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New proposal for the capacity remuneration scheme in the Chilean electricity system

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Enseñar con la actitud, el gesto y la palabra.”
— Gabriela Mistral

Agradecimientos

Aquí vienen los agradecimientos que se deseen colocar.

Por ejemplo a familiares, amigos, compañeros, proyectos, etc...

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Abstract

Chapter 1

Motivation

The energy transition toward renewables-based power systems is fundamentally transforming how electricity grids are developed, managed, and operated worldwide [1] [2]. This process involves not only the integration of new clean generation sources but also the progressive phase-out of fossil-fuel-based thermal power plants. While this shift is essential to mitigate the effects of climate change and requires urgent action, it also presents significant challenges related to expanding generation capacity, managing installed capacity, and ensuring the reliability and flexibility of power systems [3][4]. These challenges are exacerbated in markets with high renewable energy penetration, where traditional generators are forced to operate fewer hours per year, leading to growing economic uncertainty—a challenge that Chile is no stranger to.

From an operational perspective, the variability and uncertainty inherent in renewable sources present new challenges for secure system operation, limiting the effective availability of these resources and increasing reliance on peaking generation units. Therefore, an innovative approach is required to ensure both supply security and economic stability, as discussed in [5]. From an economic standpoint, large-scale integration of renewable energy leads to a sustained reduction in marginal costs [6][7], which depresses market prices and weakens the profitability of conventional thermal generators. This environment also reduces investment signals for low-emission, capital-intensive technologies such as concentrated solar power and hybrid systems with storage. It is thus essential to develop mechanisms that connect market outcomes with the revenue streams required to incentivize investment in flexible and zero-emission technologies [8]. This need is illustrated in [9], where the authors analyze the negative effects that arose in the German power system due to the absence of mechanisms that ensured revenue for natural gas plants—resources considered essential to guaranteeing supply security during the transition [10][11].

In this context, *Capacity Remuneration Mechanisms* (CRMs) have emerged as a key tool to ensure the availability of reliable and flexible energy resources during periods of high demand or scarcity [12]. While these mechanisms may introduce certain market distortions by altering generator revenues and shifting the economic equilibrium, a well-designed CRM can lead to more efficient outcomes than those achieved solely through energy and ancillary services markets. By allowing regulators to guide the system toward solutions that ensure desired levels of adequacy and reliability, CRMs can improve overall system performance. Additionally, by providing incentives to build a more cost-efficient system aligned with energy transition goals, a well-structured CRM can serve multiple purposes: integrating renewable and flexibility resources while aligning market outcomes with strategic regulatory goals. This multi-objective approach allows CRMs not only to ensure capacity availability but also to drive a structural transformation of the electricity market, in line with decarbonization and system modernization priorities.

In much of Europe, capacity mechanisms have been introduced in markets that were previously based solely on energy transactions [13]. In contrast, systems such as PJM and **Chile** already had such mechanisms in place even before the onset of the energy transition. In the Chilean case, the existing capacity payment mechanism was originally designed to ensure supply security and provide investment signals in a hydrothermal-dominated system. This mechanism played a key role in supporting the development of large reservoirs and thermal power plants. However, the Chilean power system is currently undergoing a structural transformation toward a matrix primarily based on non-conventional renewable energy sources. This transition is driven by the country's high solar and wind potential and is accompanied by a decarbonization process that includes the progressive retirement of coal-fired plants, which still accounted for approximately 23% of electricity generation in 2022 [14].

Despite this transformation, Chile's current capacity mechanism has significant limitations. It is based on a static approach that uses historical consumption to determine the required capacity, without adequately anticipating the system's future needs. Additionally, it sends weak investment signals for key technologies such as energy storage and other flexible, low-emission solutions. This is further compounded by transmission constraints and increasing water scarcity that affects hydroelectric generation availability.

Several studies have evaluated the performance and applicability of capacity mechanisms. For instance, [15] qualitatively examines the integration of traditional CRMs (CA, CP, SR) into the Chinese electricity market, using international experiences as a reference. However, by omitting a quantitative evaluation of CRM–energy market interactions and disregarding system-specific characteristics, its conclusions may not be applicable in other contexts. In [16], the performance of capacity auctions in Poland—similar to the mechanism implemented in the United Kingdom [17]—is analyzed, highlighting the importance of distinguishing between existing and new resources to provide adequate incentives for fleet modernization in the context of the energy transition. Nonetheless, a key limitation is the omission of geographic location, which prevents targeting incentives to strategic areas. In addition, [18] outlines policy guidelines for integrating capacity mechanisms across the European Union and discusses the challenges related to incorporating energy storage. A central issue identified is the technical inconsistency in how storage is treated: while the LOLE calculation assumes a "depth minimization" model, the adequacy assessment uses a "duration minimization" approach, which more accurately reflects real system operation. This inconsistency can distort adequacy estimates and increase total system costs.

The current literature proposes several alternatives for designing or adapting CRMs to support energy transition processes. For example, [19, 20] emphasize the need to integrate flexibility resources, such as energy storage, to address the challenges of decarbonization. These studies stress the importance of developing targeted methodologies to ensure that participating units exhibit the required flexibility attributes, as well as mechanisms to assess their performance. However, they do not quantify the impact that integrating such resources may have on baseload units, such as insolvency risks or premature retirements, which could affect system adequacy. Meanwhile, [21] proposes a methodology to enable both explicit and implicit demand-side participation, offering flexibility in CRM commitments. Nevertheless, it identifies a gap in determining the volume of capacity that should be supported by the CRM, which limits the effective sizing of demand response (DR) resources. In [22], a long-term framework is presented to assess the optimal mix of generation technologies, based on scarcity pricing and reliability contracts in decarbonized systems. However, this study does not account for hybrid units, which are expected to play a central role in future energy systems.

This study seeks to answer the following question: **How can a capacity remuneration mechanism be designed for the Chilean power system that balances adequacy, flexibility, and decarbonization in transitioning electricity systems?**

To this end, this paper proposes an innovative methodology for designing and evaluating CRMs, applied to a case study of the **Chilean power system**. The contribution is structured around three key pillars that address gaps identified in the existing literature:

1. Assessing the impact on unit profitability and how it is influenced by the introduction of mechanisms with different allocation, remuneration, and evaluation schemes—interactions that have not been jointly examined through both qualitative and quantitative perspectives.
2. Introducing technical and economic design criteria to support the energy transition within CRM frameworks, including unit selection, implementation timeline, geographic location, and investment costs—all addressed in an integrated manner.
3. Simultaneously incorporating adequacy, decarbonization, and revenue signal objectives—through active constraints in the model when possible, and through ex post calculations otherwise—to enable a comprehensive and coherent analysis of these interrelated dimensions.

Chapter 2

Context

This section seeks to contextualize this research and analyze the state of the art of Capacity Remuneration Mechanisms, highlighting the specific characteristics of the Chilean capacity payments in light of the international experience.

2.1 Capacity Remuneration Mechanisms

Different Capacity Remuneration Mechanisms (CRMs) are operational in various electricity markets worldwide, including PJM (USA), European Union markets such as Spain and Portugal, and even in South America, including Chile and Colombia. These mechanisms generally exhibit one or more of the structures shown in Figure 2.1, and regardless of the scheme used, their primary objective is to ensure an adequate supply of energy in the electrical system.

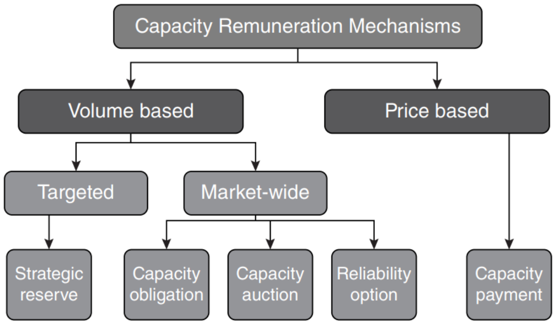

Figure 2.1: Possible models for capacity mechanisms[23].

However, in today's context, CRMs also incorporate more specific objectives into their design. For instance, they aim to achieve an effective transition to more sustainable energy sources, as discussed in the study mentioned in [24], where the impacts of incorporating various types of CRMs to adequately assess renewable resources as thermal units exit the system are evaluated. Additionally, these mechanisms allow for the diversification of the energy matrix by including different resources to provide reliability to the system, as addressed in [25], where the incorporation of Demand Response in the European market to address the crisis of 2021 is discussed. Nevertheless, beyond the appropriate design of a CRM, it is essential to monitor and evaluate the mechanism's performance over time, as discussed in [26], which analyzes the incorporation, performance, and future modifications of CRMs present in the EU. This becomes particularly relevant for the development of this proposal when analyzing the case of the Chilean CRM, where the mechanism has not undergone significant changes since its inception and maintains the initial objectives presented below.

2.2 Bridging Operational Needs and Investment Signals in the Energy Transition through CRMs

The global energy transition presents significant challenges for both regulators and system operators. From an operational perspective, the uncertainty associated with primary energy resources has introduced substantial complexities, which have been extensively addressed in the literature [27] [28], and therefore are not the main focus of this study. In contrast, from a regulatory standpoint, the integration of renewable resources alters the economic dynamics of electricity markets, particularly the allocation of financial resources, putting the viability of baseload units at risk. This phenomenon has been widely discussed in systems with a high dependence on thermal generation. For example, [29] highlights how the European Union's transition has revealed socio-economic vulnerabilities in its smaller systems, such as Bulgaria, that are not always visible from a purely operational perspective. Similar concerns are found in larger-scale systems within the EU, such as Germany and the UK , as shown in [30], which examines the challenges arising from the integration of new resources into the grid. In this context, the operational decline of baseload resources due to the ongoing energy transition necessitates temporary support during the replacement of the existing generation fleet. However, this need was not initially anticipated in regulatory frameworks, leaving systems exposed to a range of operational, economic, and social challenges that must be addressed to ensure a secure and sustainable transition.

Figure 2.2 highlights that generator revenues are determined not solely by the electricity market's structural components, but also by complex interactions between operational realities and evolving regulatory frameworks. While simplified, the diagram illustrates how revenue streams from different market segments–including Power Purchase Agreements (PPA), energy markets (e.g. Day-Ahead, Intraday, and Real-Time, depending on the market design), Ancillary Services (AASS), and CRMs–combine to cover both capital (CAPEX) and operational (OPEX) expenses, while also enabling a profit. In particular, CRMs play a complementary role by helping close revenue gaps left by energy and ancillary service markets, thereby enabling generators to not only recover costs but also earn a return sufficient to motivate new investment.

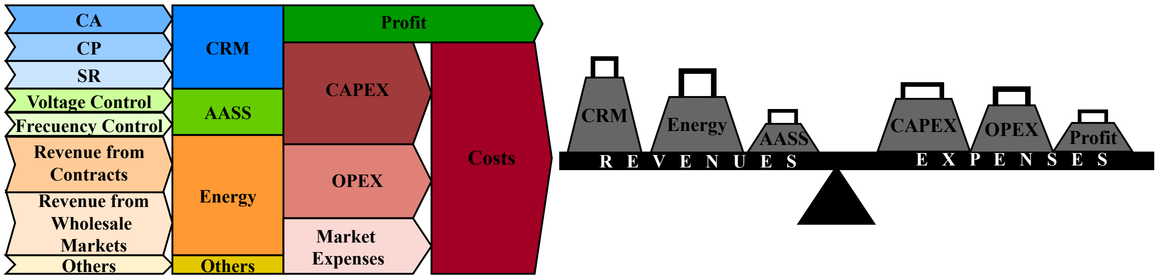

Figure 2.2: Conceptual diagram of the revenues earned by a generator participating in different segments of the electricity market.

A clear example of this dynamic is the Chilean electricity market, which has historically relied on a Capacity Payment model. This mechanism provided additional income that supported the development of thermal units and large hydro reservoirs [31], sending investment signals that enabled capacity expansion during the first two decades following deregulation at the end of the 20th century. However, as renewable energy (RE) penetration increased, the limitations of the scheme became more evident–particularly in projecting system adequacy and promoting low-emission technologies that contribute to supply security. Over time, the system has also faced several supply security events, driven primarily by natural gas shortages from Argentina and a prolonged drought exacerbated by climate change [32]. More recently, the lack of flexibility in the capacity mechanism has contributed to increased market volatility and stressed system operations, particularly regarding the availability of water and fuel. Despite an installed capacity nearly three times peak demand, these pressures ultimately led to the issuance of a rationing decree in 2022, which forced the dispatch of diesel-fired units to cover supply shortages during periods of high demand. While this short-term measure helped avert immediate supply risks, it also led to higher energy prices and increased emissions. As a result, there is a growing need to develop mechanisms capable of addressing the long-term decarbonization, adequacy, and flexibility challenges of the Chilean power system—challenges that, to date, remain unresolved. Another capacity mechanism implemented that has generated controversy in recent years is the Reliability Pricing Model (RPM) of PJM [33]. This model is based on competitive capacity auctions, where resources are acquired three years in advance to ensure that the system has adequate capacity. The purpose of this mechanism is to provide price signals that encourage both the conservation of existing resources and the development of new generation sources. However, in [34], the reasons why RPM has been under litigation before the Federal Energy Regulatory Commission (FERC) are investigated, due to high prices and a lack of competition in its annual capacity auctions. One of the most peculiar features of the PJM RTO is its segmented capacity market, where key suppliers have managed to separate from the larger market and create captive Locational Deliverability Areas (LDAs), where they hold a dominant market share. Despite the system's intention to ensure competitive prices, in [35] concerns are raised about how state subsidies for carbon-free generation may be distorting the market, depressing capacity prices. The analysis shows that PJM's clearing algorithm deviates from economic theory, inflating prices instead of reducing them.

By comparison, Germany offers an alternative approach to managing supply security. In response to high energy prices and winter operational challenges, the country implemented a strategic reserve comprising units selected based on geographic and technical criteria, and kept outside the energy market to avoid distorting price signals[23]. Unlike traditional CRMs, this reserve provides reliability without compromising market efficiency. The European Union——through the Agency for the Cooperation of Energy Regulators (ACER)——considers strategic reserves the preferred CRM design and discourages capacity payments. The Clean Energy Package Regulation (EU) 2019/943 [36] stipulates that strategic reserves must be dispatched only under extreme system stress, remain outside wholesale markets, and comply with strict participation criteria to prevent market distortion. Germany's model reflects these principles by applying transparent, competitive selection processes and requiring technical capabilities such as flexibility and fast dispatch. Once in the reserve, units are barred from participating in other market segments, reinforcing their role as a last-resort resource. This approach highlights the value of careful CRM design—linking participation to system needs and aligning with broader decarbonization goals. Moreover, [37] underscores the importance of integrating flexible resources—such as storage and demand response—into CRMs to help manage renewable variability. Incentivizing such technologies is essential to maintain supply-demand balance during periods of high volatility.

Therefore, it is crucial that the implementation of capacity mechanisms considers how new resources—such as storage, demand response, and hybrid plants—affect the distribution of revenues across market segments. Failing to account for these dynamics can lead to suboptimal outcomes in system configuration, operation, and investment. In particular, poorly designed mechanisms may fail to attract flexible, low-emission resources, increasing the risk of future capacity shortfalls. This challenge also presents an opportunity: to design CRMs that explicitly recognize and integrate these evolving interactions, ensuring a more effective and adaptive integration of resources into the power system.

In this context, CRMs play a central role in shaping system adequacy and resilience over the short, medium, and long term. The objective of this paper is to propose a mechanism that evaluates the performance of CRMs in supporting both security of supply and investment in decarbonization, from a systemic and economically grounded perspective. By integrating flexibility, reliability, and emission reduction objectives, the proposed model seeks to ensure that CRMs become an effective tool for promoting the sustainability of electricity markets and the deployment of technologies that enable a flexible, resilient, and low-carbon energy system.

2.3 The Chilean CRM

The capacity payment mechanism emerged after the liberalization of the Chilean electricity market, and the General Law of Electric Services was established in 1982 [38]. Its main objective is to ensure that the system can supply the demand during periods of scarcity. Additionally, it aimed to generate incentives for installing power plants with high investment costs, such as thermal and reservoir hydro units, providing income to recover their sunk costs that they could not readily recover from participation in the energy market. Moreover, these payments were deemed necessary because of the country's general process of electrification, which required expanding the generation capacity. For this, complementary market signals were needed to provide certainty to investors. In [39], the authors point out that the main reasons for the emergence of capacity remuneration mechanisms are the issue of missing money and the lack of capacity in the system.

The mechanism chosen in Chile is an administrative capacity payment. The total amount to be paid to all resources is obtained by multiplying quantity by price. The quantity is the sum of the Capacity Values (CV) of all resources (Final Adequacy Capacity), which is adjusted to match the peak demand of a system or subsystem, according to the Supreme Decree No. 62 of 2006 [40]. The price is not dynamic (as the marginal cost in the energy market) but is valued at the short-term nodal price at the injection point, which is calculated once every six months according to the provisions of Exempt Resolution No. 641 [41]. Then, the total payments are prorated between all generators according to their respective CVs, corresponding to a fraction of their maximum capacity[1].

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[1] The calculation of the Capacity Value for each resource is based on administrative rules that discriminate between different technologies and try to capture the contribution of each resource to system's adequacy

2.3.1 Current methodology

The current methodology for calculating the CV of each resource (i.e., its "Potencia de Suficiencia" is determined in the Supreme Decree No. 62 of 2006 [40]. This process is carried out for each unit of the National Electricity System (NES) as follows:

- **Maximum Capacity:** This corresponds to the maximum load that a resource can sustain during continuous operation. The Maximum Capacity of each unit is used as an input for calculating its CV, and it is estimated by the National Electric Coordinator as indicated in Article 4 of the Technical Annex "Tests for Maximum Capacity of Generating Units" of the Technical Standard for Safety and Quality of Service [42].

- **Initial Capacity:** In the first step, each system unit is assigned a quantity that is less than or equal to its Maximum Capacity. This reduction corresponds to the gross power of the plant, taking into account the uncertainty associated with the availability of the primary generation input and the environmental restrictions associated with it. Therefore, calculating this value depends on the generation technology and the type of primary resource used. This process can be represented in terms of equations 2.1 and 2.2.

  $$P_{in_i} = P_{raw_i}(fuel, renewable\ resource, environmental\ constraint) \tag{2.1}$$

  $$P_{in_i} = min(P_{in_i}, P_{max_i}) \tag{2.2}$$

- **Preliminary Adequacy Capacity:** In this case, the Equivalent Capacity of each unit must be calculated. This magnitude is obtained by dividing the recorded power of the generating unit in the respective operational state (OS) by its duration and dividing it by the total calculation period during which the unit was in those states. Subsequently, the obtained value should be compared with the Initial Capacity, a process reflected in equations 2.3 and 2.4.

  $$P_{Eq} = \frac{\sum_i^n P_{OS_i} \cdot \Delta t_i}{\sum_i^n \Delta t_i} \tag{2.3}$$

  $$P_{in_i} = min(P_{in_i}, P_{Eq_i}) \tag{2.4}$$

  Afterwards, the Initial Capacity must be reduced by a factor proportional to the unit's own consumption and a factor proportional to major maintenance.

  $$f_{cons} = 1 - \%\ own\ consumptions \tag{2.5}$$

  $$f_{main} = 1 - \%\ major\ maintenance \tag{2.6}$$

  $$P_{pre_i} = P_{in_i} \cdot f_{cons_i} \cdot f_{main_i} \tag{2.7}$$

  Finally, the Preliminary Adequacy Capacity is obtained through an analysis based on statistical information, evaluating the expected value of the power it contributes to the Adequacy for meeting peak demand, considering the set of generating units, their Initial Capacity, and the Forced Outage Rate of each unit (FOR).

- **Final Adequacy Capacity:** The Final Adequacy Capacity for each generation unit corresponds to the Preliminary Adequacy Capacity scaled by a unique factor for all units, such that the sum of the Final Adequacy Capacity of the generation units is equal to the system's Peak Demand, as exemplified in Figure 2.3.

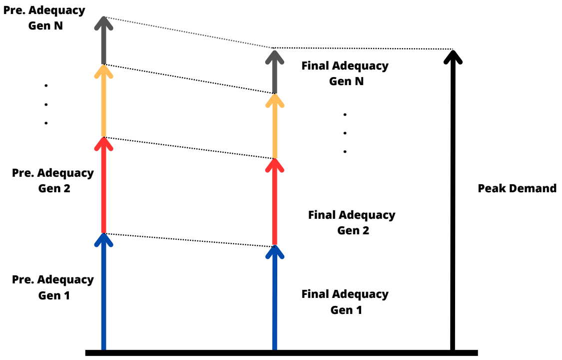


Figure 2.3: Adjustment of Preliminary Adequacy Capacity to Peak Demand.

To calculate the adequacy power, the Peak Demand corresponds to the average of the 52 highest hourly values from the annual load curve of each system or subsystem for the calculation year, as exemplified in Figure 2.4.

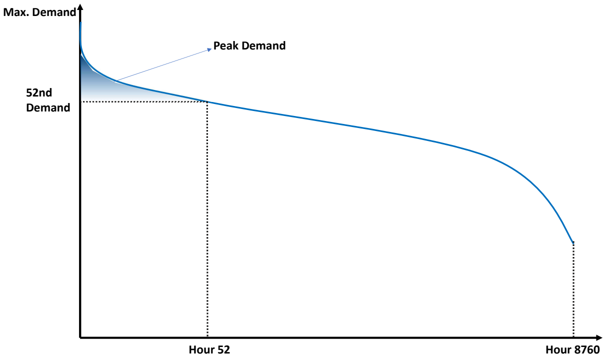


Figure 2.4: Methodology for calculating peak demand.

2.3.2 Valuation of Adequacy

According to the regulations of Power Transfer [40], the injections and withdrawals of power used to determine power transfers will be valued using the short-term nodal price of power. Below is the methodology for calculating this value and its historical evolution.

2.3.2.a Calculation of nodal price

The Nodal Power Price (NPP) is used to evaluate capacity, which is obtained from the Basic Peak Power Price (BPPP). The BPPP calculation is based on the most economical generating units capable of supplying additional power during the hours of annual peak demand.

The BPPP must be weighted by the Theoretical Reserve Margin (TRM), which is calculated based on the Power Margin (PM). The Power Margin is the ratio between the sum of the initial powers of the system's units and the peak demand, as indicated in the equation 2.8.

$$PM = \frac{\sum_{i=1}^{n} P_{in_i}}{\text{Peak Demand}} \tag{2.8}$$

If the PM exceeds 1.25, the TRM is set to 10%

$$TRM = \begin{cases} 15\% - \left[\frac{PM-1}{0.05}\right]\% & PM \leq 1.25 \\ 10\% & PM > 1.25 \end{cases} \tag{2.9}$$

Finally, the Basic Peak Power Price must be weighted considering the TRM to obtain the Nodal Power Price, as indicated in the equation 2.10

$$NPP = BPPP \cdot (1 + TRM) \tag{2.10}$$

2.3.2.b Hystorical SEN Nodal Power Price

In this case, the average nodal power price of the Chilean electrical system has been observed since the interconnection was made in 2017. As shown in Figure 2.5, there is a low variability in the price associated with the adequacy resource. If we relate this phenomenon to the process of determining the basic peak power price, it means that the units capable of providing adequacy during peak demand hours at minimum cost have not changed over the years, even though the generation fleet has incorporated large volumes of capacity.

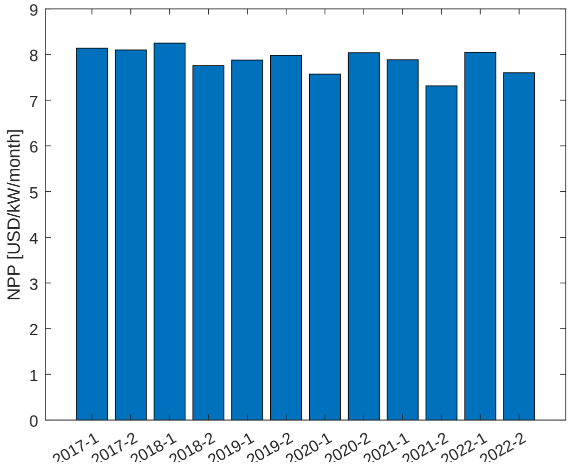


Figure 2.5: The Evolution of NPP in Chile [43].

2.4 Reality of the National Electricity System

Below is the historical evolution of the capacity levels of the Chilean system, as well as the adequacy levels of the system. Additionally, the distributions of both variables are presented regarding the technologies present in the system. Moreover, the evolution of the energy value in the national electrical system is shown. Finally, the effect of the process of decarbonization of the energy matrix on the adequacy levels of the system is evaluated.

2.4.1 Installed capacity

The capacity of the Chilean electrical system has grown exponentially in recent years, a change that began with the Argentine gas crisis in 2007[44], which required the integration of thermal generation to cope with the deficit of the primary resource. Subsequently, a process of integrating renewable energy sources began, which has significantly increased in the last 10 years due to the country's enormous wind and solar potential and the decreasing costs of these technologies [45].

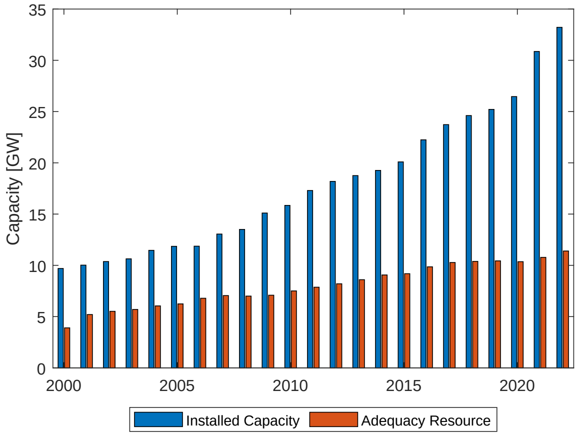
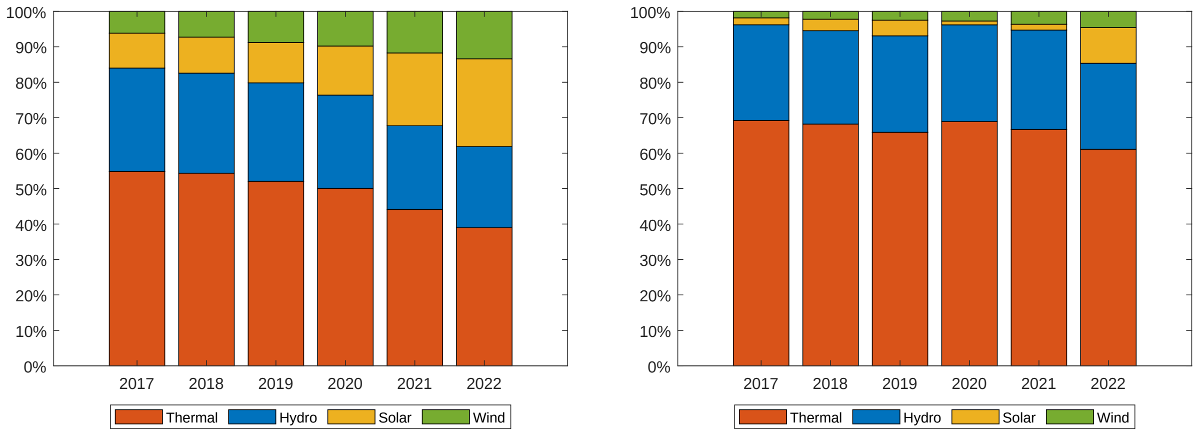


Figure 2.6: Evolution of Capacity and Adequacy [46][47].

However, as observed in Figure 2.6, the adequacy resource has not shown the same behavior because it does not depend on installed capacity but rather on systemic demand. Therefore, incorporating new capacity into the system influences the distribution of the adequacy resource but not its volume. This can be seen, for example, in 2007 with the installation of coal or diesel-fired thermal power plants to cope with the Argentine gas crisis, or since 2015 with the integration of renewable resources, where capacity levels varied significantly, but adequacy levels did not. Additionally, since it is based on demand data from the previous year and does not consider ongoing construction or retirements from the grid, it is not sensitive to possible changes in the system. In other words, it functions as a retrospective rather than a prospective mechanism.

2.4.2 Adequacy Distribution

As analyzed in the previous section, the installed capacity in Chile has undergone considerable evolution in recent years. However, the total adequacy capacity of the system has remained relatively constant. Therefore, the distribution of these resources is a relevant aspect to analyze to determine the impacts that the structural changes in the system may have.



(a) Capacity distribution [48]. **(b)** Adequacy distribution [47][48].

Figure 2.7: Percentage distribution by technology.

In Figure 2.7a, the evolution of installed capacity by technology shows a significant increase in the installation of renewable sources in recent years, accounting for approximately 40% of the total systemic capacity. However, as observed in Figure 2.7b, the recognition of these types of resources is limited, and the mechanism still prioritizes thermal and hydraulic technologies.

Therefore, in a system based on renewable sources, as aspired by the Chilean system, analyzing the distribution of resources is crucial to understanding the potential impacts of changes in the composition of the energy matrix and identifying areas of concern or opportunities for improvement. This allows regulators and stakeholders to make informed decisions about integrating new technologies, such as the need for energy storage, reserve capacity, and the implementation of demand-side management strategies, to ensure a reliable and sufficient electricity supply during the transition to a cleaner and more sustainable energy system.

2.4.3 Cost evolution

In addition to analyzing the capacity distribution by technology, assessing how this affects the systemic cost of supplying energy is important. For this purpose, in the graph presented in Figure 2.8, the evolution of the levelized energy costs is shown. In other words, the total sum of energy withdrawals in the SPOT market was calculated, taking into account surcharges, capacity payments calculated based on short-term nodal prices, and the 2022 sufficiency power report, as well as the amounts associated with ancillary services, including their respective surcharges.

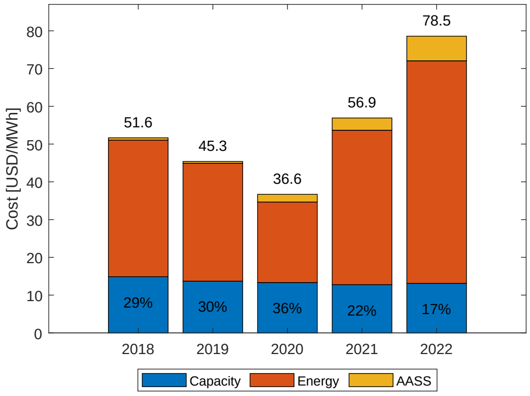


Figure 2.8: Evolution of Levelized Energy Value [14][49] .

In relation to the past few year's events, as depicted in Figure 2.8, the total cost to supply energy fluctuates between 37 and 78 [USD/MWh]. However, the cost of capacity payment varies between 12.75 and 14.78 [USD/MWh]. This is clearly evident in Figure 2.8, where the capacity payment ranges from 16 % to 36% of the total energy cost. In other words, in the face of significant variations in the final energy value, the capacity payment remains unaffected, as it lacks a temporal attribute capable of reflecting energy market conditions. Instead, it functions more like a fixed payment for each unit recognized in the market.

2.4.4 Decarbonization process

In the context of the decarbonization plan for the Chilean electrical system, the energy transition of our energy matrix begins with the retirement of coal-based thermal units, as mentioned in the Zero Carbon Energy Plan through Exempt Decree Number 50 [50]. This poses a series of technical and economic challenges for the system's operation, which also affects systemic adequacy.

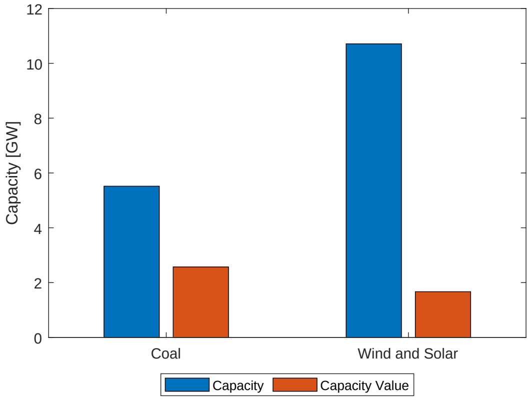


Figure 2.9: Impact of decarbonization on adequacy [46][47].

In the case of the Chilean process, the retirement of coal-fired units would result in a reduction of 5518 [MW] in the system's installed capacity, along with the loss of various technical characteristics such as inertia, short-circuit currents, and stable operation over time. However, in terms of adequacy, it would mean a decrease of approximately 2572 [MW], which accounts for about 23% of the adequacy recognized in 2022.

On the other hand, if we analyze the impact of the installed capacity of renewable resources (solar + wind) close to 10712 [MW], which contributes 1668 [MW] to systemic adequacy, it becomes evident that retiring coal-fired thermal units would require an approximate installation of 16522 [MW] of renewable resources to maintain current adequacy levels.

The above reflects one of the issues associated with the current capacity mechanism, as it does not allow for anticipating future dynamics in the composition of the energy matrix. This is due to the lack of analysis regarding future capacity conditions and adequacy requirements that the system may need. As a result, the system cannot provide market signals for installing new resources, such as energy storage or demand response, which could compensate for the retirement of thermal units.

2.5 International experience

The structures of electricity markets worldwide are in constant evolution. An example of this is seen in the capacity remuneration mechanisms in Europe, which have changed in recent years to align with emerging technologies like energy storage and renewable resource-based generation, as illustrated in Figure 2.10.

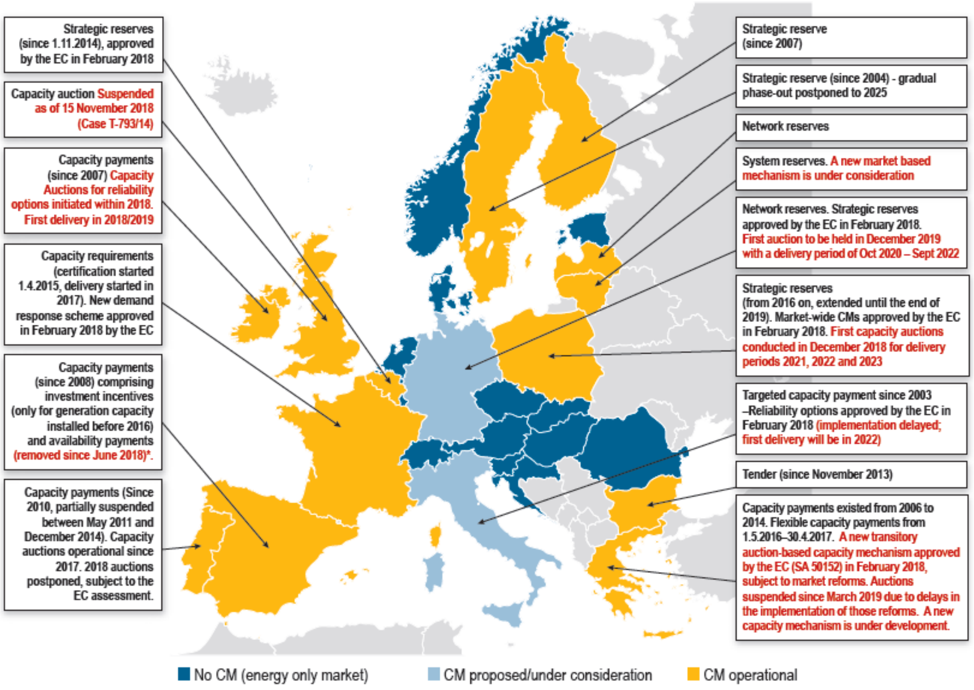


Figure 2.10: European Capacity Markets [13].

In this context, the most prevalent market structures for capacity remuneration are presented below, along with examples of how they have been implemented in various countries.

2.5.1 Other forms of capacity remuneration

Strategic Reserve: Strategic reserves consist of a set of generation units selected to address exceptional situations in the electrical system. Although each system presents different construction characteristics and exceptional operational conditions, strategic reserves share a series of common features outlined below:

- Static Mechanism: The capacity of the reserve is constant, as it corresponds to the sum of the power of each of the units that make up the reserve. Furthermore, the remuneration price is usually fixed and determined by the operator, therefore it lacks the quantity and price dynamics present in the energy market.
- Use in Specific Situations: The capacity that makes up the reserve is used only in specific cases, such as emergencies or critical situations in the system where the supply of electricity is insufficient to meet demand. In other words, it functions as a kind of ”insurance” for times when there is an imbalance between demand and generation or when uncommon conditions arise.
- Isolation from the Energy Market: The reserve must be separated from the regular energy market; this way, the strategic reserve does not impact the daily operation of units and consequently does not affect electricity prices under normal conditions. This prevents market distortions that could arise from the presence of this additional capacity.
- Activation and Remuneration: If the strategic reserve is activated due to a breach by market agents, those responsible for the breach will be accountable for covering the costs associated with remunerating this additional capacity. This creates a market incentive for agents to fulfill their commitments and maintain a stable supply within the system.
- Incentive for Unit Retirement: The strategic reserve can also serve as a market space for older or less efficient generation units to be partially retired from the system. With this additional capacity available, it reduces the uncertainty linked to unit retirements and facilitates a smoother energy transition.
- Specific Mechanism: The reserve can be allocated to specific areas within the electrical system that face unique operational challenges, such as regions with insufficient transmission infrastructure or those exposed to extreme climatic conditions at certain times. As a result, this mechanism is selective both in terms of geographical location and the period during which it can be utilized.

Capacity auction: This type of mechanism, similar to strategic reserves, establishes a level of capacity that will be needed in exceptional system situations. However, the way of allocating these resources to system agents is through competitive auctions in which they offer a certain level of power along with their respective price. Although, as mentioned earlier, each system presents different construction characteristics and exceptional operational conditions, they still share a series of common features described below:

- Competitive Mechanism: In this mechanism, each agent must place a bid for a specific capacity obligation at a determined price. However, these obligations can be transferred among market participants, creating a secondary market platform. Like strategic reserves, this mechanism is isolated from the energy market.

- Market Signaling: These mechanisms enable the generation of various market signals, such as the availability of transmission resources, incentives for new technologies, and the modernization of the generation fleet, among others.
- Demand Response: These mechanisms include not only capacity contributions during periods of scarcity but also reductions in consumption provided by demand response.

2.5.2 Analysis of international capacity markets

Based on the review of the capacity remuneration schemes presented in section 2.5.1, we proceed to analyze the implementation of these mechanisms in the markets of the United States, Germany, the United Kingdom, and Sweden.

PJM-USA: PJM is one of the grid operators in the United States, covering 13 states and being responsible for supplying electricity to approximately 65 million people. Currently, PJM has a capacity market called the “Reliability Pricing Model” [33], which is based on a capacity auction mechanism. The essential elements of this mechanism are as follows:

- Prospective Mechanism: The acquisition of resources is carried out three years before their requirement through a competitive auction to meet future demand. This provides advanced price signals to encourage the conservation of essential existing resources for the system or, alternatively, to foster the development of new generation sources in the region.
- Transmission Relationship: The mechanism assigns locational prices that reflect the transmission constraints of the system, thus allowing the operator to define areas of interest for new capacity. Moreover, it transfers risk to market participants.
- Dynamic Pricing: The system employs a variable resource requirement curve, which is the demand formula used to determine the price paid to market participants for capacity and the quantity of capacity.
- Temporal Mechanism: The Capacity Market is only considered from November to February (winter period), and only the capacity contributions that participants provide to the system between 16:00 and 19:00 hours (peak stress hours) are valued.

UK: The UK government introduced the “Capacity Market (CM)” [17] with the intention of providing something akin to an insurance policy against contingencies. This is due to the increased variability and uncertainty in the system resulting from the integration of mostly wind-based renewable sources. The mechanism is based on an auction, where capacity providers acquire an obligation within the capacity market, valued at the auction clearing price. The essential elements of this mechanism are as follows:

- Differences by Age: The mechanism establishes three categories for participants, distinguishing between existing, refurbished, and new resources. Each of these segments has different time limitations for their capacity contract, as outlined below:
    - Existing resources: One-year maximum contract in the CM.
    - Refurbished resources: Three-year maximum contract in the CM.
    - New resources: Fifteen-year maximum contract in the CM.

- Integration of New Resources: The capacity market allows technologies such as storage and demand response schemes to participate in auctions, creating an attractive market space with a significant time window.
- Performance Evaluation: Once the reserves are requested by the operator and provided by the participant, their contribution to the system's capacity is quantified to determine their actual contribution.

Germany: In this case, Germany implemented a strategic reserve designed to address periods of tightness that occur locally in the southern part of the country due to network limitations, which threaten system security. It's also aimed at maintaining sufficient system adequacy levels during the decarbonization process. The essential elements of this mechanism are as follows:

- Local Issue: The German strategic reserve operates in the southern region of the country [51], particularly during winter periods, to address transmission and generation limitations that occur in the area, which pose risks to the security of the electricity supply.
- Retiring Power Plants: The German strategic reserve was formed with thermal power units that were being retired from the system to ensure the availability of reliable units for operation during contingencies. However, this approach has led to an increase in the cost of the mechanism in recent years due to rising fuel prices. This situation has encouraged the participation of renewable resources with storage in the strategic reserve.

Sweden: The Swedish strategic reserve arises to address the closure of nuclear units without increasing the risk of energy scarcity. For this reason, the Swedish Transmission System Operator, SvK, was instructed to acquire a strategic reserve[52]. The essential elements of this mechanism are as follows:

- Temporal Mechanism: The strategic reserve is only considered during the months of Novem- ber to March (winter period). Furthermore, it has a deadline for operation until the year 2025, by which time the retired units must be compensated with new renewable resources and storage.
- Renewable Priority: Offers from all types of generation units are allowed, but it assigns a low score to units that do not meet all technical and environmental specifications (less flexible and polluting). Consequently, there is currently a focus on ensuring that from the period 2023-2025, the generation sources participating in the reserve are exclusively from power plants whose primary input is a renewable source.

2.5.3 Comparison with the Chilean case

Concerning the mechanisms discussed in Section 2.5.1 and their application in various international markets, as presented earlier in Section 2.5.2, the characteristics absent in the current Chilean capacity remuneration mechanism that need to be considered in this proposal are as follows:

- **Lacks a defined objective:** Unlike the previously analyzed mechanisms, which mostly aim to address the retirement of thermal units from the system in favor of transitioning to renewable energy sources, the Chilean case shows a lack of clarity regarding the purpose of the mechanism. There is no clear understanding of whether it intends to remunerate investment costs or to resolve the missing money problem.

- **Doesn't address a capacity issue:** Due to the lack of a defined objective, the system adequacy results are inadequate. This was evident in 2022, when a rationing decree was issued.

- **It doesn't take into account future adequacy conditions:** Unlike mechanisms in the USA and the UK that monitor long-term capacity requirements to establish capacity market levels, in the case of Chile, it relies on demand data from the previous year, which doesn't allow for anticipating potential scarcity conditions that could impact the system.

- **Not selective:** In contrast to mechanisms presented in Sweden and Germany, where market participants must meet specific technical criteria or be physically located in an area facing adequacy issues, the Chilean mechanism aims to compensate all market agents that can potentially contribute to adequacy.

- **Not Temporal:** Unlike the markets analyzed previously, where temporal characteristics are observed such as operation during winter periods, quantification of contribution to adequacy only during peak demand hours, and a deadline related to goal fulfillment, the Chilean market lacks any of these essential features. These features are crucial for the mechanism to appropriately remunerate the adequate amount of resources and value them appropriately.

- **Not competitive:** In contrast to markets in the U.S., the U.K., and Sweden, where auctions are conducted to acquire capacity commitments, the Chilean market considers all units comprising the system, assigning each a percentage of the total adequacy. Additionally, valuations are calculated by the regulatory entity, differing from valuations offered in competitive auctions. Therefore, it is possible to assert that the Chilean mechanism does not function as a market but rather as an administrative payment.

Chapter 3

Design of a Capacity Remuneration Mechanism

This section aims to introduce the process of designing, modeling, and evaluating capacity remuneration mechanisms presented in the current literature, taking into account the challenges posed by the Chilean system, such as the energy transition to a renewable matrix, a high presence of hydrothermal resources in the capacity market, and a sustained increase in energy prices. The goal is to identify potential commonalities for the design of the new mechanism, as well as to understand the modeling and verification processes of the respective CRM.

3.0.1 Detection of System needs

In the design of any market structure, it is essential to accuratel. This section aims to introduce the process of designing, modeling, and evaluating capacity remuneration mechanisms presented in the current literature, taking into account the challenges posed by the Chilean system, such as the energy transition to a renewable matrix, a high presence of hydrothermal resources in the capacity market, and a sustained increase in energy prices. The goal is to identify potential commonalities for the design of the new mechanism, as well as to understand the modeling and verification processes of the respective CRM.y identify the needs and challenges that the proposed mechanism aims to address, as suggested by the authors in [53]. In their examination of the reasons for creating capacity markets, their functioning, and the extent to which they fulfill their objectives in the United States' electrical systems, it is evident that the proposed mechanisms address issues such as the closure of coal and nuclear thermal units, the need to incorporate smart grid tools like demand response, local generation, energy efficiency, as well as the necessity of integrating renewable resources due to the significant potential in certain geographic areas. Furthermore, in [23], the authors focus on demonstrating how systemic needs vary, analyzing the different scenarios that led to the establishment of capacity mechanisms over time in Europe and how their objectives are linked to market structure.

An example of a theoretical CRM designed in accordance with current systemic needs is presented in [54], where the conceptual proposal of a mechanism for the Chinese electrical system is addressed, taking the PJM model as a reference. In this work, special emphasis is placed on ensuring that the proposed model aligns with the dynamics that the system will face in the coming years, given its decarbonization goals and the accelerated installation of renewable resources.

Furthermore, in [55], the previously mentioned points are complemented for the effective design of a Chinese CRM, where the authors argue that “An efficient design of a capacity remuneration mechanism is key to ensuring a reliable power supply and stable revenue for power generators.”

On the other hand, it is essential to analyze the impacts of not considering systemic needs properly, as addressed in [56], where the consequences of CRM in Russia are discussed. In Russia, the capacity market and CRMs for constructing new capacity associated with renewable resources were introduced in 2011. While a considerable volume of new capacity was incorporated, there was no identified need to retire older units, leading to an over-installation of resources that had to be remunerated by the CRM, increasing systemic costs. This situation is similar to the current reality of the Chilean Capacity Payment, where there is no incentive for the retirement of older units, which does not offset the entry of new capacity into the system.

3.1 Design of the CRM Structure

Once the needs and challenges of the system have been identified, a process begins to design the structures of the mechanism to address each identified need. In this context, in the literature, it is possible to identify various proposals that might relate to the challenges faced by the Chilean system. For instance, in [57] and [58], the authors study the design of a CRM for the Chinese electric system. Their focus is on facilitating an appropriate transition for thermal units during the decarbonization process, which find themselves exposed to the “missing money problem” due to the significant presence of renewable energies, environmental emission requirements, and the high operational costs of these units. Nonetheless, these units remain crucial because of their characteristics of inertia, short-circuit currents and operational stability. As a result, the traditional thermal energy units will gradually shift from being the primary source of electricity to being the main capacity support body. To this end, the article proposes a mechanism called the Base Residual Auction, which is based on bidding for the generation capacity required by the system. It is organized five years before the target year for capacity delivery, providing economic certainty for thermal units and ensuring a higher level of security for the system’s operation.

Another critical challenge faced by the Chilean system is the operation of its hydraulic units. These will be vital in managing the variability and inherent uncertainty of renewable resources. Therefore, generation with these units will decrease during standard operating periods and will primarily be used to ensure a safe and reliable system operation under adverse conditions. This reduction impacts their income from the energy market, as discussed in [59]. Faced with this scenario, the management of the water resource must align with a capacity mechanism that adequately compensates for this resource and offers economic certainty to the generating units. In this context, in the article [60], the authors introduce a CRM with a fundamental hydrothermal multi-market model. This model combines a long-term strategic approach to capacity provided by the system’s entire resources with a more detailed short-term fundamental model of the capacity supplied by hydraulic units.

Associated with the flexibility needs generated by a decarbonization process, which have already been mentioned in this proposal and emphasized by various authors in [61] [62] [63] and [64], in this context, in [65], the authors propose a CRM model that provides incentives for the integration of storage as a flexibility resource. In this document, a model is created based on a capacity auction that introduces flexibility constraints into the optimization problem, where thermal, hydro, and storage units function as agents providing flexibility and renewable resources requiring it. Therefore, in the auction process, decision-making is influenced by flexibility requirements by incorporating new storage resources.

Considering that in a decarbonization process, the main objective is the overall reduction of emissions produced by the generation fleet, a CRM aiming to contribute to this goal must consider the emissions from the participating market units. In this context, in [66], the authors create a model in which economic penalties are imposed on polluting units. In other words, an additional charge is applied to the bid price in the auction, leading to the exit of the most polluting units from the market scheme.

3.2 Design of the Mathematical Formulation of the Problem

After designing the structure of the CRM, it's not sufficient to conceptualize the mechanism or outline its potential operation. To better estimate its effectiveness and its behavior under various scenarios, it is crucial to translate that design into a quantitative model. This involves converting all the components of the mechanism and their relationships into mathematical equations and formulas. In this regard, below is a series of mathematical models used in the literature for the numerical validation of various CRM proposals, each with characteristics related to the challenges of the Chilean system.

It is crucial that the numerical model can represent both the behavior of the energy market and the capacity mechanism in a synchronized manner. The goal is to carry out a joint optimization of the volumes of energy and capacity that will be remunerated. This allows the system's reliability to be maintained at adequate levels for operation and provides sufficient returns on investment for the generating fleet.

Therefore, in [67], a two-level architecture is presented, as shown in Figure 3.1. In the upper-level model, the capacity market is represented, where capacity resources can submit supply curves and be centrally cleared. Meanwhile, the lower-level model organizes the operations of the energy SPOT market, and the clearing results are constrained by the capacity volumes. Additionally, network expansion processes will be considered in both levels.

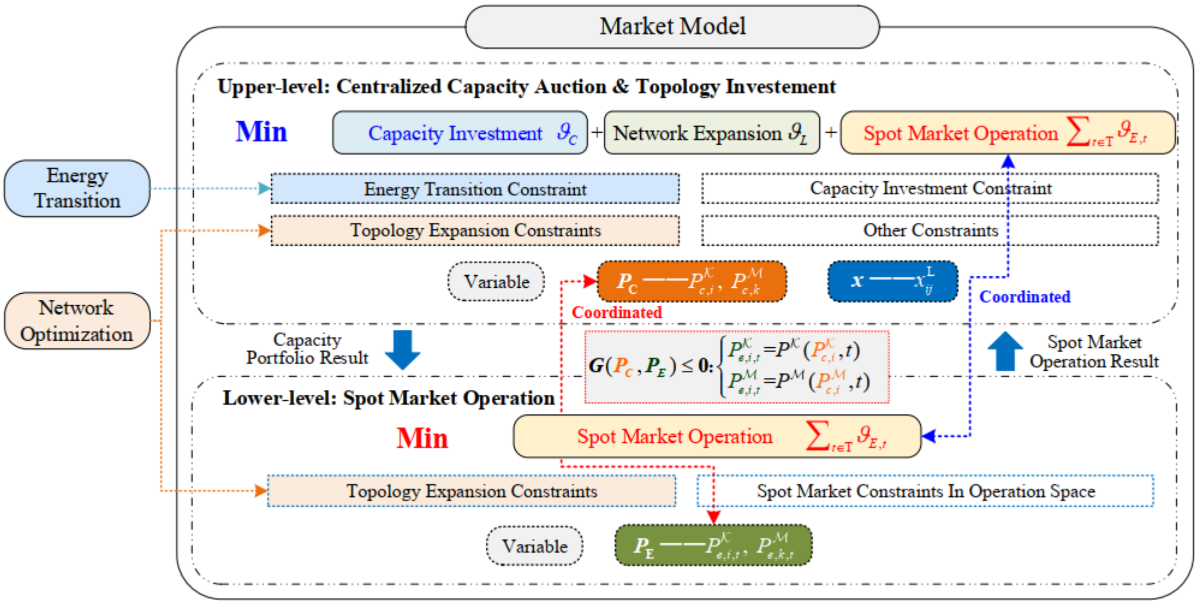


Figure 3.1: Two-tier structure proposed [67].

This two-level architecture is also present in other proposals, as outlined in [68] and[69]. However, these proposals include a modification regarding the decision-making of market agents, as they introduce risk aversion that alters the quantities offered in the capacity market. Both models aim to reflect a more realistic decision-making process beyond purely economic considerations. Another important aspect to consider is the cushioning effect of the capacity market on energy prices from the perspective of incorporating new capacity that displaces the most expensive units in the system, reducing the price of energy but increasing the price of capacity to achieve expected returns on investment. In [70], a model to quantify this effect under various CRM structures is used. This allows for an analysis of the impact of such a mechanism on the long-term development of investments in conventional capacities and electricity prices.

3.3 Analysis of the proposed CRM

Once the results of the developed model are obtained, it is necessary to carry out an evaluation process to determine whether the established objectives are met. Below, we present some guidelines observed in the current literature for conducting this process, applied in international markets that are currently in operation. In other words, we analyze the indicators commonly used to evaluate CRMs worldwide, as described in [71], [72], [73], [74], [75] and [76].

- **Security of supply:** It is essential that the designed mechanism is capable of ensuring system adequacy. To achieve this, its ability to generate sufficient incentives for installing flexible capacity with low levels of uncertainty must be evaluated. Additionally, its selectivity should be analyzed, meaning whether the incorporated units possess the desired characteristics. Factors such as the probability of system load loss, adaptability to supply crises, and performance in situations of water scarcity, among others, should be taken into account.
- **Performance of investment cycles:** It is of utmost importance that the proposed mechanism is capable of providing the necessary income for the units that are integrated

into the system and will predominantly participate in the capacity market to achieve the expected return on investment since they do not have a sufficient level of income in the energy segment. It is also necessary to evaluate whether these returns on investment are optimal, as it is essential to avoid double payments that would increase systemic costs. Furthermore, it is important to analyze if it fosters competition, which aligns with a more optimal model.

- **Volatility of energy prices:** It is relevant to analyze whether the capacity model allows for lower and more stable prices in the energy market, taking into account that the cost of the mechanism, when added to the overall cost of the energy market, is lower than a single energy system.
- **Global emissions reduction:** One of the most relevant aspects to analyze in a proposal aiming to facilitate a decarbonization process is to determine whether the proposed mechanism reduces the overall emissions of the electrical system. In other words, whether the installation of new capacity, the retirement of the most polluting units, and the operation do not result in an increase in emissions compared to the operation without the proposed scheme.
- **Addition of new capacity:** Another aspect to consider is the quality and quantity of new units introduced into the system, meaning if the mechanism incorporates the required and budgeted technologies with its mechanism and does so optimally, i.e., it does not over-install units, places them appropriately, and defines the most coherent technology.

Chapter 4

Objectives and Statement of the Hypothesis

4.1 Hypothesis

The hypotheses of this proposal are presented below:

1. The current capacity remuneration mechanism in the Chilean electricity market is unsuitable for addressing the decarbonization process that the energy matrix will undergo. This is because it doesn't provide clear market signals for the installation of new resources, fails to address potential contingencies associated with the decarbonization process, and doesn't adequately manage the available resources for future needs.
2. An electrical system like the Chilean one, historically characterized by a significant hydrothermal base, transmission issues due to its topology, and a great potential for renewable sources, aiming to address a decarbonization process efficiently, requires an update of its capacity mechanism to align its goals with this process in a cost-efficient manner.

4.2 Objectives

4.2.1 Overall objective

The main objective of this thesis is to propose a new mechanism for capacity remuneration in the Chilean electrical system. This mechanism should enable proper compensation for the necessary adequacy attributes of the system while aligning with the process of decarbonizing the energy matrix.

4.2.2 Specific objectives

- Conduct a critical analysis of the capacity remuneration mechanism implemented in Chile, examining its operation and costs and comparing it with capacity systems present worldwide.
- Formulate a new proposal for the Chilean capacity market and assess its performance compared to the current mechanism.

- Generate a model that allows a numerical comparison between the proposed mechanism and the current one.
- Provide guidelines for implementing the proposal, ensuring that these are aligned to the decarbonization process.

4.3 Methodology

This Section intends to introduce sequentially the proposed methodology to test the hypothesis and achieve the research objectives.

Evaluation of the current mechanism

Initially, an analysis of the current structure of the Chilean capacity market is conducted, including its historical functioning, cost evolution, and resource distribution, aiming to identify its deficiencies and areas for improvement. The proposed mechanism will subsequently address these aspects.

Systemic capacity study: It is necessary to identify how the system's capacity is distributed, both in terms of present technologies and their spatial distribution, considering transmission limitations and relevant consumption. Relating the above with the energy transition processes that the system will undergo to identify critical areas.

Comparison with the international market:
A comparison of the current mechanism with the international capacity markets is carried out, thus identifying possible measures for designing the new proposal to face the challenges previously addressed.

Generation of the new proposal:
A new capacity remuneration mechanism is proposed, considering the elements identified in the review of current and international mechanisms discussed in section 2, and the guidelines outlined in section 3. This mechanism is aligned with systemic objectives, aiming to facilitate a reliable energy transition, provide incentives for the integration of fundamental resources, and establish a robust system.
For this purpose, initially, it is considered that the market segments undergo the transition shown in Figure 4.1, where a competitive capacity auction mechanism is introduced. Additionally, modifications to the current payment mechanism and the composition of the strategic reserve must be made.

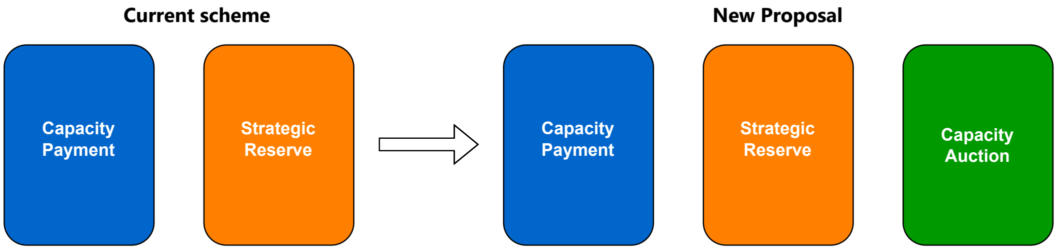


Figure 4.1: Proposed modification

Generation of a model to estimate revenues: To adequately evaluate the effects of the proposed mechanism, it is necessary to develop a model that can estimate firms' revenues from their participation in the energy and ancillary services markets. To achieve this, in the first instance, the data from the PELP is analyzed, generating a database that serves as a basis for comparison for evaluating the model. In the second stage, a simplification of the electrical model used in the PELP is performed to simulate dispatch and calculate the revenues in the energy and ancillary services market.

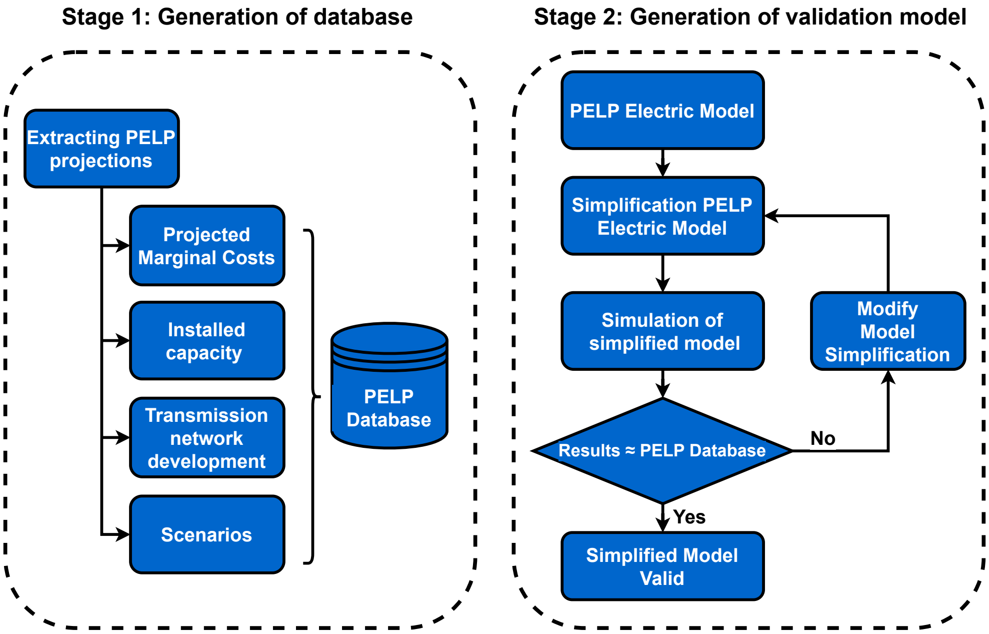


Figure 4.2: Model to estimate revenues

Validation of the proposal: A numerical model is developed to determine the costs of the designed mechanism and how it drives the integration of new resources to enhance system adequacy. This model is based on the two-level model addressed in [67] as discussed in Section 3.2 and illustrated in the schematic representation shown in Figure 4.3. The input parameters include the development plan of the national electrical system and the proposed capacity market, the latter having various configurations in terms of quantities and qualities of the three proposed market segments. These data are then used to simulate the system, from which operational costs, emission levels, transmission system limitations, and the evolution of installed capacity are extracted. This is then compared with the Levelized Cost of Energy (LCOE), and if the system proves to be cost-inefficient compared to the previously generated database, the development plan is adjusted. Finally, if the capacity proposal is found to be functional, the data is extracted, and a new proposal is tested with different attributes.

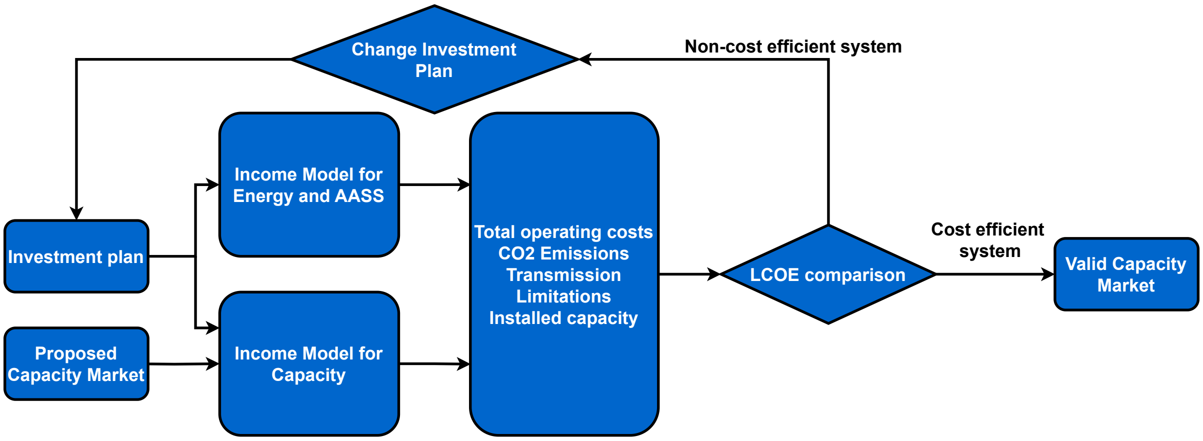


Figure 4.3: Validation Proposal

Analysis of results:

Finally, the results of the previous step are compared with the performance of the current mechanism in terms of the criteria commonly used in the literature and outlined in section 3.3, that is, in relation to total costs related to price volatility, supply security, returns on unit investment, global emissions, and new technology installation.

Chapter 5

Proposed Solution and Discussion

Building on the preceding analysis, we propose a modeling framework to evaluate how CRM design affects the distribution of revenues among different generation and storage assets. This framework captures the dynamic interaction between capacity mechanisms, energy markets, and policy/regulatory constraints to assess whether specific CRM configurations support cost-effective, low-emission, and investment-resilient outcomes.

5.0.1 Dynamics Characterization

The framework of this work aims to develop a structure that allows for the optimization of a CRM together with electricity market operation. The objective is to optimize the allocation of remuneration among system units across both segments, achieving a balance that can maximize overall system efficiency while meeting adequacy, sustainability, and flexibility targets.

The model incorporates concepts from previously used bilevel structures for optimizing various phenomena in electricity markets, as detailed in the literature [22]–[67], while introducing key innovations. These include the ability to consider endogenous investment decisions, demand-side participation, and a hierarchical decision-making framework to characterize the impact of energy price formation on CRM remuneration.

Unlike traditional approaches, the proposed framework aims to explicitly evaluate the impact of adding new capacity on electricity prices and generator revenues. The implementation of a new CRM leads to a redistribution of revenues among system units, which may incentivize the entry of new generation capacity or delay the retirement of existing capacity. Thus, supply expands and marginal energy adjust. This dynamic should be capable of capturing the relationship between investment decisions and market outcomes, including the interaction between CRM remuneration and energy revenues.

Finally, the model incorporates design constraints aligned with long-term decarbonization goals, including system adequacy, emissions limits, and operational flexibility, serving as a basis for evaluating the viability of flexible and low-emission technologies, such as energy storage, in future capacity portfolios.

5.0.2 Bilevel Programming Framework

The CRM optimization problem faced by the planner, which is affected by the revenues obtained from the energy market, can be modeled as a hierarchical decision-making process in which two agents optimize their respective objective functions in a nested manner, as shown in Figure 5.1. In the upper level, the capacity portfolio and its associated contracts, aimed at minimizing CRM costs, depend on: (1) the total amount of installed capacity, (2) the share of existing resources that secure a capacity contract, and (3) the revenues obtained from the energy market, which, in turn, are determined by the operational decisions of the energy market operator at the lower level.

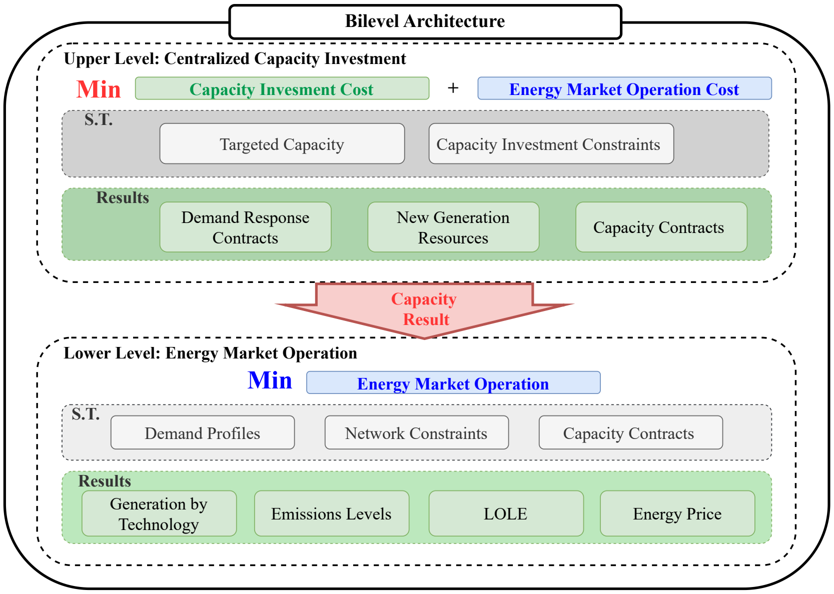


Figure 5.1: Bilevel framework

In this way, the Centralized Capacity Investment (CCI) is positioned at a hierarchically higher level relative to the operation of the Energy Market Operator (EMO). The lower-level problem, corresponding to the EMO, is parameterized in terms of the decisions made at the upper level, which themselves are optimization problems. Thus, for each decision made by the CCI, i.e., each upper-level decision, there is an associated optimal system operation, determined by the cost minimization performed by the EMO in the lower level.

The hierarchical decision-making problem, depicted in Figure 5.1, constitutes an instance of bilevel programming, formulated below in a compact manner. Interested readers can refer to the electronic companion [**EC**] for a detailed description of the bilevel program used in the computational study. The compact bilevel planning problem is presented as follows:

$$\min_{x} \quad f_x^u(x) + f_y^u(y) \tag{1}$$

$$\text{s.t.} \quad g^u(x,y) \leq 0, \tag{2}$$

$$x \in \{0,1\}^{n_b^x} \times \mathbb{R}_+^{n_c^x}, \tag{3}$$

where y is obtained from:

$$\min_{y} \quad f^{l}_{y}(y) \tag{4}$$

$$\text{s.t.} \quad g^{l}(x,y) \leq 0, \tag{5}$$

$$y \in \{0,1\}^{n^{y}_{b}} \times \mathbb{R}^{n^{y}_{c}}_{+}. \tag{6}$$

Problem (1)–(6) comprises two optimization levels: 1) the upper-level (1)–(3), associated with the CCI, and 2) the lower-level (4)–(6), corresponding to the EMO.

The CCI controls the vector of variables x, composed of both binary and continuous elements representing strategic decisions related to capacity contracting, firm capacity additions, and adequacy-related incentives. The objective of the CCI is to minimize the total cost of the capacity mechanism, considering remuneration payments, investment expenditures, and the effects induced by energy market operation. Although the total volume of capacity to be remunerated is defined exogenously, the allocation of revenues among eligible resources is determined endogenously. Three types of capacity mechanism may be incorporated: administrative capacity payments, competitive capacity auctions, and demand response. Thus, the proposed model enables the evaluation of candidate investment portfolios under constraints reflecting system adequacy, emissions limits, and operational flexibility requirements, in alignment with emerging regulatory priorities.

The EMO controls the vector of variables y, also mixed (binary and continuous), which describe the unit commitment, demand-side participation, use of flexible resources, and optimal system operation under the conditions defined by the CCI. Its goal is to minimize the total operational cost of the power system, subject to technical, balance, and capacity constraints.

The lower-level problem is parameterized by the upper-level decisions, so that the constraints $g^{l}(x,y) \leq 0$ reflect the dependence of market operation on contracted and available capacity. In turn, the results of the lower-level problem, particularly market costs and revenues, are incorporated into the upper-level $f^{u}_{y}(y)$ and $g^{u}(x,y)$, capturing the interdependence between both levels. This nested structure reflects the dampening effect that new resource entry has on electricity prices and promotes the identification of a CRM configuration that balances investment adequacy, price efficiency, and consistency with long-term policy objectives.

Overall, the proposed bilevel model provides a formal structure for analyzing the equilibrium between investment and operation, which is achieved through the coordination between capacity planning and system operation.

5.0.3 Solution Technique

The proposed model (1)–(6) constitutes a mixed-integer bilevel program, whose exact resolution is computationally complex due to the hierarchical coupling and the presence of nonconvexities, including discrete decisions related to capacity investment, contract allocation, and generation scheduling. To address this complexity, an iterative block coordinate descent (BCD) algorithm is proposed, which alternately solves the upper-level and lower-level problems until convergence is reached. Although global optimality is not guaranteed, this approach provides a practical and computationally efficient heuristic that yields consistent and coherent solutions aligned with the expected system behavior.

A. Algorithm

The iterative process begins with the initialization of the lower–level problem (4)–(6), corresponding to the EMO, using baseline data from the electricity market prior to the implementation of the CRM. These data—such as generation by technology, reliability indices (LOLE), emissions, and total system costs—represent the pre–CRM equilibrium and define the initial operating condition of the system, denoted as $y^{(0)}$.

Using this initial operating condition, the upper–level problem (1)–(3), associated with the CCI, is first solved. The CCI determines the optimal portfolio of firm capacity, investment incentives, and remuneration allocation for the system, resulting in an updated capacity decision vector $x^{(1)}$.

Subsequently, the updated decisions $x^{(1)}$ are provided as input to the lower–level EMO generation schedule. The EMO then solves the operational optimization to determine $y^{(1)}$, which corresponds to the optimal dispatch, system costs, and resulting market prices under the new capacity configuration.

The outcomes of the lower–level problem—particularly market prices, operational costs, and generator revenues—are transmitted back to the CCI. The CCI then resolves its optimization using the new information from $y^{(1)}$, producing an updated capacity decision vector $x^{(2)}$.

This alternating procedure between the CCI and the EMO continues iteratively, with each level updating its decision variables based on the most recent solution of the other level. The process stops after a pre-specified number of iterations or when convergence is reached, i.e., when the change in total system cost or decision variables between consecutive iterations falls within a predefined threshold ε. The iterative resolution procedure, sketched in Figure 5.2, is detailed as follows:

1. **Initialization:** Set the iteration counter $\gamma = 1$. Load the baseline energy market data obtained prior to the implementation of the CRM, including the generation mix, reliability indices (LOLE), emissions, and total system costs. These data allow computing the initial solution to the lower-level problem, denoted as $y^{(0)}$.

2. **Upper-level resolution (CCI):** Using the initial operating decisions $y^{(\gamma-1)}$, solve the upper-level problem (1)–(3), which determines the optimal portfolio of firm capacity, investment incentives, and remuneration allocation. The result provides the updated capacity decision vector $x^{(\gamma)}$.

3. **Lower-level resolution (EMO):** For the capacity vector $x^{(\gamma)}$ obtained from the upper level, solve the lower-level problem (4)–(6) to determine the optimal system operation. This yields the updated operational decisions $y^{(\gamma)}$, including generation schedule, system costs, and market prices.

4. **Feedback update:** The results from the lower level-such as operational costs, energy prices, and generator revenues are transmitted back to the upper level. This feedback updates the CCI's problem for the next iteration.

5. **Convergence criterion:** The algorithm is considered to have converged when the relative change in total system cost or in the decision variables between consecutive iterations is within a threshold ε. i.e.,

$$\frac{|\Delta f|}{|f|} \leq \varepsilon.$$

If this condition is not met, the iteration counter is increased $\gamma \leftarrow \gamma + 1$ and Steps 2–4 are repeated. For computational tractability, a maximum number of iterations γ^{max} is imposed; if this limit is reached before the convergence condition is satisfied, the algorithm terminates and the last feasible solution $(x^{(\gamma)}, y^{(\gamma)})$ is adopted as the final configuration.

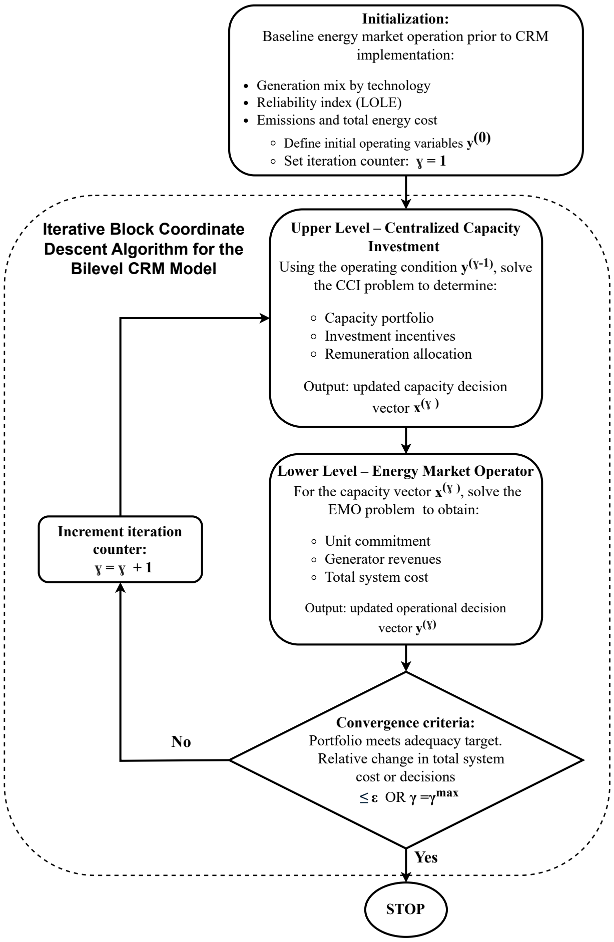


Figure 5.2: Flowchart of the proposed iterative solution algorithm

B. Convergence and Discussion

The proposed iterative scheme captures the endogenous coupling between capacity remuneration and electricity market operation. By alternately solving the upper–level investment problem (CCI) and the lower–level operational problem (EMO), the method internalizes the effect that new capacity decisions exert on electricity prices, generator revenues, and overall system adequacy. As the iterations progress, the procedure converges toward a consistent configuration that balances investment adequacy, price efficiency, and alignment with long–term decarbonization and reliability objectives.

From a mathematical standpoint, the algorithm can be interpreted as a BCD procedure. In this framework, the decision vectors of both levels, x for the upper level and y for the lower level, are updated iteratively and sequentially. At each iteration γ, one block of variables is optimized while the other is held fixed, as follows:

$$\begin{aligned} x^{(\gamma)} &= \arg\min_{x} f^{u}(x, y^{(\gamma-1)}) \\ &\text{s.t.} \quad g^{u}(x, y) \leq 0, \\ y^{(\gamma)} &= \arg\min_{y} f^{l}(y, x^{(\gamma)}). \\ &\text{s.t.} \quad g^{l}(x, y) \leq 0, \end{aligned}$$

This alternating optimization continues until both decision vectors (x, y) reach a stable configuration in which further updates do not produce significant improvements in the total system cost.

Although global optimality cannot be guaranteed due to the presence of nonconvex components, the BCD framework ensures that the algorithm approaches a consistent and economically meaningful equilibrium, where investment and operation are mutually coherent.In this equilibrium, the CCI's capacity decisions are aligned with the EMO's operational results, producing a stable balance between capacity adequacy and efficient market operation.

In our practical implementation, convergence was achieved within an acceptable number of iterations, ensuring computational feasibility while preserving consistency between investment and operational decisions. Thus, the proposed approach provides a practical and computationally tractable mechanism for capturing the dynamic interaction between the CCI and the EMO, ensuring coherent evolution of both investment and operational decisions within the CRM framework.

5.0.4 Architecture Implementation

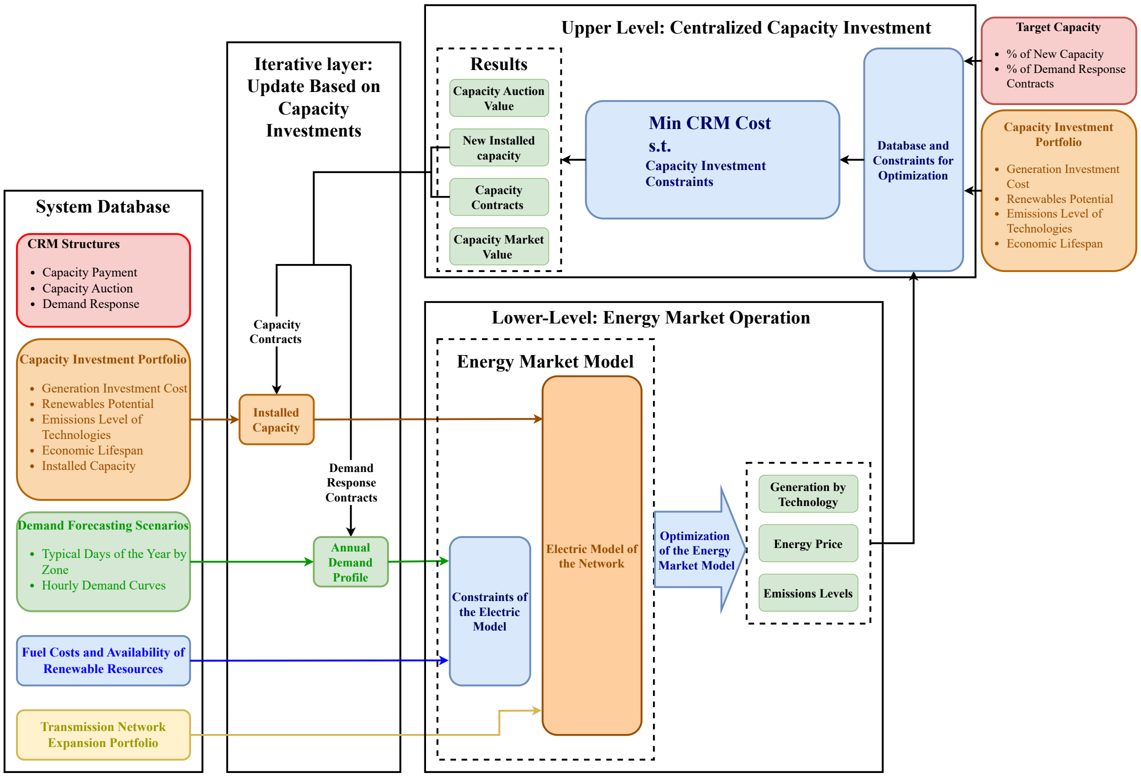


Figure 5.3: Implementation of the proposed CRM architecture

As sketched in Figure 5.3, the resulting CRM architecture integrates the proposed bilevel model incorporating data from the electrical system under study, portfolio updates, and the optimization processes at both the upper and lower levels, aiming to achieve a strategic approach to capacity investments and energy market operations. The proposed architecture comprises four main modules:

- **Database:** The database of the system under study provides the CRM configuration to be evaluated by the mechanism, as well as essential data for modeling the electrical network, including installed capacity, network topology, and renewables potential. It also includes crucial information such as technology costs, fuel costs, renewable resource availability, and system demand profiles, which are necessary to establish the constraints in both the lower- and upper-level models.
- **Iterative layer:** The iterative layer of the model updates the database whenever there are changes in the capacity portfolio or demand profiles, ensuring that the lower-level model reflects the most recent system conditions. This step is crucial for integrating the bilevel model into the designed mechanism.
- **Lower Level:** At the lower level, the updated database is used to formulate a reduced model of the electrical system. The model performs a unit commitment, generating results

such as emissions levels and energy generation by technology. These results provide qualitative insights into the capacity portfolio and, most importantly, determine the price of energy, which is then fed back to the upper level.

- **Upper Level:** The upper-level model aims to minimize the combined value of the capacity auction and the cost of energy in the energy market. It uses a database that contains the target capacity for auction, the allocation among demand-response schemes, and capacity contracts. The optimization determines the capacity to be installed, the valuation of capacity contracts, and the total market valuation, allowing for comparisons with the current scheme.

5.0.5 Implementation Challenges

The implementation of the numerical validation model presents several challenges related to the bilevel framework. Firstly, the lower-level model is a simplification of the power system. This formulation does not guarantee a globally optimal solution; however, it provides a valid and useful approximation for evaluating the proposed mechanism.

Additionally, the implementation employs a block coordinate descent algorithm in which decisions related to system operation and the CRM are computed iteratively. Although the proposed approach does not ensure convergence to global optimality, in the case study considered, the algorithm successfully converged in an accpetable number of iterations, validating its practical applicability in similar contexts.

From a conceptual standpoint, CRMs and their practical implementation face a series of challenges. First, regulatory acceptance is required, which involves navigating complex institutional processes and, in many cases, adapting the existing regulatory framework. It is also essential to align the incentives of the various system stakeholders (generators, operators, and regulatory authorities) who may have diverging interests regarding the allocation of risks and revenues.

Administrative complexity also represents a significant barrier, as operationalizing a CRM tailored to system needs requires advanced technical capabilities, effective monitoring mechanisms, and robust governance structures. Furthermore, the mechanism's design must be sufficiently flexible to respond to evolving market conditions and policy priorities.

5.0.6 Power Grid Under Study

To perform a numerical validation of the previously described model, an equivalent electrical network of the Chilean power system is required, along with its capacity projections and renewable potential. In this context, Figure 5.4 illustrates the 29-bus system from the PELP model [77], including the study zones and the transmission network. These zones were defined based on identified resource needs and transmission constraints.

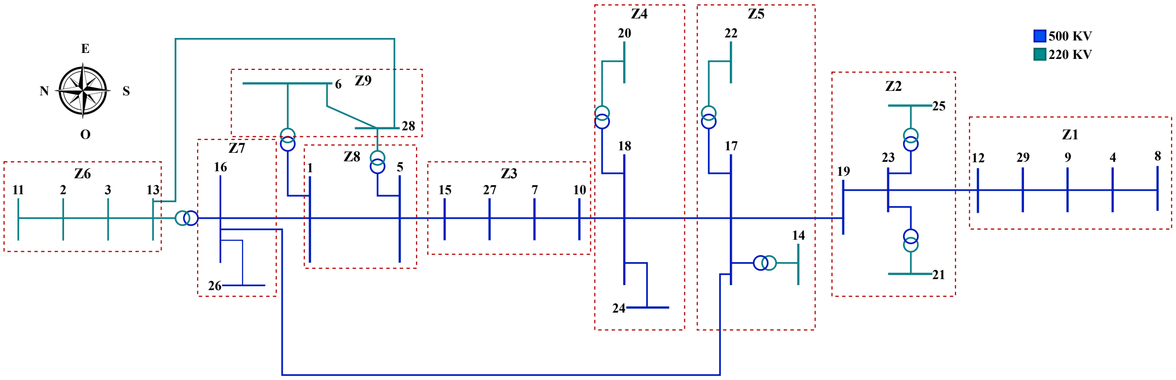


Figure 5.4: Electrical system under study with its respective zones[77].

Table 5.1 outlines the initial variables considered for the design and evaluation of the proposed mechanism. These include the composition of the generation system for the base scenario, systemic costs such as the Levelized Cost of Energy (LCOE), the total cost of the energy market, and the existing capacity payment cost. In addition, technical parameters such as Unserved Energy, LOLE, and emissions are incorporated.

Installed Capacity [MW]						
Coal	Biomass	Diesel	GNL	PV	Wind	Hydro
5477	671	4212	4121	14159	9702	7935
Costs				Systemic Variables		
LCOE [USD/MWh]	Energy Cost [MUSD]	CP Cost [MUSD]	Total Cost [MUSD]	LOLE [h/year]	CO2 Emissions [kTon]	ENS [GWh]
41,88	4327,4	1255,23	5582,63	17,72	23253,45	15,46

Tabla 5.1: Initial Systemic Variables for the Mechanism Design and Evaluation.

In the proposed electrical system, the designed evaluation model is implemented, which operates the electricity market annually and incorporates the capacity remuneration mechanism, its contracts, and the available capacity. This process generates feedback in each iteration, based on the revenues obtained, allowing the investment portfolio to be adjusted toward an optimal operating point that minimizes energy costs, ENS, emissions, and LOLE. However, for the purposes of the evaluation methodology, an exit condition is established where the total system cost exceeds the initial cost. This approach enables the analysis of the effects of incorporating an excessive volume of resources to be remunerated through the proposed CRM and evaluates its impact on energy prices and other control variables.

Chapter 6

Results

6.1 Results

This section analyzes the performance of the solution mechanism for each of the proposed CRM designs, aiming to achieve a cost-efficient energy transition. The iterative process runs until convergence is reached or until a maximum of 100 iterations.

For illustration purpose, the proposed bilevel CRM framework is evaluated against a traditional single-tier mechanism, in which investment and operational decisions are solved simultaneously [**LOPEZRAMOS2020361**]. This comparison highlights the advantages of introducing a hierarchical coordination structure between the CCI and the EMO, particularly in terms of achieving consistency between investment adequacy, cost efficiency, and market performance.

6.1.1 Comparative Evaluation with a Traditional Single-Tier Mechanism

Table 6.1 summarizes the main economic and technical outcomes obtained for the three CRM designs presented in Section **??**–-Fixed Capacity Payment (CP Fix), Variable Capacity Payment (CP Var), and Auction-Only Mechanism (CP Out)–-under both the traditional single-tier and the proposed bilevel coordination schemes. The results show that the hierarchical integration between CCI and the EMO leads to significant improvements in cost efficiency, system adequacy, and environmental performance across all CRM designs.

Indicator	**Unit**	**Single-tier CP Fix**	**Bilevel CP Fix**	**Single-tier CP Var**	**Bilevel CP Var**	**Single-tier CP Out**	**Bilevel CP Out**
Total System Cost	MUSD	5231	4211	4690	3870	3951	3722
EnergyMarket Cost	MUSD	2743	2668	2805	2698	2669	2690
CRM Cost	MUSD	2488	1542	1885	1172	1281	1032
Sunk Cost	MUSD	-350	-177	492	286	1312	774
LOLE	h/year	0,7	0,0	0,1	0,1	0,7	0,0
ENS	GWh/year	0,0	364,9	1220,0	0,0	1226,7	0,0
CO_2 Emissions	kt/year	18621	17767	18569	18696	18658	17225

Tabla 6.1: Results for the single-tier and bilevel CRM configurations.

Under the CP Fix configuration, the total system cost decreases by 20%, representing the greatest relative improvement among the three evaluated mechanisms. This reduction is mainly attributed to a 38% decrease in capacity remuneration costs, reflecting a more efficient allocation of firm capacity payments. Additionally, the bilevel scheme achieves a LOLE reduction from 0.7 to 0.0 hours/year, completely eliminating supply shortages while slightly reducing emissions by 4%. These results indicate that the coordinated approach not only minimizes redundancy in capacity remuneration but also improves system reliability and reduces carbon intensity.

In the CP Var case, a 17.5% reduction in total system cost is observed, confirming the strong cost-efficiency benefits of the bilevel approach. The model achieves a 38% reduction in capacity remuneration costs and completely eliminates Energy Not Supplied (ENS), while the LOLE remains at 0.1 hours/year, reflecting adequate operational reliability.

In turn, the CP Out configuration, which excludes direct remuneration and relies solely on market signals, also offers substantial improvements under the bilevel formulation. The total system cost decreases by 5.8%, driven by more efficient dispatch and better use of flexible resources. Emissions are reduced by 8%, while LOLE improves from 0.7 to 0.0 hours/year. These results demonstrate that even in the absence of explicit capacity payments, the iterative coordination between investment and market operation enhances both reliability and environmental performance.

Overall, the three mechanisms show that the bilevel CRM consistently outperforms the single-tier configuration by achieving lower total and capacity-related costs, improving adequacy indicators (LOLE and ENS), and reducing CO_2 emissions. The results validate the effectiveness of the proposed hierarchical framework in achieving a cost-efficient and sustainable energy transition, while maintaining consistency between long-term investment signals and short-term market operations.

6.1.2 Economic Evaluation

This section presents the comparative economic analysis of the three CRM designs under consideration. The analysis focuses on the evolution of four representative economic indicators across the iterations of the algorithm described in section 5.0.3: the capacity remuneration cost, the energy cost, the sunk costs, and the total system cost. These indicators provide insight into how each remuneration scheme affects the composition of total system costs and the overall economic stability as the model converges toward an equilibrium configuration. The curves shown in Figure 6.1 illustrate the results obtained for each CRM design, highlighting the interaction between energy and capacity components and the progressive reduction of sunk costs across iterations. The first 50 iterations represent the system's adaptation phase, during which the mechanism progressively reaches the target capacity defined by the CRM. The remaining iterations (up to iteration 100) allow the model to approach a stable configuration, achieving equilibrium between investment decisions and market operation, where variations in system cost or capacity allocation become negligible.

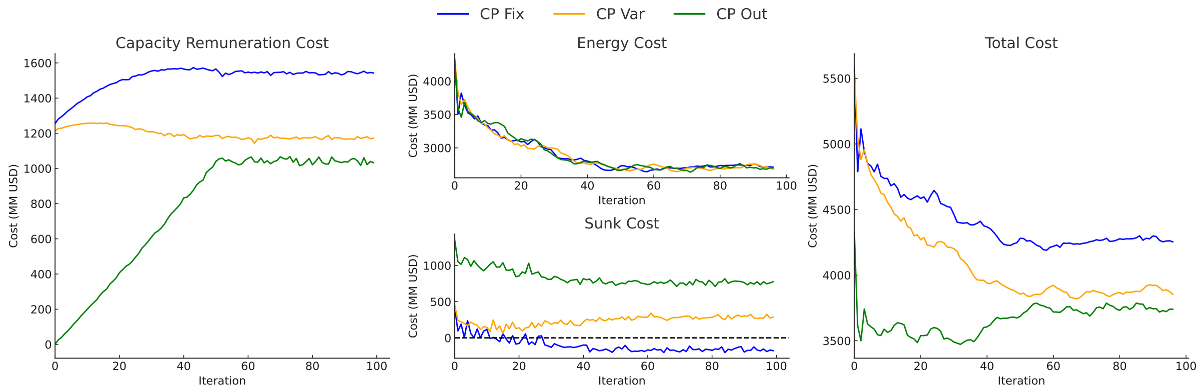


Figure 6.1: Behavior of economic variables across iterations

As can be seen, the capacity remuneration costs associated with the CRM exhibit different trends depending on the mechanism evaluated. When the system implements a fixed CP, in which the volume of resources to be remunerated remains constant, costs remain high along the iterative process. This is because the administrative payment scheme remunerates a volume of resources equivalent to the peak demand in each iteration, in addition to the payments made through the CA, which facilitate the integration of new resources into the system. This approach generates a sustained increase in the mechanism's costs, driven by the continuous growth of remunerated resources over time.

In contrast, when the CP is eliminated, capacity remuneration cost increases only due to the additional capacity remunerated through the CA. However, once it reaches its target value, this cost tends to stabilize, which at first glance suggests a more efficient strategy from the CRM perspective, as the mechanism operates with lower costs.

On the other hand, the CP Var scheme, presents an initial adaptation curve due to the integration of the CA within the CP, which initially raises the capacity remuneration cost. However, as the investment portfolio adjusts, the capacity remuneration cost stabilizes at an intermediate level compared to the other CRM designs. This progressive adjustment allows for a reduction in CP dependence, as the investment portfolio adapts more efficiently than in the fixed CP scheme, leading to a cost reduction due to the interaction between both mechanisms.

Regarding the energy cost, all three evaluated mechanisms show a decreasing trend as iterations progress. This reduction is driven by the increasing integration of renewable energy sources, whose production generally coincides with periods of greater system tightness, which were previously covered by more expensive peaking units.

At first glance, the evolution of energy costs appears similar for the three designs, which could lead to the conclusion that the mechanism with the lowest CRM cost is the best alternative, as it enables a reduction in market costs without incurring high expenditures on capacity remuneration. However, this analysis does not consider the insolvency of traditional peaking units, which is reflected in the insolvency cost curve. In the fixed CP case, overpayments to traditional units reach up to 180 MMUSD, whereas eliminating the CP results in a deficit of up to 750 MMUSD. In the mixed payment scheme, the system's initial insolvency is reduced by 38%, reaching a final value of 280 MMUSD. This is where the CRM evaluation mechanism becomes relevant, as the side payments associated with insolvency have a direct impact on the final cost of energy. If this factor is incorporated into the overall market evaluation, the alternative with the lowest capacity remuneration cost is no longer necessarily the most efficient.

The proposed mechanism enables the integration of CRM into the system, reducing total systemic costs across all designs while identifying the most profitable portfolio for the system. Additionally, it allows for comparisons between different payment modalities, aiming to minimize economic losses. In this analysis, it is observed that mechanisms relying exclusively on the CA may seem more cost-effective in terms of capacity remuneration costs but create greater financial instability in the system, leading to higher insolvency costs and, consequently, a smaller reduction in total energy costs. In contrast, schemes that effectively balance CP and CA tend to mitigate these financial fluctuations, providing a more stable and sustainable cost structure in the long term.

6.1.3 Technical Evaluation

In order to verify the behavior of the proposed approach from a technical perspective, Figure 6.2 presents the evolution of the CO_2 emissions, LOLE, and ENS for the three CRM designs under consideration.

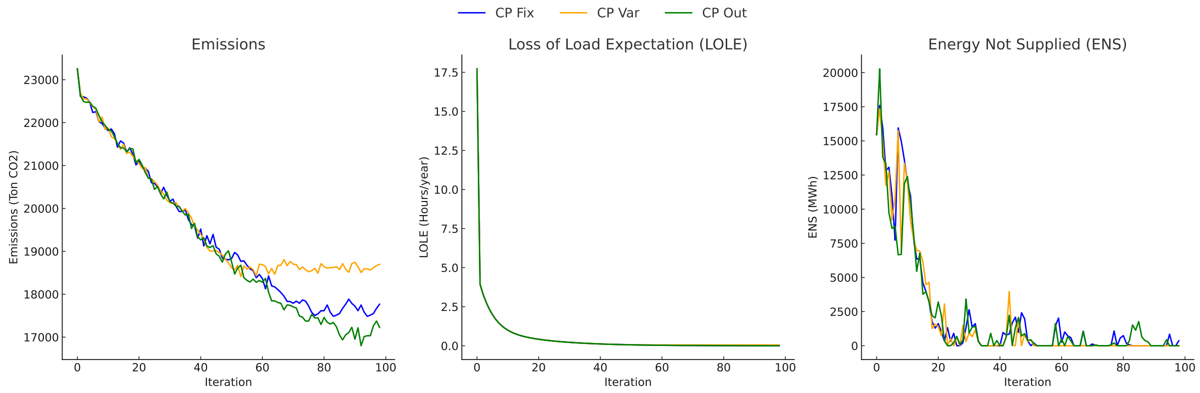


Figure 6.2: Evolution of emissions, LOLE, and ENS

First, CO_2 emissions show a decreasing trend throughout the iterations in all CRM designs. This result suggests that the generation portfolio follows a similar pattern in terms of decarbonization and transition to cleaner technologies, regardless of the CRM scheme used. However, the stability of this transition depends on the revenues received by the generation units, implying that some mechanisms may promote more sustainable long-term investments than others, as observed in the insolvency curves as show in Figure 6.1.

On the other hand, the analysis of LOLE and ENS indicates that reaching the target capacity at iteration 50 is not a necessary condition to ensure acceptable levels of system security. As can be observed, LOLE decreases rapidly in the early iterations, suggesting that system reliability improves even before reaching the planned total capacity. For example, in [78], in an analysis conducted for the German system, the minimum observed value of LOLE is 2 h/year, while ENS approaches 95 GWh/year, values that are quickly reached by the proposed mechanism. This indicates that the model is capable of identifying more efficient remuneration schemes, allowing for adjustments to the target capacity imposed by the CRM in order to optimize the balance between costs and security. In this way, it would be possible to modify capacity volumes to improve the system's economic performance and adjust the previously obtained convergence, adapting it to a more dynamic and sustainable context.

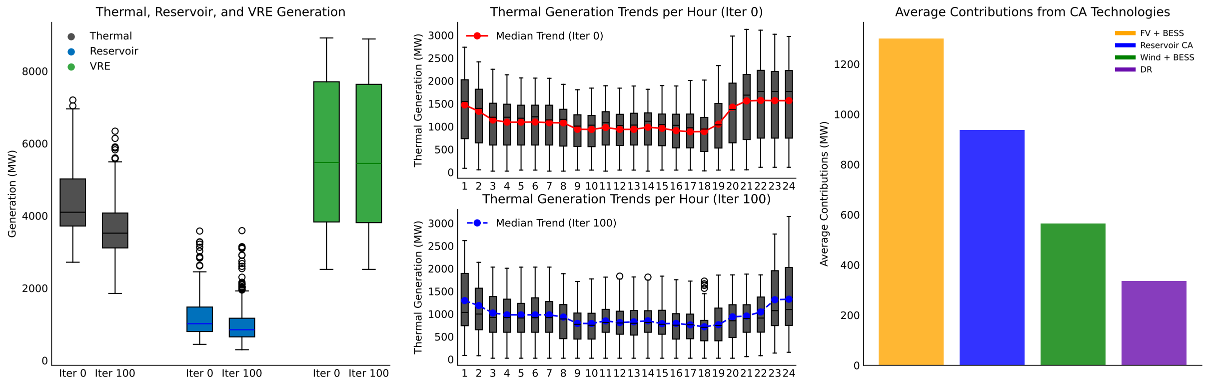


Figure 6.3: Operational results for variable capacity payment

Once the CP Var case is identified as the most efficient CRM design from both a technical and economic perspective, the corresponding system's operational behavior is analyzed at iteration 0, i.e., prior to the integration of CRM, and at the final iteration, as depicted in Figure 6.3.

The graph on the left shows the differences between the initial state of the system and the last iteration, for the variables of thermal generation, reservoirs, and VRE. At iteration 0, thermal generation represents a significant share of the supply, highlighting a strong dependence on conventional dispatchable resources. At iteration 100, the system incorporates hybrid parks, as observed in the right graph, aligning with the expected transition toward a renewables-based energy system. However, thermal generation continues to play a fundamental role, ensuring system stability and covering periods of low renewable production.

The reduction in thermal generation is not solely the result of lower demand or increased conventional renewable generation but is directly linked to the contribution of hybrid VRE units during peak periods. As shown in the right-hand figure, which presents the average contribution of resources remunerated through the CA, these units enable a more stable operation of thermal resources throughout the day. Rather than relying on abrupt variations to meet peak demand, hybrid VRE units facilitate more controlled operation of thermal plants, preventing frequent startups and shutdowns that increase costs and reduce efficiency. This effect is illustrated in the central figure, which depicts the hourly thermal generation contributions for iterations 0 and 100.

On the other hand, the decrease in hydroelectric generation does not imply a reduction in water usage but rather a redistribution of its participation within the market. As iterations progress, hydro resources are integrated into the CA payment scheme, allowing the same amount of water to be utilized within different market structures, thereby optimizing overall system performance.

This analysis confirms that the integration of hybrid technologies within the capacity remuneration framework not only optimizes the thermal generation curve but also reduces operational costs and improves overall system efficiency.

Chapter 7

Conclusion

The proposed mechanism enables the evaluation of CRM integration in transitioning electrical systems, providing a quantitative framework to analyze its impact on costs, reliability, and sustainability. Through modeling different scenarios, key differences in resource allocation and the financial stability of the system are identified, allowing for a comparison of the efficiency of schemes based on administrative payments, auctions, or a combination of both.

These findings directly align with the main contribution of this article, which is the development of an innovative methodology for designing and evaluating capacity remuneration mechanisms. The results support three key pillars that address gaps in the current literature:

- Evaluation of the impact on unit profits and how they are affected by the introduction of mechanisms with different allocation, remuneration, and evaluation characteristics. The results show that the CRM structure significantly influences the revenue streams of capacity providers, affecting their financial viability and long-term participation in the market.
- Proposal of technical and economic considerations to facilitate the energy transition within the design of capacity mechanisms. The results indicate that the remuneration structure plays a fundamental role in ensuring system stability while enabling the gradual integration of renewable energy sources without compromising the reliability of dispatchable resources.
- Simultaneous integration of remuneration, adequacy, and decarbonization aspects. The analysis highlights the trade-offs between ensuring financial stability for capacity providers and promoting the transition to a more sustainable generation mix, emphasizing the importance of dynamically adjusting remuneration criteria to optimize cost-benefit relationships.

The results indicate that the transition to a system with greater renewable energy penetration follows a similar pattern across all evaluated scenarios. However, the stability of this transition depends on the remuneration structure and the revenues received by the participating units, highlighting the importance of evaluating incentives within the proposed mechanism to prevent the premature retirement of critical capacity.

In this context, the results suggest that a hybrid CRM structure, combining fixed remuneration and auction-based remuneration, offers the best trade-off between cost efficiency and system adequacy. This approach will ensure the financial stability of capacity providers while efficiently integrating new technologies and renewable sources. The flexibility of this model also facilitates adaptation to changes in demand and public policies, making it an effective tool for the energy transition.

Additionally, it is essential for CRMs to incorporate incentives for flexible resources, such as energy storage and demand response, to ensure system reliability during periods of scarcity. As we move towards a system with greater renewable energy penetration, it is crucial to dynamically adjust remuneration criteria to avoid the premature retirement of critical resources, which could compromise the operational stability of the system.

Optimizing the target capacity does not require reaching a fixed remuneration threshold, as the reduction in LOLE during the early iterations suggests that reliability improves even before the installed capacity target is reached. This suggests that the proposed methodology can be further refined to allow for dynamic adjustments to remuneration criteria, optimizing results based on system evolution.

Finally, the application of the model to the Chilean power system demonstrates that the integration of CRM schemes significantly influences the operational stability of the generation fleet. This supports the broader scope of this work, as the proposed methodology offers a replicable and adaptable framework for analyzing the effects of different market designs on capacity allocation and the financial performance of power systems undergoing an energy transition.

This study paves the way for future research that may explore the implementation of these mechanisms in other systems with different characteristics, such as decentralized markets or systems with different geographical and political configurations. Additionally, it would be valuable to investigate the impact of the ancillary services market and how these interact with the rest of the energy and capacity segment.

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