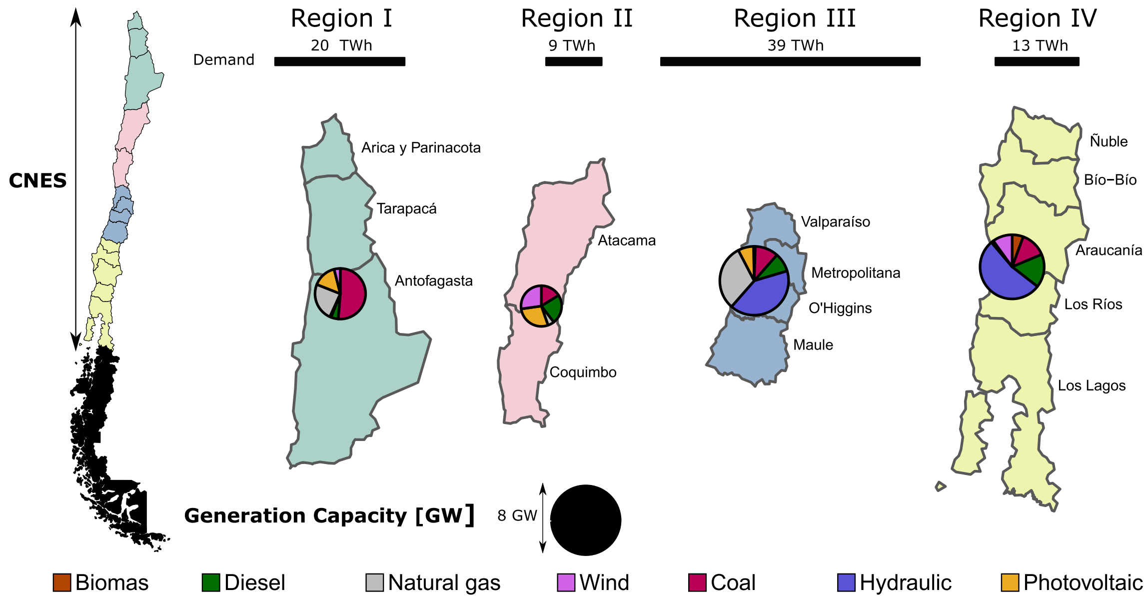

Fig. 2. Territory covered by the CNES and the regional grouping used. Annual electricity demand and installed capacity in 2018 by region modeled.

mostly in regions III and IV. Electricity generation through biogas was not considered in this study.

To quantify the electricity transfer between the place where it is generated and the main node to which it is sent, the average routes of the plants responsible for 90 % of the installed capacity for each region were characterized, integrating the information of the substations and transmission lines (Coordinador Eléctrico Nacional, 2020a, 2020b, 2020c) with the unilineal diagrams (Coordinador Eléctrico Nacional, 2015; Coordinador Eléctrico Nacional, 2017). The trade between regions is represented by the national transmission system with lines at voltages above 220 kV. For this, the transmission lines between central nodes of each region were selected, and the transmission losses are modeled following the ad-hoc model presented in Mena et al. (2019).

Decision scenarios

To obtain an idea of the impact of technological, economic, environmental and regulatory elements, three decision-making scenarios were devised. Next, the constituent elements of the studied scenarios are detailed, followed by a description of how they were configured.

NCRE capital costs: Three levels of capital costs for the NCRE were considered: high, medium and low projections, according to those proposed in Ministerio de Energía de Chile (2020a, 2020b, 2020c, 2020d). The reference scenario is based on the medium projection of capital costs for generation and BESS technologies.

Hydroelectric contribution: The activity of the hydroelectric plants was limited based on the information of the year 2016, corresponding to the most unfavorable hydrological conditions in the last 25 years (CNE, 2020a, 2020b, 2020c).

Additional parameters: The evolution of fossil fuel prices was estimated according to the projections presented in Ministerio de Energía de Chile (2020a, 2020b, 2020c, 2020d), taking the low projection for the reference case. The medium projection for annual electricity demand forecasted in Ministerio de Energía de Chile (2020a, 2020b, 2020c, 2020d) was used. The decommissioning schedule to 2040 of coal-fired thermal power plants presented in Coordinador Eléctrico Nacional (2018) was included. In Chile, CO_2 emissions have a tax of 5 $\$/tCO_2$ (Ministerio de Hacienda de Chile, 2014), which was kept constant during the study period.

Taking into account the aforementioned parameters, three studied scenarios were constructed. These are based on common elements such as coal-fired power plants decommissioning schedule, taxes on CO_2 emissions, projected electricity demand, hydrology, performance of technologies and availability of transmission and generation technologies by region. As such, the scenarios are as follows:

- Reference case (**Scenario A**): The capital cost for generation technologies, fuel costs and hydrology are set at their reference values.
- Emission pessimistic (**Scenario B**): This variant of the reference case is based on high cost projections for NCRE. Therefore, this scenario is likely to be associated to lower investment levels on low-emission technologies.
- Emission optimistic (**Scenario C**): In contrast to **Scenario B**, low cost projections for NCRE and high cost projections for fossil fuel-based technologies were selected. Therefore, this scenario is likely to be associated to higher investment levels on low-emission technologies.

These three scenarios are capable of capturing a wide range of projections with respect to investment and operational costs for different technologies. Therefore, most of the discussion and conclusions are based upon the results obtained from carrying out numerical analyses on them. However, and for the sake of completeness, we also consider two additional scenarios with the aim of measuring the sensitivity of the obtained planning strategies if higher levels of BESS or CSP-TES technologies are incorporated. These scenarios can help to understand how the electrical system could evolve if the installation of BESS or CSP-TES plants were encouraged. The first of these scenarios, **Scenario D**, corresponds to the reference case, but considering low capital cost projections for BESS technology. The second of

Table 3
Renewable generation potential by CNES region [GW] (Ministerio de Energía de Chile, 2018a, 2018b, 2020a, 2020b).

Generation technology	I	II	III	IV
Photovoltaic	>100	>100	7.6	0
Wind on-shore	11.5	1.8	0.1	24
Concentrating solar power	>100	30	0	0
Pumped-storage hydropower	1.2	0	0	0
Hydro river	0	0	3.2	5
Geothermal	1.5	0	0.3	0.2

Hydro dam technology does not have more capacity than the one already installed.

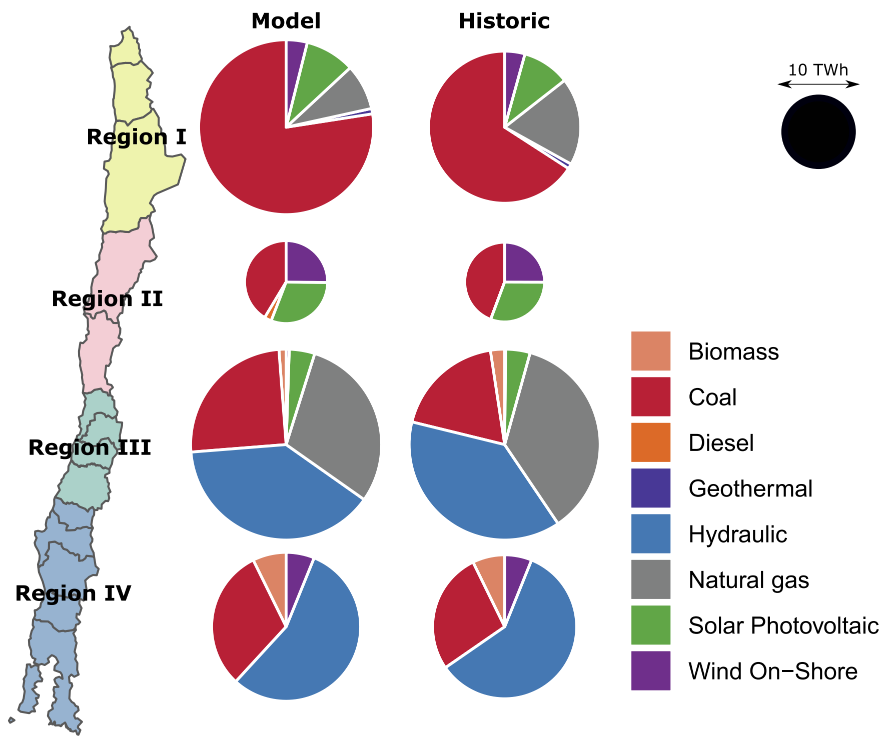

Fig. 3. Model calibration for base period 2018–2020. Historic generation and model output for CNES regions.

these scenarios, **Scenario E**, corresponds to the reference case, but considering low capital cost projections for CSP-TES technology. Results for these scenarios are reported and discussed in High BESS and CSP-TES penetration scenarios section.

Results and discussion

This section shows the cost-optimal transition of the Chilean power system between the years 2018–2050, from its current situation, towards a low-carbon future, driven by current policies and high potential for renewable generation. Components such as generation capacity (Generation capacity section), electricity trade between regions (Transmission between regions section), hourly generation profile (Hourly generation profile and flexibility section), high BESS and CSP-TES penetration scenarios (High BESS and CSP-TES penetration scenarios section) and generation mix (Mix of generation and emissions section) are presented.

Before running the different scenarios, the model was calibrated with real generation statistics of the CNES for the years 2018, 2019 and 2020 (Fig. 3), finding that, despite the level of spatial, temporal and technological aggregation on which the model is based, the generation mixes and the total amounts of energy generated by region are quite similar to the real ones.

Generation capacity

The first element to analyze is the total electricity generation capacity and the share of different technologies in the study horizon (Fig. 4), together with their regional allocation (Fig. 5).

From the first three plots in Fig. 4 (from left to right), we can observe that the total generation capacity of the CNES increases from 24 GW in

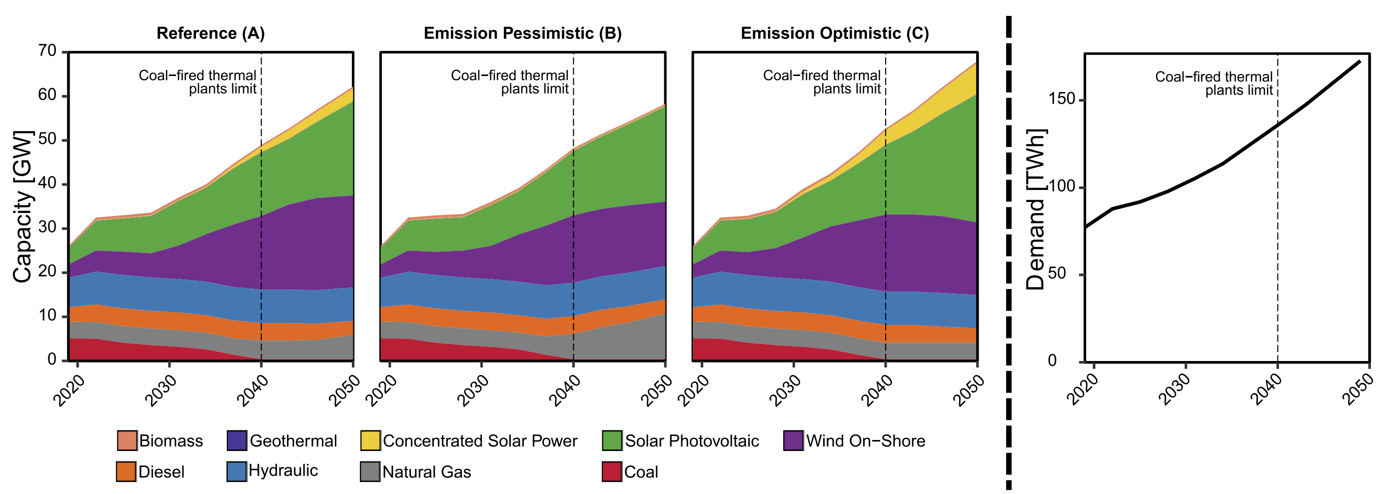

Fig. 4. Installed capacity (GW) for the studied scenarios and annual electricity demand (TWh) between 2018 and 2050.

2018, to 62 GW (**Scenario A**), 59 GW (**Scenario B**) and 66 GW (**Scenario C**) by 2050. In 2018, NCRE, hydroelectric, and thermal plants contributed to 22 %, 28 % and 50 % of the total installed capacity, respectively. The modeled scenarios show that these would contribute to 64–77 %, 11–13 %, and 11–23 % of the total installed capacity by 2050, respectively. From Fig. 5, we observe that, in absolute terms, Region I shows the highest growth, with new accumulated capacities by 2050 of approximately 23 GW in **Scenario A**, and up to 27 GW in in **Scenario C**. The second region with the most significant growth is Region III, with values between 8 and 11 GW for the three scenarios.

In the rightest plot in Fig. 4 we report the power demand estimation between 2018 and 2050. When compared to the three first plots in the figure (from left to right), we can observe that for the three studied scenarios, the generation capacity increases as the power demand increases. Likewise, for the scenarios with larger penetration of PV + WI (**Scenario A** and **C**), the designed system is characterized by a larger generation capacity when compared to **Scenario B**. This is explained by the fact that photovoltaic and wind power technologies feature lower annual capacity factors with respect to CSP-TES and natural gas plants; hence, the scenarios with larger PV + WI penetration would require a larger installed capacity to satisfy the same power demand when compared to those scenarios with lower PV + WI penetration.

When observing the generation capacity per technology type by 2050, solar photovoltaics are predominant, with an installed capacity of 21–27 GW, followed by wind, with 16–22 GW. The new photovoltaic capacities are installed mainly towards the north (Region I) - emplaced within the Atacama desert - with values between 9 and 14 GW. The south, (Region IV) on the other hand, would see a predominance of wind generation capacity, reaching values between 8 and 9 GW. The photovoltaic growth is related to the fact that it is the technology with the lowest LCOE among those with high growth potential (see Table 3), due to the region's outstanding radiation conditions.

In relation to the growth of CSP-TES technologies, their capacity would be between 0.2 and 7 GW by 2050, starting to grow after 2030 and accelerating between 2040 and 2050. The CSP-TES growth is highly dependent on capital cost projections. In general, for projections of high capital cost (**Scenario B**), its penetration is limited, but improves substantially as its capital costs tend to fall. When CSP-TESs LCOE are far higher than those of wind and photovoltaics, its growth depends on how competitive it could be against natural gas plants. For this reason, for the reference scenario (**A**), between 2040 and 2050, where the LCOE of CSP-TES is lower than that of gas plants, its growth in region I is higher than gas plants' growth (see Fig. 5). However, if the capital cost projections for CSP-TES decrease, as in **Scenario C**, LCOE can approach that of wind. This is corroborated when observing that wind growth in region I is practically zero for **Scenario C** between 2040 and 2050, coinciding with the higher CSP-TES growth (see Fig. 5).

Regarding storage, for all the scenarios studied, pumped-storage hydropower capacity located in Region I is completely maxed out between 2025 and 2040. On the other hand, BESS plants reach capacities between 10 GWh (**Scenario A**) and 18 GWh (**Scenario C**) by 2050, which are implemented mainly in the years after the installation of pumped-storage hydropower plants in regions I and II. For **Scenario A** and **B**, combined storage capacity (BESS + Pumped-storage hydropower) would not exceed 7 % of average daily demand by 2050, and is mainly associated to pumped-storage hydropower plants. However, if the capital cost projections of BESS improve **Scenario C**, the combined storage capacity could reach up to 10 % of the average daily electricity demand. These results confirm that systems with high VRE penetration could operate with much lower storage capacities than daily demands (Jayadev et al., 2020; Solomon et al., 2014).

Finally, no significant growth was observed in hydroelectric generation capacity, beyond the projects declared under construction by 2020, in any of the scenarios studied. The installed capacity in the three scenarios is approximately 7 GW, of which 4 GW are reservoir plants. The new capacities shown in Fig. 5 correspond mainly to the replacement of plants that reach the end of their operational life. For natural gas, total capacities by 2050 were found to be between 4 and 10 GW. New capacities would be installed mainly in regions I and III between 2036 and 2044, with about 1.3 GW in **Scenario A** and 5 GW **Scenario B**.

Transmission between regions

To evaluate the contribution of electricity transmission between regions, Fig. 6 illustrates annual electricity trade between regions for the years 2019, 2035 and 2050, and Fig. 7 shows hourly transfers.

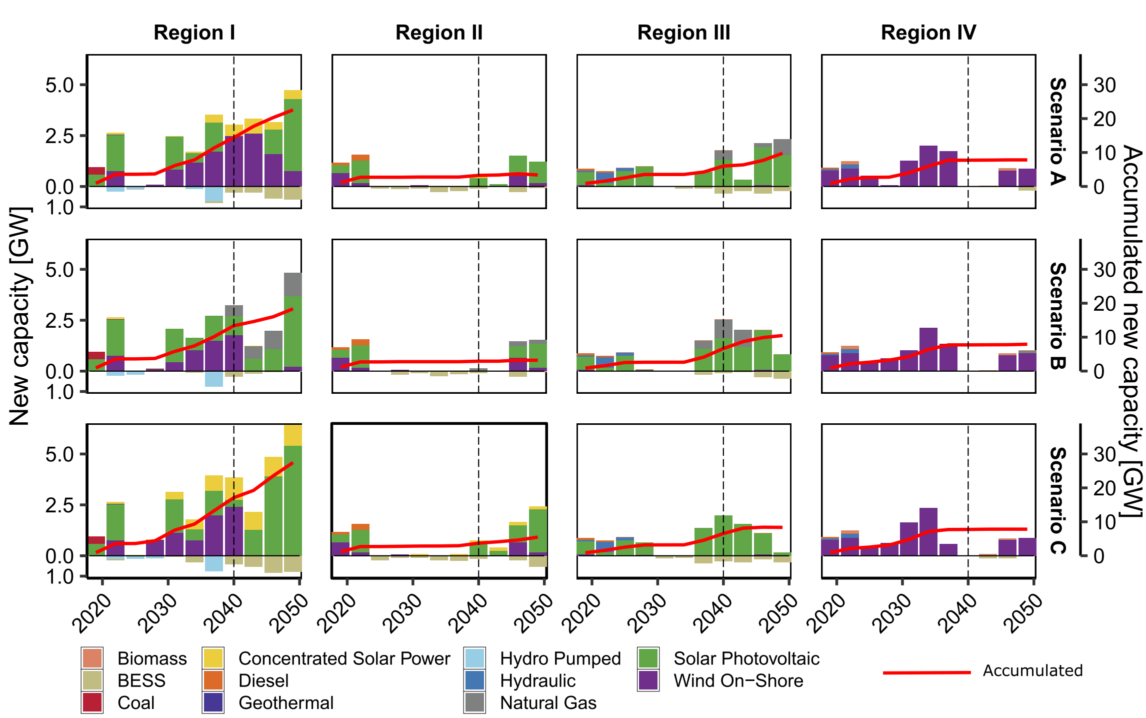

Fig. 5. New generation and storage capacities by region and scenario between 2018 and 2050.

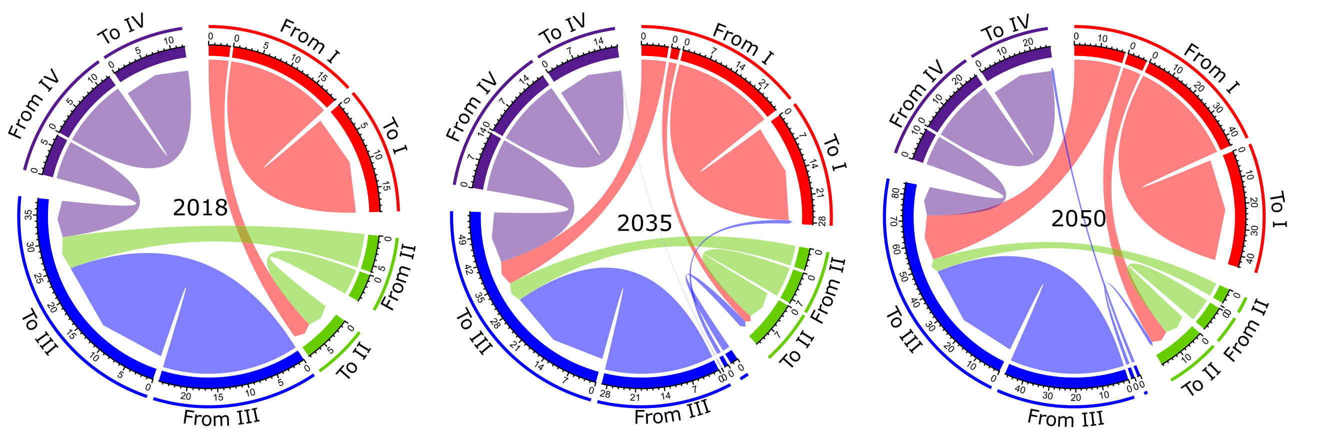

Fig. 6. Annual electricity transfer between regions [TWh] for **Scenario A**, for the years 2019, 2035 and 2050.

In general, in all scenarios it can be observed that as time passes, the energy trade between the CNES regions increases, primarily the energy flows from north to center (I to III and II to III). Of the total energy consumed in the CNES, approximately 48 % is consumed in region III. If this is added to the fact that the potential for the installation of renewable energy is lower than for the other regions, it is expected that region III will be an importer. Given the size of its demand, much of the behavior of the national transmission system can be defined based on the trade between regions I, II and IV with III, as observed in Fig. 6.

The largest contribution of this energy flow to region III would come from region I, since it experiences the greatest growth in generation capacity in all scenarios. By 2050, 26 % of what is consumed in III would come from I in **Scenario A**, 16 % in **Scenario B**, and 40 % in **C**. These transfers would require an infrastructure that supports them, so the required transmission capacity I-III would be between 3.2 and 5.0 GW by the year 2050. In this sense, a planned HVDC transmission project—Kimal-Lo Aguirre project (Comisión Nacional de Energía, 2019)—would be essential to meet transmission requirements.

Fig. 7, shows an increase in the level of hourly activity in transmission lines over time. After 2030, the transmission line that registers the greatest hourly activity is I-III. During the first years of operation, its activity increases around midday, and subsequently extends its coverage to the remaining hours of the day. This trend is more pronounced in scenarios where the penetration of renewables is higher (**Scenario A** and **C**). On the other hand, the flow from south to center (IV to III) determined by wind generation profiles presents higher hourly activity during hours where there is no solar radiation, coinciding with the low flows from north to center.

Based on these results, it is evident that the role of transmission is fundamental in the integration of the generation profiles between different modeled regions. This aspect is particularly critical in a system like Chile, which has areas that are very marked by solar generation and others by wind generation. From this perspective, the inter-regional transmission system is a key element in the flexible operation of the power system.

Hourly generation profile and flexibility

The generation dynamics can be understood through the system's hourly generation profile (Fig. 8) and net load profile (Fig. 9). These

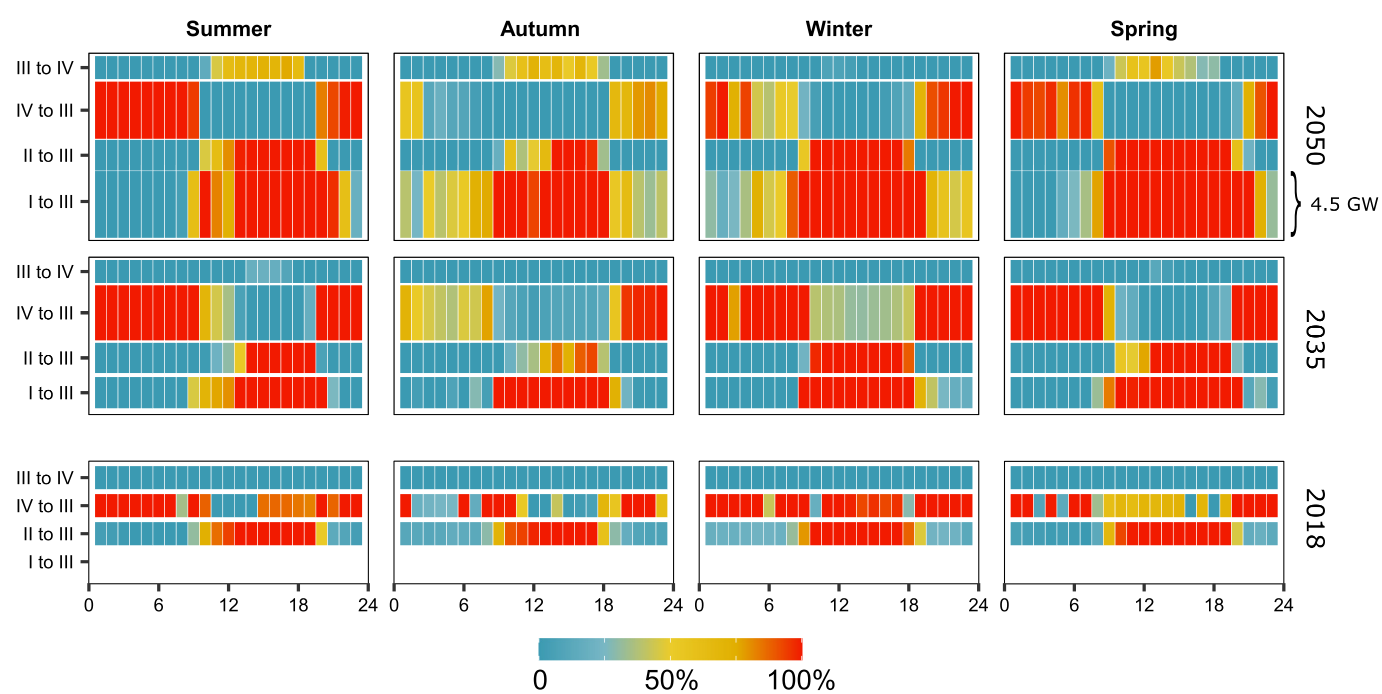

Fig. 7. Capacity and percentage of hourly use of the CNES inter-regional transmission lines for the reference scenario (**A**) during 2018, 2035 and 2050.

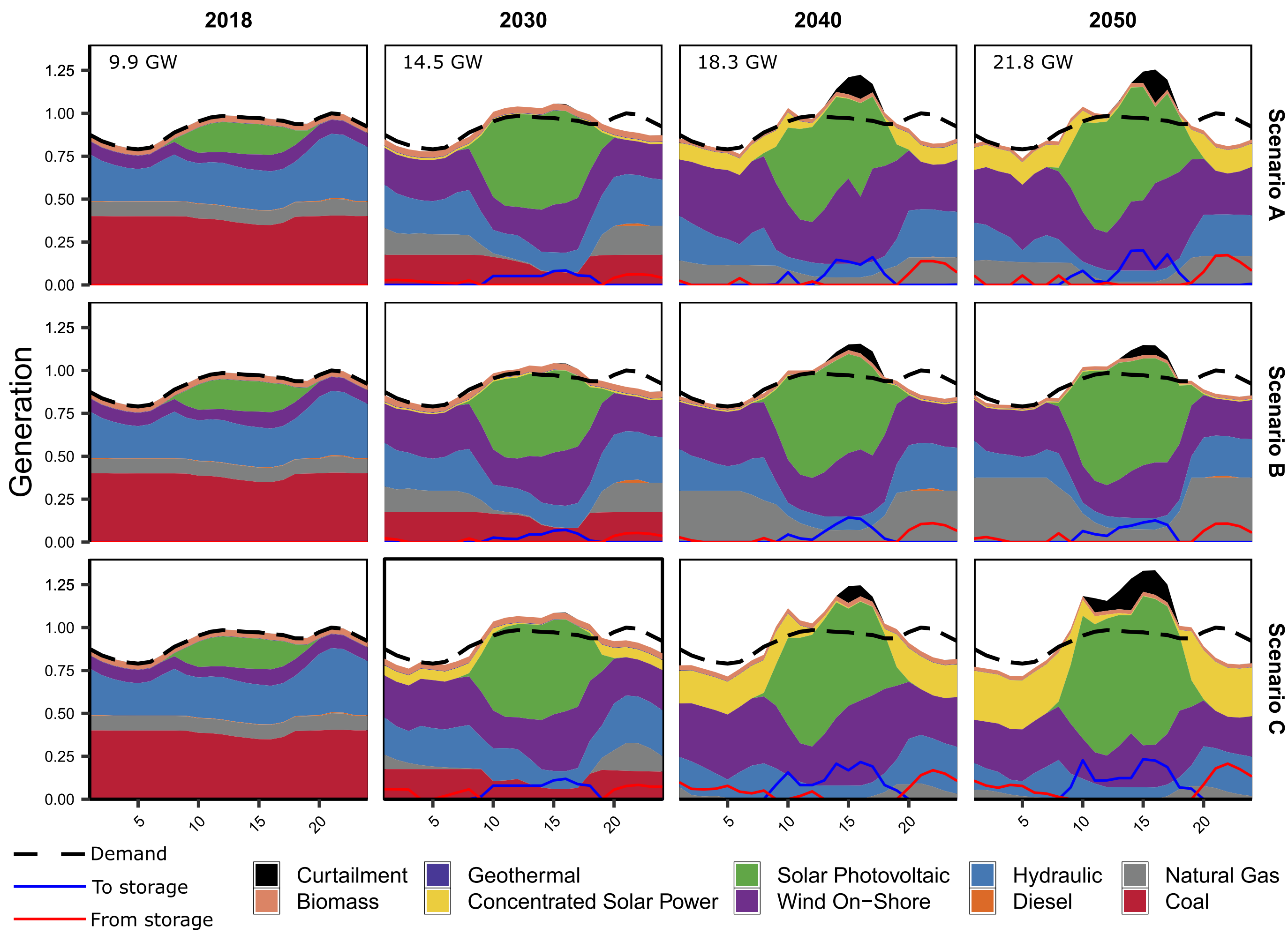

Fig. 8. Hourly generation by technology as a fraction of the maximum daily demand for a typical winter day between 2019 and 2050.

figures explain how different generation technologies are coupled to suit demand requirements.

For all scenarios, it is observed how the system goes from a hydrothermal configuration, to a more diversified one with a greater renewable generation between 2018 and 2050. In this transition, the maximum hourly demand is doubled, and thermal power plants go from providing base load to providing flexibility.

The dynamics of hourly generation are mainly determined by the photovoltaic generation profile, so the rest of the technologies adapt to balance the generation and hourly consumption of the system. Hence, it is observed that dispatchable generation technologies decrease their activity during the hours of greatest solar generation. Natural gas plants are the first to reduce their generation due to their higher marginal cost (see Fig. 8). Consequently, in the high renewable scenario (**C**), the average capacity factor could decrease to 17 % with respect to a value of 30 % registered in 2018. This mode of operation has been observed in projections for high renewable penetration systems (Jayadev et al., 2020).

Related to hydro dam generation, this technology operates as an excellent flexible supplier. However, in Chile, their role is limited because their location is restricted to only two regions (III and IV), and their maximum installed capacity in the CNES is approximately 4 GW. This represents approximately 20 % of the installed capacity by 2018, but less than 10 % by 2050. For this reason, it has been noted that their ability to provide flexibility in the CNES is insufficient even under current conditions (Haas et al., 2018).

To respond to variability in generation, the CSP-TES configuration that was found to adapt best to the flexibility requirements, has a solar multiple value between 1.5 and 1.7 and E/P of 12 h. This configuration is similar to the one proposed in Zurita et al. (2018) for the design of hybrid CSP-TES + PV plants, with values of SM = 1.8 and E/P = 12 h, and corresponds to the synergistic operation between both technologies. However, when CSP-TES is designed to supply the base load independently, the multiple solar values increase to up to 3.0, and the E/P up to 15 h, which allows reaching annual plant factors close to 86 % (Starke et al., 2016). The configuration proposed in this work allows a reduction of capital costs that justifies its more flexible operation mode, with annual capacity factors between 59 % and 66 %, which could even reach competitive LCOE levels compared to gas plants before 2040.

At the beginning of the study period, the hourly electrical generation is quite close to hourly demand throughout the day. Subsequently, between 2030 and 2040, as a consequence of BESS storage facilities and pumped-storage hydropower, the hourly generation and demand values begin to decouple. This is more evident in the year 2050, where certain hourly blocks in which the system generates between 10 and 35 % more than the maximum daily demand can be observed. The energy flow to storage is found to take place during midday, while the energy flow from storage occurs in the late afternoon to early morning. For the study scenarios, the optimal E/P configuration for BESS were between 2 and 6 h.

As the level of VRE penetration increases, the system begins to experience episodes of energy curtailment, primarily in the regions of greater VRE penetration (I and II). The maximum curtailments take place during the hours of greatest photovoltaic generation, when the energy flows to storage and to other regions reach their maximum

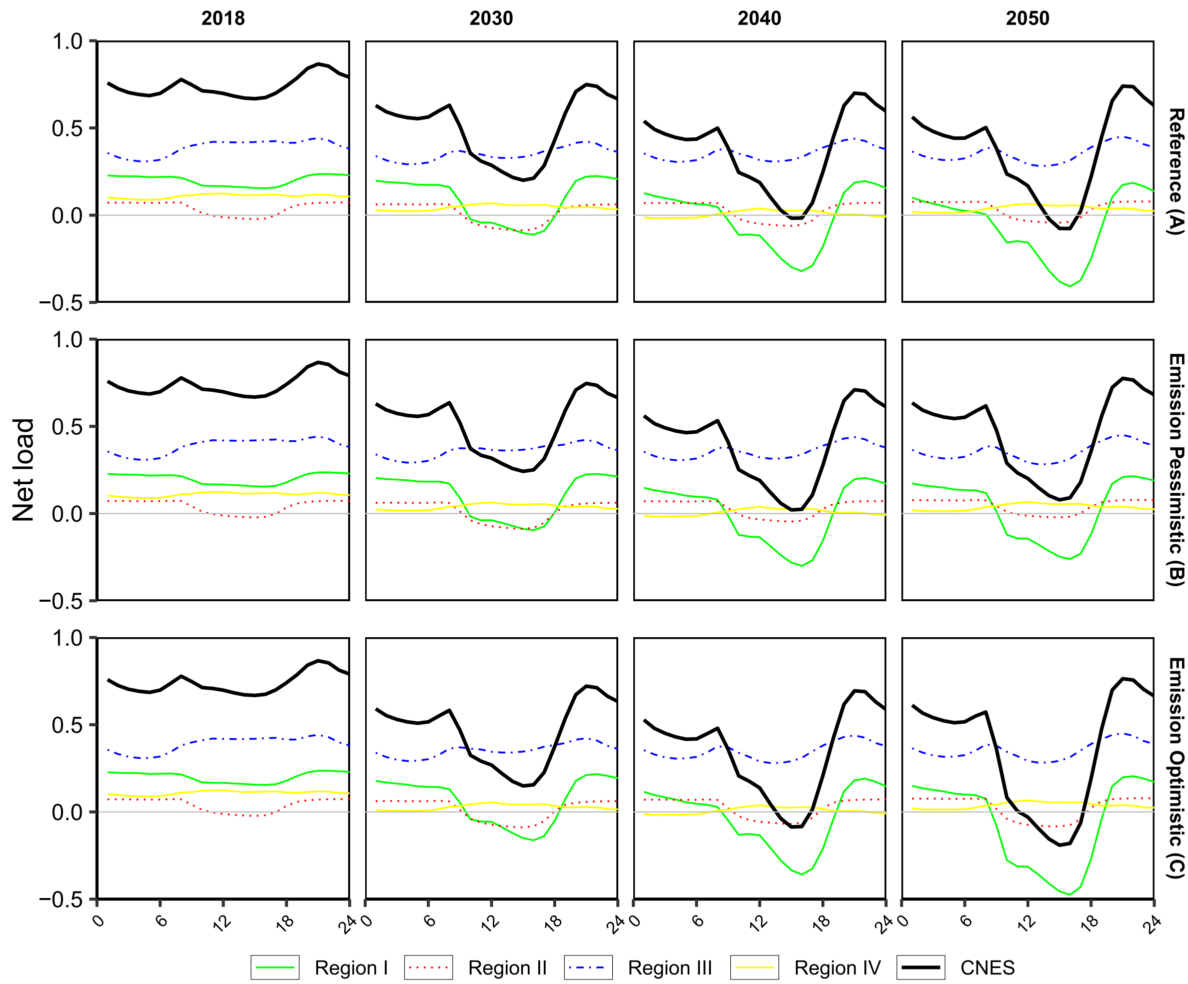

Fig. 9. Net load requirements as a fraction of the maximum daily demand by CNES region for a representative autumn day between 2018 and 2050.

values (see Fig. 7, Fig. 8 and Fig. 9). In relation to the season, the maximum curtailment would occur during the spring, coinciding with the highest capacity factors for photovoltaic and wind generation in region I. The annual energy curtailments by 2050 are found to be between 1 % and 6 % of the total energy generated depending, on the scenario, reaching up to 11 TWh per year (**Scenario C**). Although technically curtailment represents an energy loss, it can also be seen as an extra source of flexibility for the system, since its reduction would require additional investments in transmission or storage that are not always economically viable (Schermeyer et al., 2018). When curtailment by technology is explored, the highest values are found for photovoltaic plants located in region I. These values reach 14, 4 and 22 % of the total photovoltaic generation in region I, for scenarios **A**, **B** and **C**, respectively. Since the LCOE is directly related to the capacity factors of photovoltaic plants, it is to be expected that LCOE could increase between 4 and 28 % due to the curtailment effect.

In regions I and II the net load profile is determined by photovoltaic generation, while in region IV it is determined by wind generation. Region III has the highest net load requirements, associated with the highest demand and lowest potential for the installation of NCRE. As the system approaches 2050, regions I and II have negative net charges in the hours of greatest solar radiation. This net load is compensated by exporting electricity to region III and sending it to storage. When the system reaches its transmission and storage capacities, episodes of energy curtailment occur. This effect is accentuated as the installed photovoltaic capacity increases (**Scenario C**).

Over time, the maximum ramp rate requirements increase significantly in all scenarios, from values between 1 and 2 GW/h in 2018 to 6–10 GW/h by 2050. The highest values are registered in the spring and summer in which the photovoltaic generation is greater, and they occur during sunrise and sunset. These ramp rates would be provided by flexible generation technologies and storage.

In relation to the ramp rate requirements by technologies, in **Scenario A** by 2050, the highest rates would be supplied by hydro dam plants, with values of up 2.9 GW/h, followed by CSP-TES plants with 2.6 GW/h, storage BESS + pumped-storage hydropower with 2.2 GW/h, and natural gas plants with 1.5 GW/h.

To meet these levels of ramp rates, two operation modes are identified for the CSP-TES plants. First, a group of plants operates near maximum load during hours where there is no solar radiation, and they turn off the rest of the day. A second group of plants operates near the maximum load during hours where there is no solar radiation, and work at partial load near the technical minimum areas for the rest of the day. Between the years 2040 and 2050, the percentage of the CSP-TES installed capacity that must be turned off during the hours of greatest solar radiation increases steadily. This causes the start and stop frequencies to increase, so the flexibility capacity that these power stations may provide will be greater.

Similar generation patterns have been identified when designing an operating strategy that maximizes revenue in the spot market for a CSP-TES plant in Chile (Zurita et al., 2020). Although from the perspective of this energy planning model revenue is not quantified, the underlying idea in both approaches is the same. During the hours of solar radiation, the most economical energy of the system is available, which would is obtained through photovoltaic plants, so it would be convenient to minimize the CSP-TES production during these hourly blocks.

Table 4
Power system characteristics by 2050, Scenarios **A**, **D** and **E**.

Variable	Scenario		
	A	D	E
CSP-TES capacity [GW]	2.8	0.3	8.5
Photovoltaic capacity [GW]	20	28	20
Wind capacity [GW]	22	22	14
Maximum ramp rates requirements [GW/h]	6.0	8.1	4.8
BESS power capacity [GW]	3.6	8.2	1.2
BESS storage capacity [GWh]	10	47	3
BESS E/P [h]	2–3	2–7	2
CSP-TES annual capacity factor [%]	59	54	69
TES capacity [h]	12	12	12
CSP solar multiple [−]	1.5	1.3	1.9
Capital cost differential [US $ Billions]	–	↓ 1.0	↑ 1.5
Variable cost differential [US $ Billions]	–	↓ 0.1	↓ 1.8

Another flexibility component is related to the operating reserve requirements (ancillary services), through which the system could balance the uncertainty in hourly demand and variable renewable generation. Throughout the study horizon, the main supply of operating reserves is carried out by the hydro dam. As the pumped-storage hydropower and BESS plants are introduced into the system, they begin to complement the reserve requirements, displacing coal and natural gas thermal plants in this role.

High BESS and CSP-TES penetration scenarios

The impact of different levels of BESS and CSP-TES penetration on the growth and operation of the power system was studied, and some of the results are shown in Table 4. These scenarios represent routes in which BESS or CSP-TES growth could be favored, to determine the impact on the evolution of the system.

In terms of generation capacities, the system conditions in **Scenario D** and **E** mainly impact the ratio between photovoltaic + wind vs CSP-TES. For example, in **Scenario D**, BESS storage capacity by 2050 is almost 5 times higher than in the reference scenario, with an additional capacity of 8 GW photovoltaic and 2.5 GW less from CSP-TES. In **Scenario E**, the CSP-TES installed capacity by 2050 is almost three times that of the reference scenario, causing a decrease in wind capacity and in the amount of energy generated through natural gas plants.

The maximum ramp rate requirements experienced in **Scenario D** are higher than in **Scenario E**. In the reference scenario (**A**), the ramp rates are provided by CSP-TES, hydro dam, and BESS plants. However, under the conditions of **Scenario D**, they are provided by BESS and hydro dam plants, while in **Scenario E** they are supplied by CSP-TES and hydro dam plants.

Regarding the configuration of CSP-TES in **Scenario D**, it was found that the optimal configuration is with a solar multiple value around 1.3, reaching annual capacity factors of around 54 %. This configuration supports a flexible operation mode, similar to those described in **Scenario A**. Meanwhile, in **Scenario E**, this technology increases the solar multiple value to 1.9 and the annual capacity factor to 69 %. It is important to note that in **Scenario E** the system experiences much lower flexibility requirements, since it has around 7 GW less variable renewable capacity. This also impacts energy curtailment which practically disappears. Meanwhile, for the BESS configuration in **Scenario D**, the connection power is between 2.5 times higher than that of **Scenario A**, and the storage capacity is increased from 3 h to 6 h.

Mix of generation and emissions

By projecting the hourly generation profiles over a year, the annual generation mix of the system is obtained. Fig. 10 and Fig. 11 show the generation mixes for the scenarios proposed between 2018 and 2050.

The results indicate that the CNES could transition towards a more renewable generation mix, in which renewable generation could reach at least 75 % of the mix in 2050 (Fig. 11). This percentage of renewable participation increases as conditions improve for these technologies, and could exceed 90 %, which has been also predicted in previous studies (Ministerio de Energía de Chile, 2019). The increased NCRE penetration causes emissions to decrease to approximately 9 $MtCO_2$ for scenario A, 21 $MtCO_2$ for **B** and 2 $MtCO_2$ for **C**, compared to the 36$MtCO_2$ registered in 2016. These decreases would be registered despite the fact that the system generates nearly double the electricity.

It is important to note that under the most pessimistic conditions (Scenario B), emissions from the electricity system would be reduced by only 40 % compared to 2016 levels. This value would be lower than the one declared in Chile's National Determined Contributions (Palma-Behnke et al., 2019), requiring additional policies under this scenario.

Along the road to the transformation of the electrical system (see Fig. 11), two periods can be highlighted. The first takes place between 2018 and 2040, where the gap created by the growth in demand and the decrease in coal-fired generation is mainly filled by variable renewable generation technologies: wind and photovoltaics (see Fig. 10). The second period takes place between 2040 and 2050, where the increase

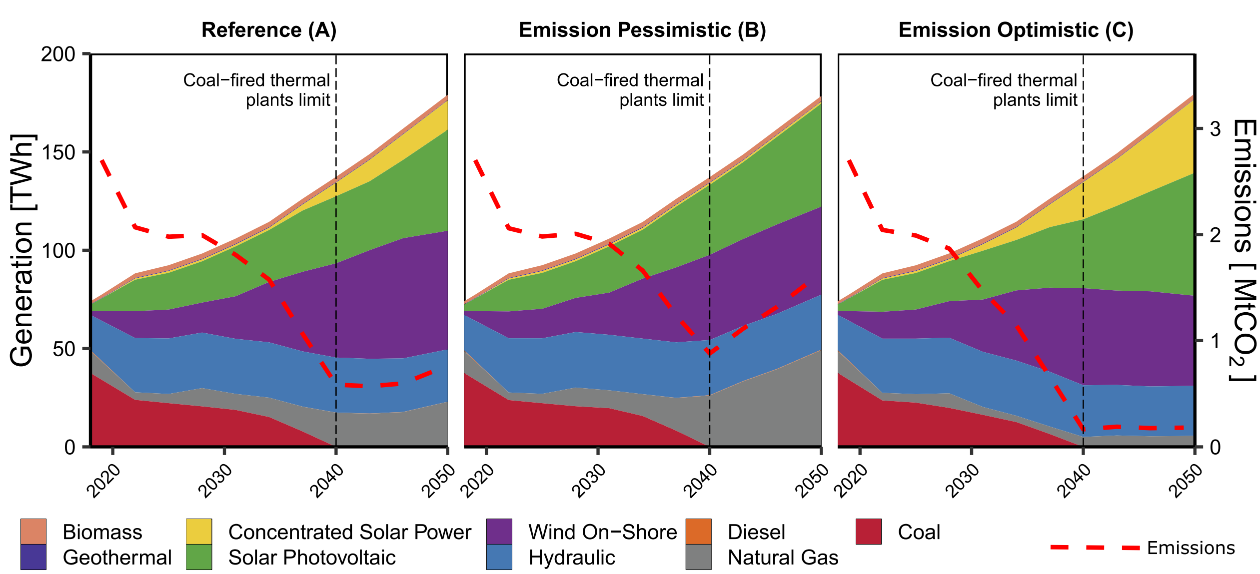

Fig. 10. Annual generation of electricity by technology between 2018 and 2050 for the study scenarios.

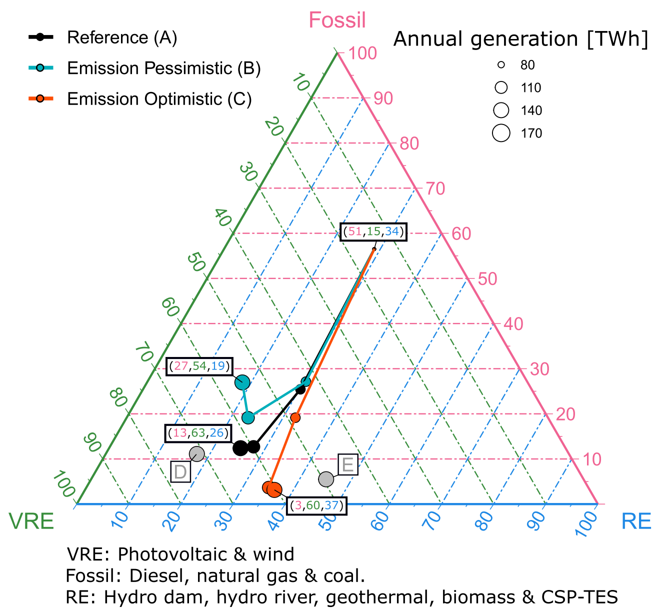

Fig. 11. Evolution of the generation mix between 2018 and 2015 for scenarios **A**, **B** and **C**, and mix to 2050 scenarios **D** and **E**.

in renewable penetration continues at a slower pace, and with different dynamics in each scenario. For example, in **Scenario A**, VRE growth is greater than that of CSP-TES; in **B**, the relative growth in natural gas generation predominates over renewables; and in **C**, the growth of CSP-TES slightly exceeds that of WI and PV.

This behavior shows that although the unit cost to produce electricity could be lower for VRE, the power system requires the presence of flexible generation to balance generation and demand. It is important to note that in the scenarios studied, hydroelectric installed capacity does not present major variations, so the growth dynamics of renewable generation technologies would be mainly determined by the VRE group (PV + WI) compared to CSP-TES.

In addition to **Scenarios A**, **B** and **C**, it can be observed how incentives to insert BESS (**Scenario D**) or incentives for CSP-TES (**Scenarios E**), could significantly change the configuration of the electric system towards greater variable or dispatchable renewable generation, respectively. When BESS growth is favored (**Scenario D**), VRE growth is higher than CSP-TES, while favoring CSP-TES growth (**Scenario E**) decreases the relative presence of VRE.

Conclusions and policy implications

In this paper, we have proposed a methodological framework for planning the long-term the energy transition of electrical systems, from systems with high levels of fossil fuel generation towards highly renewable systems. In particular, the proposed strategies emphasize the role that CSP-TES, BESS and transmission could play in providing operation flexibility, which is a critical feature required in highly renewable systems. Our methodology is built upon a customized version of the cost optimization model for energy systems OSeMOSYS (Howells et al., 2011), which allows planning both, the generation-transmission infrastructure growth and the corresponding level of activity (i.e., operation).

In order to show the capabilities of the devised approach, we consider the Chilean power system's transformation in the period 2018–2050. The main results indicate that an adequate combination of CSP-TES, BESS and transmission capacity could guarantee high levels of wind and photovoltaic penetration. In this way, the Chilean electricity system could reach at least 75 % renewable generation by 2050, and over 90 % if NCRE capital cost projections improve. Although these levels of renewable generation are high, they could fall short on more ambitious objectives, such as carbon neutrality, if the projections of capital costs of renewable generation technologies are not favorable.

The flexibility requirements that the system would have when operating with high levels of variable renewable generation, could be supplied by: dispatchable generation from CSP-TES, hydro dam plants and natural gas plants; transmission, with increased capacity and hourly activity of transmission lines, mainly those associated with the areas with the highest renewable potentials and highest consumption; storage, with combined capacity of BESS and pumped-storage hydropower (between 7 and 10 % of the daily electricity demand in the case study); and finally, energy curtailment, reaching up to 7 % of the total energy generated by the year 2050 for the Chilean system. The combined operation between CSP-TES and photovoltaic plants requires a CSP-TES configuration according to the supply of flexibility. Furthermore, a combined operation between CSP-TES and photovoltaic plants requires a CSP-TES configuration compatible with the supply of flexibility, in which lower values of the solar multiple factor are required, when compared to the values required for supplying base load.

It was found that incentive policies for the installation of BESS and CSP-TES plants could impact the evolution of the system. Firstly, stimuli for investing on BESS can favor the photovoltaic growth of the system, at the expense of CSP-TES capacity, so that the levels of renewable penetration would not be altered. Secondly, incentives for investing on CSP-TES could maintain photovoltaic generation levels, but would decrease wind and natural gas generation, so that the system would experience a reduction in emissions with respect to the reference scenario.

As future work, we aim at incorporating the inherent uncertainty of the renewables' generation profiles, addressing in this way one of the shortcomings of the proposed setting. Such challenge can be approached, for instance, by including mid and long-term climate scenarios and their impact on the renewables' generation profiles. Nonetheless, our main goal is expanding our tool to allow the evaluation of scenarios characterized by the use of hydrogen as an energy vector that provides flexibility. This requires addressing additional curtailment use and energy storage strategies as well as electrolytic production under flexible demand response strategies.

Declaration of competing interest

The authors declare to have no conflict of interest associated to the manuscript “Assessing flexibility for integrating renewable energies into carbon neutral multi-regional systems".

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2022.08.010.

References

Afful-Dadzie, A., Afful-Dadzie, E., Abbey, N. A., Owusu, B., & Awudu, I. (2020). Renewable electricity generation target setting in developing countries: Modeling, policy, and analysis. *Energy for Sustainable Development*, *59*, 83–96.

AG (2018). Análisis de largo plazo para el sistema eléctrico Nacional de Chile considerando fuentes de energía variables e intermitentes, AG (Asociación de Generadoras de Chile). URL:http://generadoras.cl/.

Cantarero, M. Vanegas (2020). Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries. *Energy Research & Social Science*, *70*, Article 101716.
Chennaif, M., Zahboune, H., Elhafyani, M., & Zouggar, S. (2021). Electric System Cascade Extended Analysis for optimal sizing of an autonomous hybrid CSP/PV/Wind system with Battery Energy Storage System and thermal energy storage. *Energy*, *227*, Article 120444.
CNE (2020). *Generación Bruta SEN, CNE (Comisión Nacional de Energía).* https://www.cne.cl/estadisticas/electricidad/ URL:.
CNE (2020). Resolución Exenta 38: Instalaciones de Generación y Transmisión en Construcción, CNE (Comisión Nacional de Energía), Santiago de Chile. URL:https://www.cne.cl/.
CNE (2020). Informe de costos de Tecnologías de Generación. Informe Anual, CNE (Comisión Nacional de Energía), Santiago de Chile. URL:https://www.cne.cl/.
Comisión Nacional de Energía (2019). Decreto Exento 231. Fija obras nuevas de los sistemas de trasmisión nacional y zonal que deben iniciar su proceso de licitación o estudio. URL:http://bcn.cl/2k3og.
Coordinador Eléctrico Nacional (2015). Diagrama Unilineal SING. URL:http://www.cdec-sing.cl.
Coordinador Eléctrico Nacional (2017). Diagrama Unilineal SIC. URL:https://sic.coordinador.cl/.
Coordinador Eléctrico Nacional (2018). Estudio de Operación y Desarrollo del SEN sin centrales a carbón. URL:https://www.coordinador.cl/.
Coordinador Eléctrico Nacional (2019). Estudio de Proyección de Generación de Unidades GNL en el sistema Eléctrico Nacional. URL:https://www.coordinador.cl/.
Coordinador Eléctrico Nacional (2020). Información de Instalaciones: Unidades Generadoras. URL:https://infotecnica.coordinador.cl/instalaciones/unidades-generadoras.
Coordinador Eléctrico Nacional (2020). Operación y Generación Real del Sistema: Generación Horaria del Sistema. URL:https://www.coordinador.cl/operacion/graficos/operacion-real/generacion-real-del-sistema.
Coordinador Eléctrico Nacional (2020). Sistema Eléctrico Nacional: Sub estaciones y Lineas de Transmisión. URL:https://infotecnica.coordinador.cl/.
Du, E., Zhang, N., Hodge, B., Kang, C., Kroposki, B., & Xia, Q. (2018). Economic justification of concentrating solar power in high renewable energy penetrated power systems. *Applied Energy*, *222*, 649–661.
English, J., Niet, T., Lyseng, B., Keller, V., Palmer-wilson, K., Robertson, B., Wild, P., & Rowe, A. (2020). Flexibility requirements and electricity system planning: Assessing inter-regional coordination with large penetrations of variable renewable supplies. *Renewable Energy*, *145*, 2770–2782.
Fichter, T., Soria, R., Szklo, A., Schaeffer, R., & Lucena, A. (2017). Assessing the potential role of concentrated solar power (CSP) for the northeast power system of Brazil using a detailed power system model. *Energy*, *121*, 695–715.
Gardumi, F., Welsch, M., Howells, M., & Colombo, E. (2019). Representation of balancing options for variable renewables in long-term energy system models: An application to OSeMOSYS. *Energies*, *12*, 1–22.
Haas, J., Palma-Behnke, R., Valencia, F., Araya, P., Díaz-Ferrán, G., Telsnig, T., Eltrop, L., Díaz, M., Püschel, S., Grandel, M., Román, R., & Jiménez-Estévez, G. (2018). Sunset or sunrise? Understanding the barriers and options for the massive deployment of solar technologies in Chile. *Energy Policy*, *112*, 399–414.
Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M., & Roehrl, A. (2011). OSeMOSYS: The open source energy modeling system. An introduction to its ethos, structure and development. *Energy Policy*, *39*, 5850–5870.
Huertas-Hernando, D., Farahmand, H., Holttinen, H., Kiviluoma, J., Rinne, E., Söder, L., Milligan, M., Ibanez, E., Martínez, S., Gomez-Lazaro, E., Estanqueiro, A., Rodrigues, L., Carr, L., van Roon, S., Orths, A., Eriksen, P., Forcione, A., & Menemenlis, N. (2017). Hydro power flexibility for power systems with variable renewable energy sources: An IEA Task 25 collaboration. *WIREs Energy and Environment*, *6*, Article e220.
IEA (2012). *Harnessing variable renewables: A guide to balancing challenge.* URL:IEA (International Energy Agency). https://www.iea.org/reports/harnessing-variable-renewables.
IEA (2019). *Status of power system transformation 2019. Power system flexibility.* URL:IEA (International Energy Agency). https://www.iea.org/reports/status-of-power-system-transformation-2019.
Jayadev, G., Leibowicz, B., & Kutanoglu, E. (2020). U.S. electricity infrastructure of the future: Generation and transmission pathways through 2050. URL:*Applied Energy*, *260*, Article 114267.
Koltsaklis, N., & Dagoumas, A. (2018). State-of-the-art generation expansion planning: A review. *Applied Energy*, *230*, 563–589.
Laha, P., & Chakraborty, B. (2021). Cost optimal combinations of storage technologies for maximizing renewable integration in Indian power system by 2040: Multi-region approach. *Renewable Energy*, *179*, 233–247.
Mena, R., Escobar, R., Lorca, M., & Negrete-Pincetic, D. Olivares (2019). The impact of concentrated solar power in electric power systems: A Chilean case study. *Applied Energy*, *235*, 258–283.
Ministerio de Desarrollo Social y Familia de Chile (2021). Precios Sociales 2021. URL: http://sni.ministeriodesarrollosocial.gob.cl.
Ministerio de Economía (2006). Fomento y Reconstrucción de Chile, Ley General de servicios eléctricos en materia de energía eléctrica. URL:http://bcn.cl/2fdga.
Ministerio de Energía de Chile (2018a). Proceso de Planificación Energética de Largo Plazo: Informe Final Corregido. URL:https://acera.cl/.
Ministerio de Energía de Chile (2018b). Mesa de Geotermia: Rol de la Geotermia en el desarrollo de la Matriz Energética Chilena. URL:https://www.energia.gob.cl/.
Ministerio de Energía de Chile (2019). Planificación Energética de largo Plazo. Periodo 2018-2022: Informe de actualización de antecedentes. URL:http://www.energia.gob.cl.
Ministerio de Energía de Chile (2020). Decreto Exento No 50. Aprueba acuerdos de retiro de centrales termoeléctricas a carbón. URL:https://www.energia.gob.cl/panel/mesa-de-trabajo-descarbonizacion.
Ministerio de Energía de Chile (2020a). Explorador solar. URL:http://www.minenergia.cl/exploradorsolar/.
Ministerio de Energía de Chile (2020b). Explorador eólico. URL:https://eolico.minenergia.cl/.
Ministerio de Energía de Chile (2020). Planificación Energética de Largo Plazo. Informe de actualizaciÃ3n de antecedentes 2020. URL:https://energia.gob.cl.
Ministerio de Hacienda de Chile (2014). Ley 20780. Reforma Tributaria que modifica el sistema de tributación de la renta e introduce diversos ajustes en el sistema Tributario. URL:http://bcn.cl/1uv0u.
Ministerio del Ambiente de Chile (2019). Anteproyecto de Ley Marco de Cambio Climático. URL:http://consultasciudadanas.mma.gob.cl.
NREL (2015). Implications of model structure and detail for utility planning: Scenario case studies using the resource planning model, NREL (National Renewable Energy Laboratory). URL:https://www.nrel.gov/.
Ortega, N., Curto, A., Dimitrova, A., Nunes, J., Rasella, D., Sacoor, C., & Tonne, C. (2021). Health and environmental impacts of replacing kerosene-based lighting with renewable electricity in East Africa. *Energy for Sustainable Development*, *63*, 16–23.
Palma-Behnke, R., Barría, C., Basoa, K., Benavente, D., Benavides, C., Campos, B., de La Maza, N., Farías, L., García, M., Carrasco, L. Gonzales, Guarda, F., Guzmán, R., Jofré, A., Mager, J., Martínez, R., Montedonico, M., Morán, L., Muñoz, L., Osses, M., ... Vicuña, S. (2019). Chilean NDC mitigation proposal: methodological approach and supporting ambition. URL:http://www.minenergia.cl/.
Palmintier, B., Member, S., & Webster, M. (2015). Impact of operational flexibility on electricity generation planning with renewable and carbon targets. *IEEE Transactions on Sustainable Energy*, 1–13.
Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews*, *33*, 74–86.
Poncelet, K., Delarue, E., & William, D. (2020). Unit commitment constraints in long-term planning models: Relevance, pitfalls and the role of assumptions on flexibility. *Applied Energy*, *258*, Article 113843.
Reyseliani, N., & Purwanto, W. (2021). Pathway towards 100% renewable energy in Indonesia power system by 2050. *Renewable Energy*, *176*, 305–321.
Ruiz-Rudolph, P., Arias, N., Pardo, S., Meyer, M., Mesías, S., Galleguillos, C., Schiattino, I., & Gutiérrez, L. (2016). Impact of large industrial emission sources on mortality and morbidity in Chile: a small-areas study. *Environment International*, *92–93*, 130–138.
Santana, C., Falvey, M., Ibarra, M., & Monserrat, G. (2014). Energías Renovables en Chile. El potencial eólico, solar e hidroeléctrico de Arica a Chiloé. URL:https://www.4echile.cl/.
Schermeyer, H., Vergara, C., & Fichtner, W. (2018). Renewable energy curtailment: A case study on today's and tomorrow's congestion management. *Energy Policy*, *112*, 427–436.
Schmidt, O., Hawkes, A., Gambhir, A., & Staffell, I. (2017). The future cost of electrical energy storage based on experience rates. *Nature Energy*, *2*, 17110.
Solomon, A., Kammen, D., & Callaway, D. (2014). The role of large-scale energy storage design and dispatch in the power grid: A study of very high grid penetration of variable renewable resources. *Applied Energy*, *134*, 75–89.
Soria, R., Lucena, A., Tomaschek, J., Fichter, T., Haasz, T., Szklo, A., Schaeffer, R., Rochedo, P., Fahl, U., & Kern, J. (2016). Modelling concentrated solar power (CSP) in the Brazilian energy system: A soft-linked model coupling approach. *Energy*, *116*, 265–280.
Starke, A., Cardemil, J., Escobar, R., & Colle, S. (2016). Assessing the performance of hybrid CSP+PV plants in northern Chile. *Solar Energy*, *138*, 88–97.
Taliotis, C., Shivakumar, A., Ramos, E., Howells, M., Mentis, D., Sridharan, V., Broad, O., & Mofor, L. (2016). An indicative analysis of investment opportunities in the African electricity supply sector — Using TEMBA (The Electricity Model Base for Africa). *Energy for Sustainable Development*, *31*, 50–66.
Tsai, C., Figueroa-Acevedo, A., Boese, M., Li, Y., Mohan, N., Okullo, J., Heath, B., & Bakke, J. (2020). Challenges of planning for high renewable futures: Experience in the U.S. midcontinent electricity market. *Renewable and Sustainable Energy Reviews*, *131*, Article 109992.
Valickova, P., & Elms, N. (2021). Potential gains from regional integration to reduce costs of electricity supply and access in Southern Africa. *Energy for Sustainable Development*, *62*, 82–100.
Wassie, Y., & Adaramola, M. (2021). Socio-economic and environmental impacts of rural electrification with Solar Photovoltaic systems: Evidence from Southern Ethiopia. *Energy for Sustainable Development*, *60*, 52–66.
Weitemeyer, S., Kleinhans, D., Vogt, T., & Agert, C. (2015). Integration of Renewable Energy Sources in future power systems: The role of storage. *Renewable Energy*, *75*, 14–20.
Welsch, M., Howells, M., Hesamzadeh, M., & Gallachóir, B. (2015). Supporting security and adequacy in future energy systems: The need to enhance long-term energy system models to better treat issues related to variability. *International Journal of Energy Research*, *39*, 377–396.
Zhang, J., Li, H., Chen, D., Xu, B., & Mahmud, M. (2021). Flexibility assessment of a hybrid power system: Hydroelectric units in balancing the injection of wind power. *Renewable Energy*, *171*, 1313–1326.
Zurita, A., Mata-Torres, C., Valenzuela, C., Felbol, C., Cardemil, J., Guzmán, A., & Escobar, R. (2018). Techno-economic evaluation of a hybrid CSP+PV plant integrated with thermal energy storage and a large-scale battery energy storage system for base generation. *Solar Energy*, *173*, 1262–1277.
Zurita, A., Strand, A., Guédez, R., & Escobar, R. (2020). Identifying optimum CSP plant configurations for spot markets using a dispatch optimization algorithm – A case study for Chile. *AIP Conference Proceedings*, *2303*, Article 120004.