An optimization-based analysis of decarbonization pathways and flexibility requirements in the Chilean electric power system

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Abstract

Achieving global carbon neutrality within the first half of this century is required to limit the increase of global average temperature to 1.5°C, and thus to mitigate the effects of the ongoing climate crisis. Due to this, several countries have laid out decarbonization plans for the next few decades. In particular, a decarbonization schedule has been recently announced for the Chilean electric power system, which aims to entirely phase out coal generation by 2040. This implies a major change on the operational features and flexibility requirements of such system since coal still occupies a very large energy share of about 40%. This paper presents an assessment of various decarbonization pathways for the Chilean power system based on a generation and transmission expansion planning model specially enhanced to capture key flexibility aspects. This model employs the concept of representative days, an approximation of the unit commitment problem, a thorough modelling of the hydro network, and also thermal-based and battery-based energy storage. The results show that more strict decarbonization goals remain in a similar cost range as compared to the base case scenario, and for such scenarios the balance between variable and flexible attributes, including ramping, storage, and transmission capacity, becomes critical in earlier stages of the planning horizon. Based on this, a policy recommendation from this paper is that appropriate operational methods and market structures must be implemented to harness all the benefits of renewable and flexible energy in a reliable, sustainable and efficient way.

Index Terms

Decarbonization, energy planning, flexibility, optimization, power systems, renewable energy.

1. Introduction

Sustainable development has become a major global challenge in the last few decades due to unprecedented levels of CO_2 and other greenhouse gases in the planet's atmosphere, and the massive risks associated with climate change. To tackle this problem, several countries have adopted decarbonization plans which seek to greatly reduce emissions across all industries, the energy system being a major concern, as it accounts for nearly a 70% of global CO_2 emissions [1]. In this context it is paramount to achieve low-emissions power systems. For some of these countries, the decarbonization of the power system requires a significant technological change with a massive adoption of variable renewable energy sources such as wind and solar, which poses several challenges for the grid operation due to the attributes of these technologies. This is the case of the Chilean power system, where coal generation currently accounts for nearly a 40% share of the total generation mix [2], and a decarbonization plan has been laid out to completely phase out coal of the power system by 2040 at maximum. In order to correctly asses the effects of such process on the power system, an effective mathematical representation of the operational characteristics of the system is required. This paper proposes an optimization-based analysis of several decarbonization pathways for the Chilean electric power system based on a Generation and Transmission Expansion Planning (EP) model.

The implementation of a binding decarbonization plan in the power system motivates several questions. Some aspects of general interest include how may the binding mechanism be defined, how tight can the plans schedule be in a temporal perspective, what impacts will the plan have on local jobs and over private business that should be taken into account, and how effective will it be on terms of emission reductions if not complemented with proper electrification goals across heating and transportation sectors or other measures for the rest of the energy system. These questions, which are central to the issue, require a wide systemic approach and must be taken into account when analyzing this transition [3]. However, regarding the direct impact of a decarbonization schedule on the power system, additional questions arise, which can be very pressing and

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have a major relevance for the successful and reliable implementation of such schedule. These questions include how will the existing and new technologies replace coal based generation, how will the operational features of the system change over time, and which market structures incentive an efficient and reliable transition, among others. In this paper we will focus on the latter set of questions for the Chilean case, as insights and understandings in such questions will aid and support the discussion of the first set.

To address these questions, the use of a Generation and Transmission EP optimization model is considered. This problem aims to optimize investments on generation and transmission infrastructure over a planning horizon, in order to minimize total investment and operational costs over such horizon [4]. In this context, the representation of the operational features of the power system becomes a key aspect of the model, due to the temporal, spatial and technical characteristics of technologies such as wind and solar generation, and energy storage, which are expected to play a major role in future low-emissions power systems. Under this assumption, the concept of flexibility, understood as the capacity of a power system to respond to variations on load and generation to maintain proper power balance, becomes paramount. This poses an important challenge to the EP model, as various flexibility aspects are not typically captured in such models [5].

This challenge has recently gained a lot of attention. Several new approaches have been developed to allow better representations of the temporal aspects, technical constraints and operational uncertainty within the context of EP. Some of these approaches include the use of chronologically ordered time points through the concept of representative intervals [5], the inclusion of key technical aspects through convex relaxations [6], and the inclusion of uncertainty through robust optimization [7] or stochastic programming [8]. More importantly, all of these works agree that for larger shares of variable renewable energy, the representation of such aspects becomes more critical, and may have a greater impact on the systems cost, reliability and environmental performance.

On the other hand, the assessment of decarbonization plans through the use of optimization models has also become an important area of research. Some applications include the study of decarbonization plans for the power systems of Canada [9], China [10] and the Western Electricity Coordinating Council [11] among others, resulting in valuable information and discussion on various dimensions for the decarbonization process of these systems. The specific characteristics of the models employed differ among these analysis, thus providing different type of insights.

In this context, this paper aims to assess several decarbonization pathways for the Chilean power system considering the use of an advanced optimization based EP model to properly account for the operational structure of future low-emissions power systems, based on the recently announced decarbonization plan for the country, which intends to completely phase out coal-based generation by the year 2040. To this purpose, three different scenarios are defined considering the original full decarbonization by 2040, and two alternative plans which consider full decarbonization by 2035 and 2030, respectively. These scenarios are then studied through an EP model considering an effective representation of various key flexibility aspects, which allow to gain insights on the possible operational features for the Chilean power system.

The main contributions of this paper can be summarized as follows:

1) Enhancement of EP models to effectively represent the short-term operational features of a power system with a very large adoption of variable renewable energy, through the use of representative days built using recently developed data clustering techniques.
2) Use of advanced optimization-based power system expansion planning models to study various plausible decarbonization scenarios for the Chilean electric power system over a time horizon spanning from 2020 to 2040.
3) Assessment of the flexibility requirements in the future Chilean electric power system under decarbonization and a large presence of variable renewable energy.

The remainder of this paper is organized as follows. A brief discussion on decarbonization and flexibility is presented in Section 2. The mathematical models employed, the case study and the definition of the decarbonization scenarios are presented in Section 3. Section 4 presents the EP model results, and Section 5 concludes.

2. Decarbonization and flexibility: A brief outlook

There exists large scientific evidence regarding the relationship between the atmospheric concentrations of CO_2 and the increase on the global average temperature due to the greenhouse effect. This concentration has seen a massive increase over the last few decades due to human action, reaching unprecedented levels. Consequentially, global average temperature has seen a 1.0^{o}C increase since the late 19th century. Other currently observed phenomena which are largely related with these trends include the warming and acidification of the oceans, shrinking of the ice sheets and glacial retreat, rise of the sea level and the increase of extreme heat related events, among others [12]. Recent reports by the Intergovernmental Panel on Climate Change (IPCC) claim that an increase on the global average temperature higher than 1.5^{o}C would have severe impacts both on the environment and on human communities and economies. This already implies setting a more ambitious goal as compared to the 2.0^{o}C increase limit set on the Paris Agreement [13]. In addition to the prior, Chile presents a high vulnerability to climate change. The presence of low coastal regions, arid and semi-arid zones, forests zones, areas exposed to natural disasters, areas prone to droughts and desertification, polluted urban areas and mountainous ecosystems are seven of the nine criteria of vulnerability met by the country, as defined by the United Nations Framework Convention on Climate Change [14].

The transition to sustainable pathways which limit the temperature increase to 1.5^{o}C require unprecedented changes through many sectors such as energy, transport and buildings infrastructure, industrial processes and land usage. In particular, a 45% decline in global anthropogenic CO_2 emissions from 2010 levels must be achieved by 2030, and global net zero, or carbon neutrality, must be achieved by 2050 at maximum [13]. Within the context of this transition, the energy system plays a major role, as it accounts for nearly a 70% of global CO_2 emissions. These emissions are associated mainly with electricity, heat, transport, manufacturing and construction [1]. The consistent reduction of these emissions will require changes on all of these systems, which comprise both technical and social components, thus, a *sociotechnical* transition is required. For such transition to be successfully achieved many factors must come together, and particularly, innovations and systems must align, as discussed in [3]. Under this paradigm, the confluence of several technological innovations such as the deployment of electric cars, capital cost reductions on variable renewable energy generation and on energy storage, and recent developments on distributed energy resources and demand response, suggest that there exists an opportunity for decarbonization based on the power system, through electrification processes and the generation of electricity through low or null-emission energy sources.

Many countries have acknowledged this opportunity by setting goals and policies which aim to achieve such transition. Some examples include renewable generation goals or renewable portfolio standards, carbon taxes, renewable feed in tariffs, efficiency and electrification goals, or explicit decarbonization plans, either for the power system or across industries. Some have even set overall carbon neutrality goals in law for the next few decades: Norway by 2030, Sweden by 2045, France and UK by 2050, with several other countries being involved in discussions, pledges or political agreements towards similar goals [15]. In a similar fashion, Chile has recently announced an overall net zero carbon goal for 2050 based in the reduction of emissions from the energy sector (which accounts for 78% of the countries emissions) and through reforestation to increase the capture of CO_2 emissions [16]. In particular, the reduction of emissions on the energy sector has been specifically addressed through a coal retirement plan, in agreement with the coal based utilities in electricity generation. This coal retirement plan for the electricity sector is to be fully completed by 2040, and it also prevents new coal units from being built in the future, thus setting the path for a highly renewable power system. This implies a major change in the Chilean power system due to the fact that coal has currently the largest share in the generation mix, accounting for nearly a 40% of the generated electricity [2]. In addition to the prior, coal is used mainly as base generation and provides security and stability to the system through the provision of inertia and other ancillary services. Due to this, it becomes relevant to analyze how will the power system ensure the reliability and cost efficiency of a coal-free operation.

Together with the retirement of coal generation units, a substantial growth of variable renewable energy sources is expected to support the emissions reduction. This is due to several factors. On one hand, renewable generation technologies such as PV and wind have seen great capital cost reductions in the last few decades, more notably in PV, where an estimated 73% decrease was observed on its global weighted average levelized cost of electricity between 2010 and 2017 [17]. On the other hand, Chile has abundant renewable potential. The Atacama Desert is regarded as having the world's best solar resource, and the Andes mountains together with the Chilean Coastal Range, parallel to an extensive shoreline, provide high potential for wind, hydro, geothermal and even ocean energy resources [18]. Due to the prior, in the recent years, the adoption of wind and solar power in the Chilean electric power system has increased considerably, with wind and solar now jointly accounting for more than 10% of the energy share in the generation portfolio. In addition to this, various large projects are currently under construction and many more in a planning phase [19]. With these two important processes of deep variable renewable integration and quick decarbonization, the operation and market structure of the Chilean electric power system will face significant challenges associated to the flexibility requirements of the system. The unpredictability and quick variations in the power output of wind and photovoltaic power plants need to be met with significant flexibility sources that can quickly adjust their power outputs in response to such variations. As coal is removed, and is replaced with wind and solar power, it is imperative to ensure that sufficient flexible generation sources are deployed in the system, and that proper market rules are in place to efficiently employ their flexibility for the secure operation of the power system.

Flexibility is typically understood as the ability of a power system to mantain the energy balance as a response to changes in demand and supply, i.e. changes in load and generation [20]. As the share of variable sources such as PV and wind energy increases in the power system, flexibility becomes scarcer and more critical for the operation, changing the existing operational paradigm. Several ways exist to provide flexibility [21], with flexible generation units being one of the main alternatives, along with others such as energy storage, demand response or distributed energy resources. Flexible generation units are defined mainly as units with a great capacity to change their generation from one moment to the next (ramp capability), fast start-up and shut-down times and low or null minimum stable levels. Given the expected growth in uncertain and variable energy sources, it is necessary to understand possible future scenarios of high renewable integration and how can the system be better prepared through flexible generation for such scenarios, and to fully allow the incorporation of new technologies and their benefits [22]. This change also motivates major market challenges and the need for new market structures which reward flexibility and incentive long-term investments [23], [24]. This is due to the fact that current market designs have a series of assumptions which are less valid under the energy cost structure and significant volatility of renewable sources [25], and thus, may not provide the appropriate incentives for the deployment of technologies required for the reliable operation of the power system. In Chile, evidence of this market challenges are the new definitions for implementing an ancillary services market by 2020 and the preliminary announcement of a law bill to remunerate flexible resources in the power system. This measures aim to create the incentives which ensure the correct balance among flexible and variable resources, to secure an efficient and reliable operation in the future.

Under this major challenges and transitions, several technologies have recently gained attention due to their particular characteristics. This is the case of concentrated solar power (CSP), battery systems, pumped hydro storage and geothermal energy, among others. These technologies may aid by providing flexibility to the system without creating further CO_2 emissions. Some of these technologies have seen fast development in the recent years, through experimental and commercial deployments and capital cost reductions, mainly CSP and battery systems. This raises the question of what role would such technologies play on a optimal decarbonization pathway, and how could the market design process create the appropriate incentives to achieve an optimal decarbonization pathway for the Chilean power system.

In this context, the use of advanced EP models to study such question may provide valuable assessments regarding the role of new technologies through the decarbonization process. The challenge of modelling flexibility in EP models is complex due to computational capacity and tractability issues, however, recent progress in the EP literature provides useful mathematical and methodological frameworks to address these aspects of a given power system over a planning horizon. Due to this, in the remainder of the paper, we propose an analysis based on an EP model enhanced with an effective modelling of key flexibility aspects to assess a set of decarbonization scenarios for the Chilean power system.

3. Case Study

This section presents the input data used to analyze the decarbonization process of the Chilean power system, and the characteristics of the considered optimization model.

3.1. Generation and Transmission Expansion Planning Model

The decarbonization schedule for the Chilean power system spans over approximately a 20 year horizon. In order to study possible transitions of the power system over such horizon, a capacity expansion planning optimization model is employed. The objective of such model is to minimize both investment and operational costs through a planning horizon divided into discrete planning periods, while maintaining a correct energy balance and certain operational standards. For this case study, the start of the planning horizon was set in 2020. For analysis purposes, 6 periods of 4 years each are considered: 5 periods from 2020 to 2040 and a final complementary period from 2040 to 2044 to avoid end period effects on the results.

The decisions of the model consist on investment decisions, such as where, when and which technology capacity investments should be made over the planning horizon, and operational decisions within a mathematical representation of the system operation, which allows the assessment of the mentioned investment decisions. The variability and uncertainty of variable renewable energy and the operational features of new technologies, such as batteries and CSP, pose a challenge in terms of the mathematical representation of the systems operation, which should be sophisticated enough to correctly asses the advantages and disadvantages of each technological option. In order to adress this issue, we use a generation and transmission expansion planning model based on [26], which employs the concept of representative days as a proper modelling framework to analyze the decarbonization pathways for the Chilean System. This concept consists on using a discrete set of days with hourly resolution to represent the power systems operation while preserving the chronological order and enabling the inclusion of key flexibility constraints [7]. This model also includes a thorough modelling of the hydro network [8] and a detailed model for thermal storage, and it was enhanced with an approximate representation of the unit commitment problem [6] and the inclusion of constraints which model battery energy storage systems.

3.2. 20-Bus Representation

In this paper we employ a scaled version of the Chilean power system considering 20 buses or load zones, where power demand and supply are aggregated. These load zones are distributed through the country, as illustrated in Figure 1.

3.3. Transmission Lines

Based on the 20 load zones previously defined, a simplified transmission system is defined by aggregating the transmission capacity of high-voltage lines (220 kV $\leq$) connecting such zones. The data for these lines is adapted from the *Comisión Nacional de Energía* [27]. The cost for expanding transmission capacity in units of base year dollars $ per MW per km is set as 850. The fraction corresponding to the fixed O&M costs per year is considered to be $\beta = 3\%$. Finally, the lifetime of a transmission line, ly^L_ℓ, is set to 20 years.

3.4. Generators

A set of 137 existing units and 208 candidate units is employed. The existing units were adapted from real data of the Chilean power system reported by [27], where an aggregation was made for small diesel, hydro-RoR, PV and wind generation units based on their geographical location as related to the simplified representation of the power grid. A portfolio of new

Fig. 1: Load zones defined for this study

generation projects is employed for the candidate units, based on [26]. Battery energy storage system projects were included on such portfolio in every node of the power system. Based on this portfolio, the model finds the optimal expansion decisions to meet the growing power demand joined with the decarbonization process. The values of variable O&M (c_g^{om}), overnight capital $(\hat{c}_g^{G,inv})$ and fixed O&M $(c_g^{G,fix})$ costs by technology are derived from reports by the *Comisión Nacional de Energía* [28], the U.S. Energy Information Administration [29] and the Commonwealth Scientific and Industrial Research Organization [30]. Finally, the flexibility characteristics for the different dispatchable technologies are obtained from [31] .

3.5. Hydro-network

The Chilean energy system has a large share of reservoir hydro plants, and large potential for run of river generation. These energy sources present certain characteristics which differ from other thermal or even renewable generation units, such as the fact that there exists a water network which creates relations between several units, and that reservoir units do not present a variable generation cost but may have the ability to provide water storage. In this work, the Chilean water network is represented by a graph composed of nodes and lines, based on [8]. Rivers, lakes or reservoirs are represented by nodes, whereas lines represent potential water flows between nodes and, therefore, possible locations for hydro plants. Figure 2 shows an example of two hydraulic basins of Chile that have been modeled using this methodology.

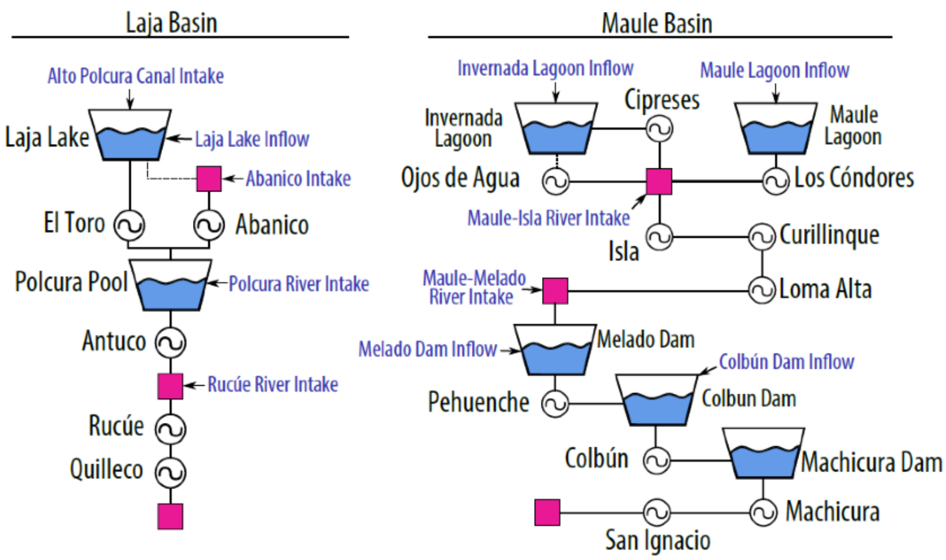

Fig. 2: Two modeled hydraulic basins of Chile with hydroelectric generators

3.6. Operational Conditions

Operational conditions are a key element for the proper characterization of flexibility in the EP problem. The load and renewable profiles considered through the planning horizon will directly determine the optimal units in terms of technology and location to meet expected demand over such horizon. Thus, the selection of operational conditions becomes a critical issue with great impact on the problems result.

To effectively capture the operational features of the power system through the planning horizon while mantaining computational tractability, a set of representative days were selected using a clustering technique.

3.6.1. Base Data and Clustering: The base data for the operational conditions were obtained from real operation data of 2015 provided by the system operator, called *Coordinador Eléctrico Nacional* [32]. This data consisted on 365 real days of operation including daily load an resource availability profile for PV, wind and Hydro RoR projects.

From this base data, representative days were selected using a hierarchical clustering method [33]. This method was applied over a set of operational conditions of interest within the base operational data, specifically, the hourly load and solar resource profiles by load zone. By doing this, groups of days with similar hourly operational conditions are obtained. Finally, representative days for each group are selected, assigning an individual weight depending on the number of days they represent. From this process, a set of six representative days was selected to be employed in the capacity expansion planning problem, which are specified on Table I.

These days set the base operational conditions for the planning problem. Loads profiles for the case study were obtained by combining such days with a load growth profile. Renewable profiles were considered to remain unchanged through the planning horizon, and were built based on [26].

3.6.2. Load Growth: The evolution of the total power demand in the system is constructed based on the projections presented by the *Comisión Nacional de Energía* in [34]. This projection is considered homogeneous over all zones.

3.7. Costs and Cost Projections

3.7.1. Fuel costs and carbon tax: Fuel costs and their respective projections are derived from [26] for coal, diesel and gas, and are considered to be uniform among all load zones. Also, the Chilean power system sets a carbon tax of 5 US$ per ton of CO_2, that applies to emissions produced by power generators with a capacity equal to or larger than 50 MW [35].

In order to analyze greenhouse gas emissions for fossil fuels in this study, fuel emission rates are employed. These values are adapted from [36]. These emission rates are also considered in the generation cost through the fuel usage and the previously mentioned carbon tax.

3.7.2. Capital costs projections: The capital or investment cost for candidate generation projects of each technology may variate over the planning horizon. This depends on many factors, including the maturity of the technology. For this case study, technologies such as coal, gas, diesel and hydro generation units are considered mature. This means that their capital cost remains constant through the planning horizon. On the other hand, technologies such as PV, wind, CSP and batteries are still evolving and thus their capital cost projections are built based on the information reported in [26] and [30].

3.8. Scenarios

Finally, under the presented data, three different scenarios were considered for the EP problem, which represent three different decarbonization goals, namely, 2040 (D40), 2035 (D35) and 2030 (D30). The decommissioning dates for existing coal units were adapted for each plan based on the preliminary schedule defined by the Chilean ISO *Coordinador Eléctrico Nacional* [37], where D40 considers the original dates, whereas D35 and D30 respect the retiring sequence but consider a tighter schedule. All models were programmed on Pyomo making use of the SWITCH-Model [38], a Python-based, open-source optimization modelling language, using Gurobi as solver.

4. Results

This Section presents the results of the Case Study presented in Section 3 under the presented Generation and Transmission EP model.

4.1. Cost Decomposition and Capacity Mix Evolution

This part studies the cost decomposition and evolution of the capacity mix through the planning horizon given by the solution of the EP problem for the Chilean power system.

First, Table II presents the cost structure for the solutions obtained for each scenario. Note that D2035 and D2030 incur respectively in a 2.8% and a 6.9% increase on the total cost over the planning horizon, as compared to the base scenario. This is mainly due to an increase in generation investment and fixed operation and maintenance costs, whereas the variable operation and maintenance, fuel consumption and carbon taxes cost decrease. In particular, these scenarios present respectively a 10% and a 21% reduction in fuel consumption costs over the planning horizon.

Figure 3 shows the evolution of the capacity mix over the planning horizon for each scenario. The accelerated coal phase out process can be observed in scenarios D35 and D30, as compared to the D40 base scenario. It can also be observed that all scenarios share a significant growth in variable PV and wind generation capacity, which is consistent with the decarbonization process and the evolution of capital costs. This also partially motivates the entrance of CSP and batteries, which play a more

TABLE I: The six representative days selected

day-month	n^o of days in cluster	weight
31-Jan	67	0.1835
12-Apr	53	0.1452
21-May	42	0.1150
31-Jul	97	0.2657
19-Oct	28	0.0767
11-Nov	78	0.2136

TABLE II: Systemic cost decomposition over the entire time horizon (discounted) under all scenarios studied (all values in Billion US$_{2018}$)

Scenario	D40	D35	D30
Total Cost	43.63	44.86	46.65
Generation Investment	16.98	19.21	22.10
Transmission Investment	9.06	9.07	9.05
Generation Fixed O&M	3.37	3.74	4.29
Generation Variable O&M	2.46	2.33	2.13
Generation Fuel Consumption	10.56	9.50	8.30
Carbon Taxes	1.20	1.02	0.78

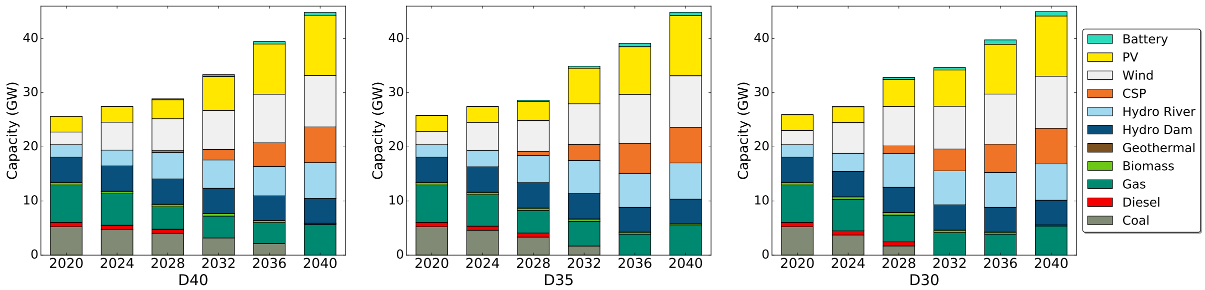

Fig. 3: Capacity installed by generation technology over the planning horizon under all scenarios studied

important role in faster transitions, as seen from scenarios D35 and D30. Finally, it can be noted that by the end of the planning horizon, the capacity mix is similar for all the considered scenarios.

To gain a better understanding of the capacity evolution through the planning horizon for the considered scenarios, it is useful to analyze the isolated capacity investments. Figure 4 shows the optimal investment decisions by planning period for the whole planning horizon of each scenario. Note that D30 and D35 scenarios require larger investments both in variable and flexible capacity in earlier stages of the planning horizon. This becomes more evident by 2028, where investments on D30 are clearly larger on batteries, PV, wind, CSP and mini hydro, and also on flexible gas generation technology, which gets postponed to 2032 in D40 and D35. A similar phenomena can be observed for D35 on 2032, where a notable investment peak occurs, which is due to the period where coal is completely phased out. Finally, note that for all scenarios, the presented EP model aims to balance variable capacity investments in PV, wind and mini hydro, with flexible resource placement in CSP, batteries and gas. This is due to an effective modelling of key operational flexibility aspects, and strengthens the need for appropriate market schemes which can properly acknowledge such aspects and create the appropriate incentives for achieving such investment dynamic.

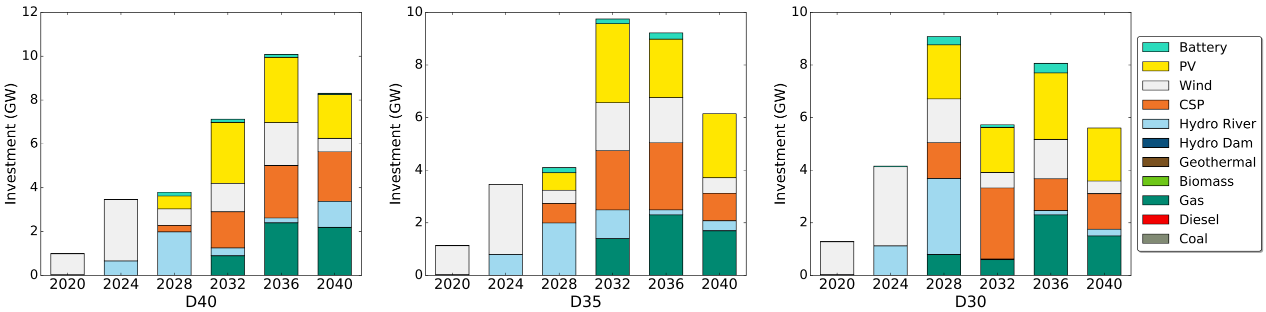

Fig. 4: Generation investments over the planning horizon under all scenarios studied

From the above results, we can observe that the optimal capacity transitions for the considered scenarios consists of a specific balance between flexible and variable capacity investments. Based on the economic expectations, variable sources such as PV and wind should be replacing fuel based generation in the next few years, which in turn should be efficiently complemented with flexible sources such as CSP, gas and battery systems. In what follows, we analyze the operational features through the planning horizon, which explain the need of such balance and provide insights on the role of the considered technologies.

4.2. Generation and Operational Features Evolution

This part studies the evolution of the generation mix through the planning horizon, and the changes in the operational features of the Chilean power system under the considered decarbonization schedules.

First, Figure 5 shows the evolution of the generation mix through the planning horizon. The phasing out of coal from the generation mix can be observed, with accelerated rates for D35 and D30 as compared to the base scenario. Note that CSP plays a key role on the transition of the generation mix with a considerable increase in its share through the planning horizon. This increase occurs at a faster rate for D35 and D30 as compared to the base scenario. Also note that in consistency with the capacity investments, the phasing out of coal from the generation mix is partially accompanied by an increase in gas generation for further flexibility. Finally, all scenarios present a large and constant increase in variable renewable generation, achieving a highly renewable generation mix which is necessary to achieve overall carbon neutrality in the next few decades.

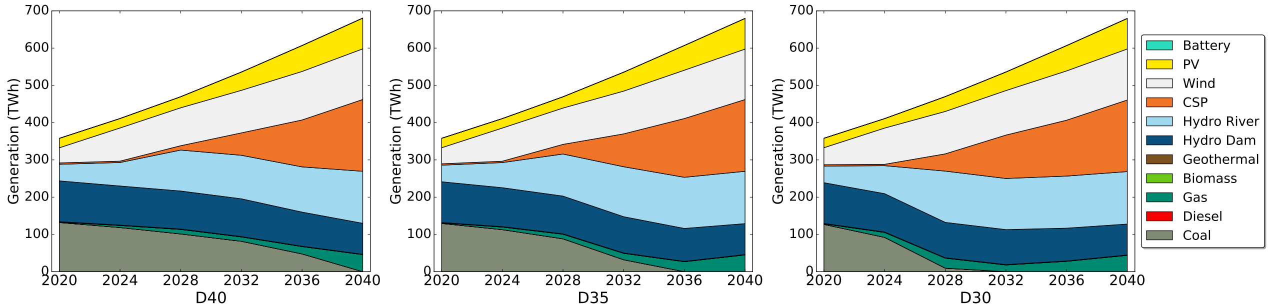

Fig. 5: Dispatched energy by generation technology throughout the planning horizon under all scenarios studied

Regarding this last point, Figure 6 shows the emissions evolution for the compared scenarios. It can be observed that the coal phase out creates a significant reduction on CO_2 emissions, with reduction trajectories being significantly lower for D35 and D30 as compared to the base scenario. A transition pathway such as D30 may pose important technical, social and regulatory challenges, but it may have outweighing benefits under the current climate crisis. Finally, note that both D35 and D30 present an increase in CO_2 emissions through the final planning periods, due to an increase in gas generation. Even though the magnitudes are considerably smaller (approximately 5 millions of tons in 2040 as compared to the 30 millions of tons in 2020) this is a trend that must be carefully regarded in the long term through the appropriate assessment of the externalities of such CO_2 emissions. This further highlights the importance of emission oriented policies that support the required reductions across technologies and even across industries for achieving overall carbon neutrality.

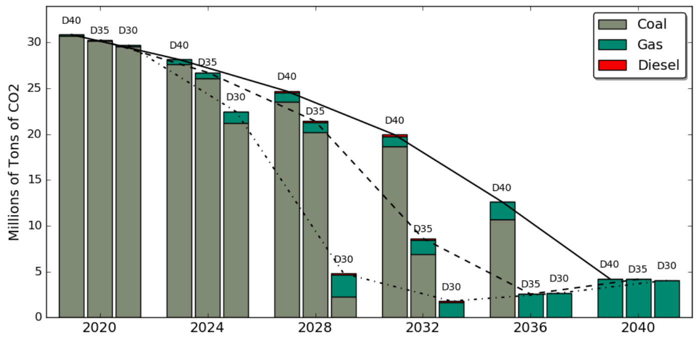

Fig. 6: CO_2 emissions throughout the planning horizon under all scenarios studied

Previous results show that the final capacity and generation mix are similar for the considered scenarios. This also applies for the operational features under a highly renewable mix. In what follows we will compare these features for the base scenario in the initial and final planning period. First, Figure 7 presents a percentage comparison between the generation mix for the first and last planning periods. Note the large increase in variable PV and wind energy (18.5% to 32.1%) and the large decrease in fossil fuel energy (36.9% to 6.7%), which shifts from coal to gas. CSP also increases from 1% to 28.3%. A reduction in the share of hydro dam is observed (30.6% to 12.2%) together with an increase in hydro river (12.5% to 20.5%).

Figures 8 and 9 show the hourly dispatched energy by technology for the six representative days under the base scenario for the first and last planning period. Note that for the last period the large penetration of wind and solar create significant ramps, which are met mainly through gas and hydro dam generation which can rapidly shift their generation levels. In particular, note the change in the role of hydro dam technology, from mainly base generation in the first planning period, to a major source of flexibility on the last. Also in the last period, note that hydro river and CSP provide relatively constant levels of energy through each representative day, even though flexibility and ramping capacity from CSP is also required on some occasions.

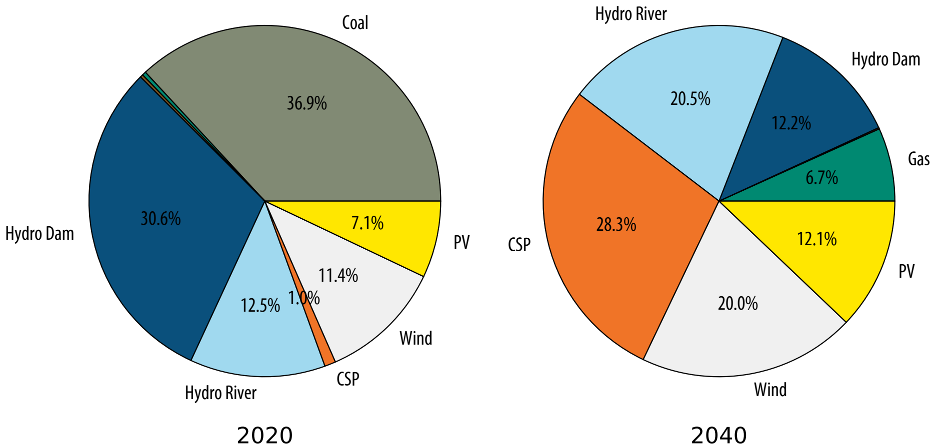

Fig. 7: Generation mix on 2020 and 2040 under base case scenario D40 (number in percentage of total energy production on 2020 and 2040, respectively)

Finally, note that batteries play a minor but interesting role on the final planning period, smoothing out peaks of generation and load, and consistently helping to met ramping requirements when PV generation drops in the afternoon.

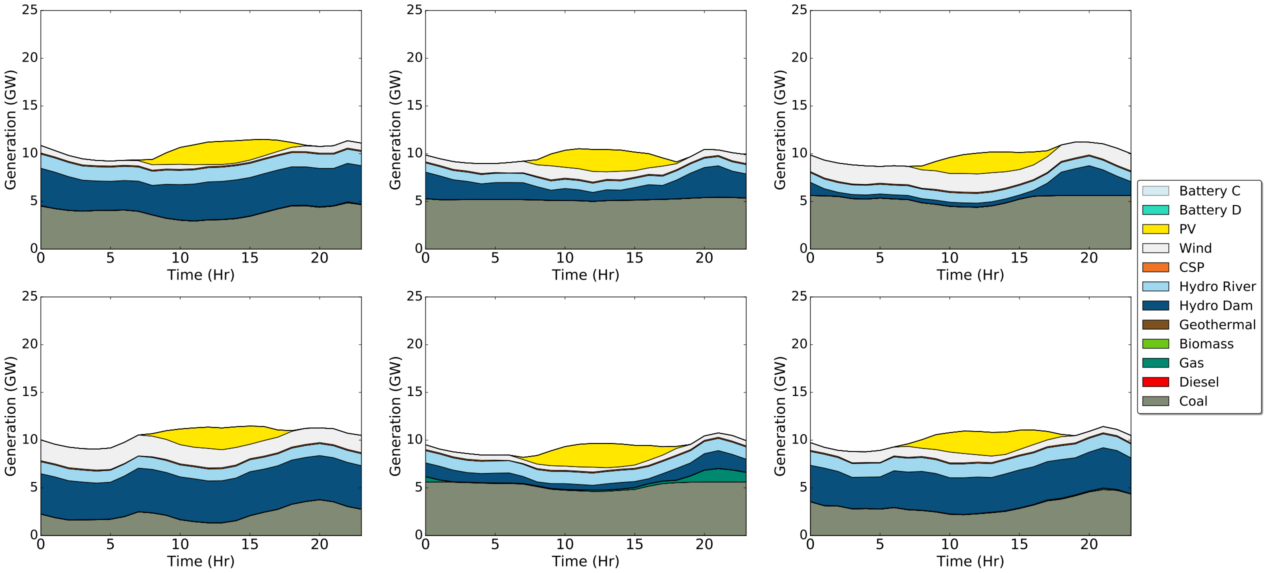

Fig. 8: Dispatched energy by generation technology throughout representative days of year 2020 under base case scenario D40

The presented results highlight the need for appropriate market schemes and an appropriate definition of flexibility requirements which allow the operation of a highly renewable system, with high volatility and short term uncertainty. This is particularly important to achieve significant reductions in CO_2 emissions as fast as possible within the energy sector to enable overall carbon neutrality.

4.3. Levelized Cost of Energy

Sections 4-A and 4-B discuss the evolution of the power system through the planning horizon in terms of capacity and generation mix and dynamics. This part studies a cost based metric, namely the levelized cost of energy (LCOE), for the different considered technologies through the planning horizon under the various decarbonization schedules considered. For this case study, the LCOE is calculated as the total cost related to a generation technology (capital and operation) divided by the total energy dispatched from such technology, based on the investment and operational decisions made by the EP model. Thus, it can be interpreted as the minimum price at which the energy generated by that technology should be sold to balance the costs of any new generation units. Existing generation plants are excluded from this analysis.

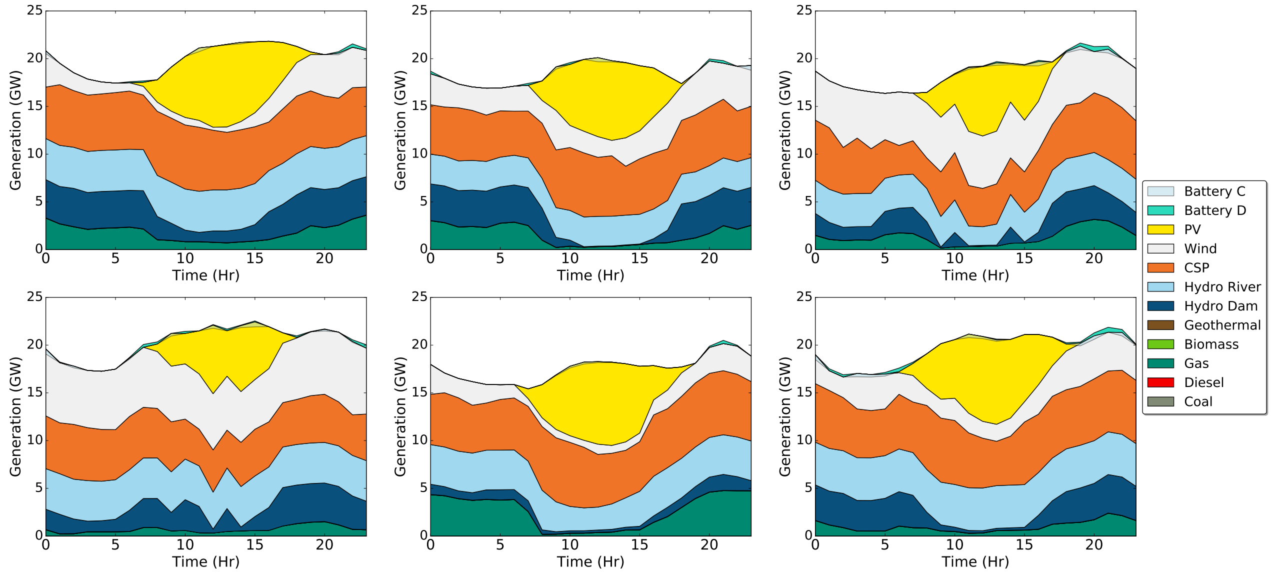

Fig. 9: Dispatched energy by generation technology throughout representative days of year 2040 under base case scenario D40

Table III shows the LCOE by generation technology for each scenario. Recall that these scenarios share the same cost structure for the presented technologies, however the LCOE by technologies shows higher values under more strict decarbonization scenarios. This is due to the fact that investments are made earlier and under higher capital costs for developing technologies, and also because under such scenarios flexibility becomes more critical and motivates investments which are less explained by dispatched energy. This last point is also supported by the high LCOE of gas investments, which is a more expensive source of energy but a competitive source of flexibility under this case study.

The LCOE provides useful insights on the cost based performance of generation technologies through the planning horizon. However, it is hard to compare other flexibility assets which are not directly involved in generation. In what follows we analyze the specific dynamics of such assets, namely storage and transmission.

4.4. Storage and Transmission

This part studies the investment decisions on storage and transmission capacities, which are key to the power systems flexibility, over the three considered scenarios. In particular, investments on CSP and batteries are analyzed, which respectively provide thermal and electrical storage, and investment on transmission lines capacities.

First, Table IV shows the evolution of battery technology on the system through the planning horizon for the considered scenarios. As discussed in previous sections, investments in battery technology are modelled as two separate components, namely storage and power capacity, which can be build independently from one another. Thus the results for each component is presented separately in the table. Note that more strict decarbonization scenarios present larger investments on battery systems, and in earlier stages for D30 as compared to D35 and D40. Also note that all scenarios present large investments in storage capacity, which are then progressively met by investments in battery power for faster charging and discharging rates. This is consistent with the increase in ramp requirements as the generation mix of variable PV and wind increases through the planning horizon.

TABLE III: LCOE by generation technology under the different scenarios studied (US$$_{2018}$/MWh)

Scenario	D40	D35	D30
Gas (CCGT)	91.7	101.2	113.6
Gas (OCGT)	195.9	189.2	189.7
CSP (solar power)	57.7	61.8	65.5
Hydro-River (RoR)	65.2	65.5	76.2
Hydro-River (Mini)	63.7	65.4	70.0
PV (solar power)	37.8	38.3	42.1
Wind (wind power)	62.7	63.6	67.5
Total	61.7	64.3	68.6

TABLE IV: Batteries capacity over the planning horizon under decarbonization scenarios

D40	2020	2024	2028	2032	2036	2040	Total
Power (MW)	-	-	176.3	145.8	136.2	57.1	515.4
Storage (MWh)	-	-	515.4	-	-	-	515.4
D35	**2020**	**2024**	**2028**	**2032**	**2036**	**2040**	**Total**
Power (MW)	-	-	193.3	180.0	237.8	-	611.1
Storage (MWh)	-	-	611.1	-	-	-	611.1
D30	**2020**	**2024**	**2028**	**2032**	**2036**	**2040**	**Total**
Power (MW)	-	33.7	312.9	100.6	360.7	-	807.9
Storage (MWh)	-	226.4	581.5	-	-	-	807.9

Table V shows the evolution of CSP capacity through the planning horizon for the considered scenarios by storage capacity, due to the fact that CSP units were modelled as having a fixed power to storage rate defined by the storage hours. Note that all scenarios have the same total capacity for every configuration at the end of the planning period, but present various differences through the decarbonization sequence. One of these differences is the fact that for more strict decarbonization plans, investment shifts towards CSP units with larger storage capacity in earlier stages of the planning horizon. In D40 the first installed units have a storage capacity of 9 hours, whereas in D35 a combination of 9 and 13 hours storage is installed, and in D30 the first installed units are all of 13 hours storage capacity. This is due to the fact that as coal is being phased out, CSP is partially becoming a base generation technology, for which it requires larger storage capacities, and this effect becomes critical earlier under strict decarbonization scenarios.

Finally, Table VI shows the increments on transmission capacity through the planning horizon for each scenario. In this table, lines are presented geographically from north to south in descending order. Note that the total transmission capacity is similar among all the considered scenarios, with a slight decrease for D35 and D30 as compared to D40. This is due to increased generation capacity investments in those scenarios, which postpones certain transmission requirements. Note also that for all scenarios early investments on transmission capacity are made mostly in the northern area, and progressively shifts towards the center and south of the country in the final part of the planning horizon. Early investments on the north are made to export PV generation to the rest of the system, but as the load and flexibility requirements increase, further transmission is required in other areas of the power system.

TABLE V: CSP investments over the planning horizon under decarbonization scenarios by storage capacity (MW)

D40	2020	2024	2028	2032	2036	2040	Total
CSP 9 hours	-	-	300	450	750	750	2250
CSP 13 hours	-	-	-	1200	1650	450	3300
CSP 17 hours	-	-	-	-	-	1050	1050
Total	-	-	300	1650	2400	2250	6600

D35	2020	2024	2028	2032	2036	2040	Total
CSP 9 hours	-	-	300	900	1050	-	2250
CSP 13 hours	-	-	450	1350	1350	150	3300
CSP 17 hours	-	-	-	-	150	900	1050
Total	-	-	750	2250	2550	1050	6600

D30	2020	2024	2028	2032	2036	2040	Total
CSP 9 hours	-	-	-	1650	450	150	2250
CSP 13 hours	-	-	1350	1050	750	150	3300
CSP 17 hours	-	-	-	-	-	1050	1050
Total	-	-	1350	2700	1200	1350	6600

TABLE VI: Transmission investments over the planning horizon under decarbonization scenarios (MW)

D40	2020	2024	2028	2032	2036	2040	Total
CE-M	-	-	447.1	-	-	-	447.1
DA-C	-	-	-	-	-	24.2	24.2
C-M	-	-	-	-	246.1	1102.9	1349
M-PA	-	-	-	87.9	41.2	854.3	983.4
LV-N	-	-	-	-	24.6	796.2	820.8
C-H	-	-	-	-	-	274.3	274.3
Total	0	0	447.1	87.9	311.9	3051.9	3898.8

D35	2020	2024	2028	2032	2036	2040	Total
CE-M	-	181.8	97.9	-	-	-	279.7
DA-C	-	-	-	-	-	15.1	15.1
C-M	-	-	-	-	620.9	711.5	1332.4
M-PA	-	-	-	-	396.3	587.1	983.4
LV-N	-	-	-	-	348.2	456.4	804.6
C-H	-	-	-	-	113.7	107.1	220.8
Total	0	181.8	97.9	0	1479.1	1877.2	3636

D30	2020	2024	2028	2032	2036	2040	Total
CE-M	-	192.1	-	-	-	-	192.1
DA-C	-	-	-	-	-	-	0
C-M	-	-	-	55.6	368.8	902.1	1326.5
M-PA	-	-	-	-	235.9	749.5	985.4
LV-N	-	-	-	-	190.7	617.6	808.3
C-H	-	-	-	49.3	64.4	160.6	274.3
Total	0	192.1	0	104.9	859.8	2429.8	3586.6

In conclusion, the presented results show that for the decarbonization process, an optimal transition results on the balance of flexible and variable resources, not only limited to generation and ramp capacities, but also through strategic storage and transmission investments. These balance becomes even more critical for more strict decarbonization scenarios. It is paramount to develop a thorough understanding on these flexibility requirements and to ensure that new market structures create the appropriate incentives for a reliable transition of the power system, to enable a fast and effective decarbonization process. The Chilean electric power system presents many favorable conditions for such transition, which are reflected in the large deployment of PV, wind, hydro river and CSP generation units across all the analyzed scenarios. Early decarbonization goals may be achieved maintaining a similar cost range as compared to the base case scenario through an effective balance between variability and flexibility. This is a challenging task but advances in literature, regulations and policies are currently aiming towards it.

5. Conclusion

We have presented an optimization-based assessment of various decarbonization pathways for the Chilean power system, considering the use of an advanced EP model which employs the concept of representative days, a thorough modelling of the hydro network, an approximation of the unit commitment problem and constraints for modelling both thermal and electrical storage. This allows to gain insights on the flexibility requirements and operational features of such scenarios, which are a key aspect under a highly renewable variable generation mix. Three decarbonization scenarios were studied: D40, D35 and D30, based on achieving full decarbonization by 2040, 2035 and 2030, respectively. The results show that ambitious decarbonization scenarios remain in a similar cost range as compared to the base case scenario. Large penetration of PV and wind energy is expected due to economical expectations, and thus an optimal transition to a carbon free power system requires a strategic balance between variable and flexible resources, including ramping, storage and transmission capacity. Further, the optimal investments on flexibility present different characteristics for more strict decarbonization scenarios, which may depend more on the ramping and storage capacity of flexible technologies such as CSP, battery systems and natural gas. Achieving ambitious decarbonization goals may be fundamental to respond quickly to the current climate crisis, which in turn poses other important technical, social and regulatory challenges. It is essential that new market and operational structures properly account for the whole flexibility requirements and capacities of the power system to incentivize an effective and reliable transition to a cleaner power system.

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