A novel inclusion of intermittent generation resources in long term energy auctions

Rodrigo Marambio, Hugh Rudnick

Pontificia Universidad Católica de Chile, Casilla 306, Correo 22, Santiago, Chile

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ABSTRACT

Long term energy auctions are positioning as a valuable tool in order to attract new investments into power systems, especially in Latin American countries where emergent economies characteristics and their correspondent risks are usually present.

Even though the focus of these auctions is the long term, there are short term issues involved which actual auction designs fail to include, resulting in an energy allocation that is not necessarily optimal for the system, a condition which becomes more evident in the presence of intermittent renewable technologies.

A novel mechanism is formulated to obtain the optimal allocation in long term energy auctions, considering short term generation profiles from both intermittent and conventional base load technologies, and also their risk aversions.

The proposed mechanism is developed and simulations are made for some scenarios in the Chilean power market, with different levels of renewable penetration. Significant cost savings are achieved for the final consumers in relation to energy purchases, in comparison with a mechanism that follows the demand profile. As more renewable intermittent capacity enters the power system it is evident the need for changes in the energy auctions allocation mechanisms, including elements to exploit the synergies among participants in the short term.

1. Introduction

Latin America has been leading the effort worldwide to introduce long term electricity auctions as an instrument to promote competition in electricity procurement. Other countries such as Australia, Vietnam, Thailand and Philippines are also using actions to attract new capacity, the last three within single buyer schemes (Maurer and Barroso, 2011).

In essence, those are processes where contracts to provide a certain amount of energy in the long term are auctioned, so that the awardees can reduce their perceived risk when financing the projects that will be used to supply that energy.

The application of these auctions has developed well in Latin-American countries such as Brazil, Peru, Colombia, Chile and Panama, where emergent economies characteristics usually are present, like a strong but uncertain demand growth, low competition, and immaturity in certain market elements, which fail to reflect an accurate representation of the market conditions. Additionally, several of those countries have a considerable share of hydro generation, which contributes to the already volatile spot price inherent of those markets.

For these reasons, the classic elements of the peak load pricing theory (a spot market plus a capacity complement) have not been enough to attract an adequate level of new investments, required to supply the demand in an efficient way.

As mentioned, South East Asia has also carried out such auctions, with Vietnam, Thailand, Philippines and South Australia, in this last case specifically to attract new investments in some predetermined renewable technology.

In all the examples indicated there are various distinctions present in the auction designs, such as:

- They are carried out in a centralized or decentralized way (i.e. an entity represents a group of Load Serve Entities (LSE) versus each LSE implements their own process).
- Different time horizons are used for the auctioned contracts.
- Auctions consider specific technologies (e.g. one or more renewable technologies) or are technology neutral (e.g. any technology).

But the objective remains the same, to attract new investments into the system.

Abbreviations: ERNC, Spanish acronym for Non Conventional Renewable Energy

* Corresponding author.

E-mail addresses: rmarambi@uc.cl (R. Marambio), hrudnick@ing.puc.cl (H. Rudnick).

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Even though these auctions are designed to respond to long term energy requirements, they have to supply load as soon as contracts start. And there are short terms issues involved, even at the hourly level. In effect, the group of auction winners has to supply the actual aggregated load of the demanding entity, independent of the dispatch made by the Independent System Operator (ISO). In this sense, the hourly power obligation for an auction participant will determine a short term risk that it will have to face. In the actual auction designs, this issue has not been considered with enough detail in order to determine an optimum allocation.

For example, in the presence of renewables technologies among the auction participants, the approach that countries like Brazil and Peru have followed is to assign “production contracts” to the renewables, that is, to let those technologies fulfill their accorded energy whenever they produce it, leaving the conventional technologies to manage the increase in their short term risk that such decision leaves. On the other hand, trying to equate the treatment to all technologies, in the majority of auctions carried out in Chile, each auction winner (being conventional or renewable) has to supply an amount of the required hourly power proportional to its awarded energy. Being this required supply response a short term issue, auction design alternatives have failed to include some optimization in the auction design, coupling short term issues when the focus is long term.

In this work, a novel framework is proposed in order to design the auction, so that it considers a representation of the short term within the long term problem. Instead of a unique price and a quantity, auction bidders are required to provide both preferred short term supply profiles and indifference curves (price curves as functions of how much of the assigned energy is within or outside the provided supply profile).

An implementation of this framework is developed, where we consider that the short term supply profile provided by each bidder is an hourly profile of a typical day of the year. Simulations for this implementation are carried out for various levels of renewable penetration in the Chilean power system, showing that the proposed mechanism minimizes the expected payments from the demand and improves the allocation among the bidders.

2. Background

2.1. Auctions

As mentioned in (Maurer and Barroso, 2011), an auction is a selection process designed to distribute goods and services competitively; and in most of the cases in the electricity market, generation companies offer their products because they are interested in selling power contracts to large clients or distribution companies with a design that is focused on obtaining the best price (this is the so-called reverse auction).

Within the auctions oriented to attract new capacity, we can find ones that (i) include all types of technologies or technology neutral (direct competition among all technologies), (ii) only renewable energies, (iii) specific renewable technologies, (iv) specific projects (for example, to award a concession in a specific site) and (v) for demand resources.

Another distinction is the product that is auctioned as capacity per se (as in (Hobbs et al., 2005), (Hobbs et al., 2007), (Cramton, 2006), (Cramton and Stoft, 2005)), which normally correspond to short term auctions (annual, monthly) whose target is to keep the system reliability within certain margins in peak hours, or if the auctioned product is energy to be delivered within a certain period, which generally are long term contracts (up to 20 years) as in (Moreno et al., 2009), (Moreno et al., 2010) and (Chacon, 2013), among others.

These last types of auctions (where long term contracts for delivering energy are the products) are the ones that we are going to be referring for the rest of the article.

2.2. Renewable technologies in auctions

In the context of renewable energy, several countries have decided to foster the development of renewable technologies through exclusive auctions for one or more of those technologies, which necessarily implies a regulatory decision about the quantity of the demand intended for those kind of technologies. According to (Maurer and Barroso, 2011), these types of auctions have proven to be a viable alternative to the more traditional approaches like feed-in-tariff to attract renewable energy into the system. As the traditional auctions to attract new capacity, there are different combinations of target participants in these renewable auctions, being some of them: a) all types of renewable technologies, b) technology-specific or c) technology and site specific. In this context, (del Río and Linares, 2012) declare that there are mixed results in the implementations of such auctions, being one positive aspect the low level of subsidies in general. On the contrary, some of the negative elements include the low effectiveness to attract the expected renewable capacity, the low technological diversity, low innovation and high transaction costs.

On the other hand, technology neutral auctions are those where there are not restrictions on the types of technologies that can participate, being them renewables or conventional.

2.3. Short term issue of hourly power obligation

Clearly the long term is the main focus of the energy auctions, but also there are short terms issues involved, even at the hourly level. One of those issues is that the group of auction winners has to supply the actual aggregated load of the demanding entity, independent of the dispatch made by the ISO. The hourly power obligation will determine a short term risk that every auction participant will have to face in the case of winning. This issue becomes especially relevant as more renewable technologies enter the system, because unlike conventional base load technologies it is common for some renewable technologies to present several hours without generation, which raises the question of who has the obligation to supply the power on those hours.

2.3.1. Existing hourly assignments between auction winners

In most long term energy auctions, what has been done until now is to let the renewables fulfill their awarded energy supply according to a production logic (whenever they generate, their energy is recognized by the Load Serving Entity demand at that time $D_{LSE}^h$, multiplied by the percentage that represents its $E_i$ awarded energy with respect to the total awarded $E_{LSE}$, as seen in the following equation.

$$P_i^h = D_{LSE}^h \frac{E_i}{E_{LSE}}$$

Moreover, the power system’s economic dispatch is cost based (respects to the real audited costs associated to the units’ generation, considering restrictions such as technical minimums and reserves). As

\footnote{The auction scheme was modified in 2014, allowing a small percentage of the energy to be auctioned at different time windows during the day.}
mentioned, such economic dispatch is carried out by the ISO, independent from the commercial obligations that each generation company has acquired beforehand. This implies the full separation of the system’s physical operation from the contractual obligations between the generation companies and demand. Due to this, there might be the case where a generation company has a contractual obligation to supply X power at a specific hour of the day during which its generation units are not dispatched by the ISO, in which case that company will have to buy that energy in the spot market. On the other hand, if we assume that the same company has no surpluses or deficits (that is, through its supply contracts it sells the total exact amount of energy it produces), it will necessarily generate that X energy at another time of the day, which will have to be sold in the spot market. This situation makes the generation company face a risk that involves the spot market, with the need to cover with its own money the supply and generation time differences ($\Delta \text{spot}_{\text{supply}} - \Delta \text{spot}_{\text{gen}}$).

In the case of Chile, the situation described had not been a major issue with conventional base load generation, because when spot prices are high, the base power plants (coal and hydro in Chile) are usually running, mitigating in this way the spot price risk associated with their contracts. On the other hand, the ERNC power plants do not necessarily have that characteristic, so their entry in the system starts questioning the logic behind such hourly assignment.

2.3.2. Alternative hourly assignments between auction winners

In relation to the described hourly assignment scheme, two major features presented by some ERNC which have an important impact when being considered in supply auctions are the non-manageable intermittency and uncertainty of their generation. However, in this work we will only consider the non-manageable intermittency issue.

To illustrate this issue, we will use a simplified example in order to understand its essence. Although demand in a distribution company is not usually flat, in this example we will consider what could correspond to an industrial consumption, which is a flat demand. On the other hand, we will assume that there are two participants in the auction, a coal and a solar generation company, and both are necessary to satisfy the daily demand.

Considering an auction granted only based on energy (as has been the case up to now), as can be observed in Fig. 1, due to the solar generation characteristics there would be an area (hatched area) that, independent from who is awarded, would have to be necessarily marketed (that is, supplied without having own backup generation at that time). The figure shows the two extremes in the award, they are:

1) The energy to be marketed is in charge of the ERNC (like in the Chilean scheme).

2) The energy to be marketed is in charge of the conventional generator (like in a feed-in-tariff-like scheme).

In addition, there is a continuum of possible assignments between these two extremes.

With this range of possible hourly assignments, probably a proportional assignment such as Eq. (1) is not optimal in all the cases and it is also not clear how much that assignment will affect the prices for the end consumers due to the resulting offers by the bidders.

Although it is clear that if the solar and coal generators are risk averse, both would prefer the hourly assignment that is more similar to their power generation profile in order not to be exposed to the spot price risk.

In this work we use the term “backed” energy in reference to a participant’s awarded energy that fits within its power generation profile; therefore that participant will have a power plant backing up that energy requirement. On the contrary, we use the term “marketed” energy for the participant’s awarded energy that does not fit within its generation profile, and will have to be acquired in the spot market in order to fulfill the supply contract requirements.

2.4. Chile case

As we will use the Chilean power market as a background, a brief description of its two auction schemes where renewables can bid is presented. As mentioned in (Rudnick and Mocarquer, 2006), through short law II (Law 20.018), Chile decided to award long-term energy contracts to supply distribution companies through non-discriminatory, technologically-neutral auctions where the winners correspond to those agents that offer the most economic alternatives. Such auctions must be carried out at least three years in advance in order to give time to the investors to obtain funding and building a project.

Another auction scheme was created in 2013, when the law on renewables incentive was amended. This amendment authorised the government to carry out annual auctions only for non-conventional renewable energy projects in case it is estimated that the renewable quota” required by law will not be reached with the installed capacity. To participate, the bidders must: (i) have an Environmental Qualification Resolution accepted for the Project, (ii) have a capital equal or higher than 20% of the total required for the Project, (iii) give proof of the land ownership, (iv) provide a bid performance bond and (v) provide a collateral for the project implementation. This auction

\[\text{ERNC as marketer, Load}\]

\[\text{Coal, ERNC, Load}\]

\[\text{Coal, ERNC as marketer, Load}\]

**Fig. 1.** Assignation according to coal and ERNC profiles.
considers a cap price for energy equal to the mean cost for the long-term development of an efficient generation project in the relevant system. This second scheme is oriented to attract new renewable technologies in a technology-specific manner (that can be oriented to attract more than one type of renewable energy simultaneously). The winners of the auction are awarded a feed-in-tariff-like product, essentially becoming a production contract. This scheme has not been used, as the renewable quota has been reached without need for support. Thus, the following analysis and proposals consider only the first scheme, technologically-neutral auctions.

Given the fact that the Chilean system is presenting new dynamics due to the growing ERNC incorporation (partly due to the incentives mechanisms such as the RPS implemented by the authority), there is the challenge to find new mechanisms that adapt to such characteristics. The need is to obtain the best of each world, namely, allowing to obtain the low prices and environmental benefits that the ERNC can provide, but without disregarding the risk transfers toward conventional power stations that such incorporation could trigger, effect that would finally cause an impact on the price paid by end consumers.

2.5. New framework proposed for auctions

We believe that a methodology for optimal assignment should consider the hourly assignment issue when deciding the energy awarding among auction participants, to allow the LSE (or distribution company in the Chilean case) to make a better decision, considering the different variables at stake. In this sense, we are proposing a framework for energy auctions that considers the short term power profiles from the participants in order for the LSE to obtain a lower purchase total cost through a contract allocation that is more suitable to each generating technology. Like the existing long term energy auctions schemes, the proposal follows the logic of a centralized clearing mechanism for the long term contract market and is not a reliability auction per se. Moreover, it does not deal with the problem of capacity adequacy and rather assumes that sufficient generation capacity is always available in the electricity system via capacity mechanisms.

For the numerical experiments we will consider a future projection of the Chilean power system as the context, which is a hydrothermal system that has a high variability due to its possible hydrological conditions. Besides that we will be using the main auction scheme used within the Chilean market as the base case, and also considering the full spectrum of risk preferences of the auction participants.

3. Methods

Nomenclature

\[ q_{it}^{B} : \text{backed energy awarded to generator } i \text{ in hour } t \]
\[ q_{it}^{M} : \text{marketed energy awarded to generator } i \text{ in hour } t \]
\[ x_i : \text{binary variable representing if there is energy awarded to generator } i \]
\[ p_{\text{back}} : \text{price offer for backed energy by generator } i \]
\[ p_{\text{mark}} : \text{price offer for marketed energy by generator } i \]
\[ k_{d} : \text{percentage of the energy produced by generator } i \text{ in hour } t \text{ of the day} \]
\[ D_t : \text{LSE total load in hour } t \text{ of the day} \]
\[ E_i^p : \text{annual energy offered by generator } i \]
\[ \text{var}_\text{cost}_i : \text{variable production cost for generator } i \]

AIC : annualized investment cost for generator i
\[ \text{green}_\text{taxes}_i : \text{cost or benefit for generator } i \text{ related to environmental taxes} \]
\[ \text{max}_\text{energy}_i : \text{annual maximum energy produced by generator } i \]
\[ c_f_{ih} : \text{capacity factor of generator } i \text{ in hydrologic scenario } h \]
\[ \text{spot}_{\text{supply}} : \text{cost of buying } 1 \text{ MWh in the spot market at a certain hour} \]
\[ \text{spot}_{\text{gen}} : \text{income of selling } 1 \text{ MWh in the spot market at a certain hour} \]

To find the optimal assignment considering the short term supply issue, we must consider both the generation profiles of the participants and their risk management capability. The latter skill is required when acting as a marketer. With this information, the LSE can make awarding decisions for the energy to be bought and the hourly assignment for each participant, which includes both elements through the co-optimization of both dimensions.

This section gives the details of the bid structure to be submitted by each bidder and the awarding and assignment problem that the LSE must face.

3.1. Bid structure

3.1.1. Offered energy

First, for a generator \( i \) the bid must include the energy available for awarding \( E_i^p \). This can be a monthly or annual quantity or the quantity for the entire horizon, among others, but in this case we shall consider an annual resolution.

3.1.2. Generation profile

In addition to the bid, there must be an hourly generation profile for an average day. The idea of this profile is that it assumes what has been assigned within it will have dispatched generation backing up such assignment, hence eliminating the spot market exposure risk.

In this work we consider an hourly resolution for a typical day of the year in the assignment; therefore the profile submitted must be a 24-hour vector with the percentage of the daily generation that will be produced on each hour of a regular day. The symbol \( k_d \) is used to represent the elements of this 24-hour profile vector presented in the auction by generator \( i \).

Fig. 2 presents a sample profile for a solar generator in a graphical form. It can be seen that in this particular case the solar generation
company is providing information that says that its generation is mostly between 8:00 and 17:00 h, therefore in case it supplies energy to the LSE, during such interval it will be backed up by its own generation.

It is worth mentioning, that although we are considering one typical day as the bidders provided profile, the implementation could equally consider several types of typical days at once, like winter and summer days, which would further improve the mechanism performance.

3.1.3. Price indifference curve

For a generator, we are using the concept of price indifference curve as the function that maps the possible combinations of awarded backed and marketed energies with an offer price that varies in order to make the awarded combination indifferent for the generator. In other words, if a quantity is awarded to a generator, it will be indifferent if all of its energy is within or outside its generation profile, because the offer price function will reflect that in the form of a risk premium.

Therefore, each participant must provide a price indifference curve with the detail of the price offered in function of the total awarded energy that is assigned beyond the generation profile. It must be mentioned that although this curve can be complex for the generators to calculate, it is an exercise that at least the ERNCs are already implicitly done giving that the current hourly assignment mechanism (Eq. (1)) implies that a certain amount of its awarded energy will have to be marketed. The proposed mechanism makes explicit this process to all participants to allow the LSE to consider this additional information at the moment of the award, hence resulting in a better solution.

The price indifference curves could be quadratic in order to reflect a cost that increases quadratically because of higher exposition to spot prices. They can also be linear, similar to the indifference curves used in the different duration contract auctions made by Electricité de France (Ausubel and Cramton, 2010).

We will use the variables \( q^B_i \) and \( q^M_i \) to represent the backed and marketed energy that is awarded to generator \( i \) in hour \( t \) of the day (i.e. the assigned energy within and outside its generation profile). Additionally, in order to obtain general conclusions without over-complicating the model, in this work we will limit our analysis to the linear case only. Therefore the price function will be defined by only two values, joined by a straight line, with the parameters \( p^{back}_i \) and \( p^{mark}_i \) representing the price offers made by generator \( i \) for a MWh of backed and marketed energy respectively.

The linear case serves well the purpose of this work, but it is worth noting that for a more detailed implementation of a price indifference curve one can search in fields like decision making in economic theory and finances (Glimcher and Fehr, 2009), where creating profiles that trade off risk and return is a central issue.

3.2. Awarding

On the other hand, the LSE must award the following among the generation companies that participate in the auction:

1) The total amount of energy that will be purchased from each company.
2) The hourly assignment profile for the company, which will result on the purchase price depending on the amount of energy assigned within and outside of the generation profile provided by the company (backed and marketed energies, respectively).

In this manner, the problem to be solved by the LSE will be the following:

\[
\min \sum_i \sum_t \left( p^{back}_i \cdot q^B_{it} + p^{mark}_i \cdot q^M_{it} \right)
\]  

3) The linear case serves well the purpose of this work, but it is worth mentioning the following:

\[
\sum_i B_i = D_t \quad \forall t 
\]

\[
\sum_i (q^B_{it} + q^M_{it}) = x_i \cdot E^O_t \quad \forall i, t
\]

\[
q^B_{it} \leq k_i \cdot E^O_t \quad \forall i, t
\]

\[
q^B_{it}, q^M_{it} \geq 0 \quad \forall i, t
\]

\[
\sum_i q^B_{it} = \sum_i q^M_{it} = q_t \quad \forall i
\]

It can be seen that the presented equations solve the problem in the case where a linear objective function is considered, ensuring that the total demand is supplied at the least cost for the LSE, caring not to assign to a participant more energy than what it is offering. It is worth noting that the model works in our case because we will consider combinations of offers that exactly match the demand in order to fulfil Eq. (4). The problem presented here must be adjusted based on the particular characteristics of the price indifference curves (e.g., quadratic, exponential, linear, etc.) and the considered typical days (summer day, winter day, etc).

3.3. Modelling

We try to obtain an estimate of the impact of the supply cost of this new mechanism in an auction process, where the main factors of influence are the following:

3.3.1. Technologies that participate in the auction

We considered three; coal, solar and wind technologies. These are technologies that can be competitive in the Levelized Cost of Energy, but they have different production profiles. On the other hand, we consider two cases in relation to the total amount of energy offered (including backed and marketed energy, namely within and outside the generation profiles of the generation companies):

1. The energy of three generation companies is required to satisfy the auctioned demand.
2. The total energy auctioned can be satisfied by two of the generation companies (namely, one is excluded).

Independent from the case, we assume that each generation company makes a competitive bid, trying to offer the minimum price considering the expected return and their risk aversion.

3.3.2. Participants’ risk aversion

We consider that each participant can have a low, medium or high-risk aversion level, which will be reflected in its bids.

3.3.3. The system’s spot price

Clearly, the participants’ perception about the spot market risk will depend on the system configuration, both on the generation mix and the demand. Although we considered a deterministic annual demand level, we considered 3 possible ERNC inclusion levels equivalent to 20%, 30% and 40% of the system’s total energy generated by generation units that fulfil such characteristic, where for each level there is a corresponding complementary thermal generation pool.

The calculation of the system’s spot price is described in Section 3.4, while the modelling of the participants is detailed in Section 3.5.

3.4. System

The actual auction will be a process that occurs within the context of a physical power system, with more generation units and demand that the ones present in the auction itself (we will assume that the system is large enough so that not being able to buy energy in the spot market will not be a concern for the participants). Next we present a
brief summary of the methodology used for the installed capacities calculation and the resulting spot prices for the year 2030.

First, ERNC inclusion levels equivalent to 20%, 30% and 40% of the system’s total energy generated in year 2030 were considered. In each level, approximately 10% of that energy comes from mini hydros, geothermal and biomass sources, while 47% and 43% come from solar and wind sources, respectively, keeping the projected percentages of the Chilean National Energy Commission.

Considering these ERNC inclusion levels as a fact, we calculated the optimal thermal mix in order to complement each level in particular. This is equivalent to assume that each ERNC inclusion level results from the country’s energy policy decisions, while the rest of the system adjusts itself accordingly (assuming a perfect competition, absence of congestions in the transmission system and omitting technical constraints such as start-up times and technical minima).

The calculation of the optimal installed capacity in each inclusion level was made through the screening curves methodology (Phillips et al., 1969) (Baldick et al., 2011), which is explained briefly in Appendix A.

Through such methodology an optimal thermal mix is obtained in terms of investment and operating costs, considering both the generation uncertainty given by the ERNC and the hydrological uncertainty that highly impacts the hydraulic power stations’ generations. Fig. 3 presents the resulting installed capacity by technology for each ERNC level considered..

As we need an estimate of the hourly spot price for the year in question, we simulated the system’s daily operation in each case. In this manner, for each ERNC inclusion level, the resulting installed capacity, the hydrological statistics available for the Chilean system (56 annual hydrological scenarios) and the hourly statistics of solar and wind plants from 2013 were used. This allowed obtaining different dispatch scenarios for a typical day for such year, and the hourly spot prices in each one of those scenarios were calculated. Fig. 4 presents the average spot price for each hour and level of ERNC inclusion..

On the other hand, the hourly distribution of the demand considered corresponds to Fig. 5 that is the total demand profile of the Central Interconnected System (SIC) (main Chilean system), where 64% of its demand is regulated or residential.

It can be observed that although the curve is not flat, most of its energy could be circumscribed in a rectangle, approximately matching the situation with the example presented in Fig. 1.

3.5. Bid curves

As mentioned in Section 3.1.3, there are several possibilities to represent the bid or indifference curves. However, in our modelling we used linear functions for such representation in order to prevent complicating the problem and centre ourselves in its essence. With this, the bid is defined with the offered energy, the generation profile and a price indifference function.

3.5.1. Generation profile

We assumed the daily generation profile as the average profile for each technology, calculated from the statistics used. Fig. 6 shows the generation profile for each technology participating in the auction.

It can be observed that the coal profile is modified as additional ERNC percentage is considered in the system. This happens because
the nil marginal cost of such technologies displaces the generation of more expensive technologies such as coal. On the other hand, the solar and wind technologies do not show any modification in their generation in the different scenarios, because as they have nil generation prices, there is no technology that displaces them (this would happen if at any hour there is more nil-price ERNC generation than demand, something that does not happen in our scenarios).

It is necessary to take into account that we are not considering operational aspects such as technical minima or start-up costs, which, albeit it is a simplification, it is not the essence of the problem we are analysing.

3.5.2. Backed price

The backed price corresponds to the bid price that a generator is ready to offer provided the hourly assignment of its energy matches with the generation profile included in the bid, which we assume is known by the generator with a certain level of certainty.

We assume that the backed price will correspond to the minimum price to charge for one MWh that guarantees the generator a predetermined profitability, considering both the investment and operating costs and taxes or subsidies associated to environmental issues. The revenues and costs values that influence the calculation of the backed price of the participant technologies are shown in Table 1.

Note that the ERNC attribute item corresponds to a cost for the coal generator (that depends on the ERNC quota fixed by the authority) but it is considered as revenues for the ERNC generators. The value considered for this attribute corresponds to an approximation of the attribute’s average price for 2013. On the other hand, for the CO\(_2\) tax, it is considered as revenues for the ERNC generators. The value considered for this attribute corresponds to an approximation of the CO\(_2\) tax (US$/MWh) of 9.7 t CO\(_2\)/MWh for each generating unit, which we assume is the same for all technologies.

In addition, each generator will need an estimation of the amount of energy to be generated in the year in question. This estimate will depend on the generator’s risk aversion. As we are assuming that the annual ERNC production must correspond to an annual fixed value (as percentage of the demand), such generation will not be displaced by large hydro electric power stations, therefore we assume that both the solar and wind participant have certainty about how much they will generate in the year independent of the present hydrological scenario. However, this cannot be assumed for coal, because its annual generation will indeed be displaced by hydraulic generation. Table 2 shows the backed prices for the different participant technologies in function of their level of hydrological risk aversion (note that offer prices for coal technology are higher as there are more ERNCs in the system, cause its capacity factor will be lower).

For a generator \(i\), these prices were calculated as in the following equation:

\[
p_{\text{back}} = \frac{\text{Backed Price}}{\text{Energy Flow}} = \frac{\text{Max Energy Flow}}{\text{CVaR(\text{ERNC})} + \text{Green Taxes}}
\]

where CVaR(\(p_{\text{mark}}\)) corresponds to the Conditional Value at Risk (CVaR) (Uryasev, 2000) of the plant factor considering the 56 statistical hydrological scenarios, where the Low, Medium and High aversions are equivalent to the production confidence levels of 5%, 50% and 95%, respectively. On the other hand, green taxes correspond to the revenues or costs for the generator given by the ERNC attribute and the CO\(_2\) tax.

3.5.3. Marketed price

As mentioned in Section 2.3.1, the excess cost paid by a generation company when supplying 1 MWh at an hour of the day different from the generation time is \((p_{\text{supply}} - p_{\text{gen}})\). Therefore, the random variable that represents the price that a generator \(i\) will charge to sell 1 MWh at a time different from the generation time (during the same day) shall correspond to the following equation:

\[
p_{\text{mark}} = p_{\text{back}} + (p_{\text{supply}} - p_{\text{gen}})
\]

As an approximation to the probability distribution given by \((p_{\text{supply}} - p_{\text{gen}})\), we considered many daily scenarios based on the statistics generated before in Section 3.4. We assumed that for a specific day, a generator considers that the LSE can request the MWh to be supplied in an equiprobable manner during each one of its 24 hours. However, that same MWh will not be generated at any hour with the same probability (for example, as seen in Fig. 2; for the solar generator such MWh will be generated in hour 4 with 0% probability, while there will be a 11.4% probability to generate it at hour 15). With this information and the amount of days in the statistics, it is possible to obtain a discrete estimation of the random variable \((p_{\text{mark}} - p_{\text{gen}})\), which in turn allows us to calculate an estimate of the \(p_{\text{mark}}\) variable.

Table 3 shows the marketed prices for the different participating technologies in function of their risk aversion level.

As it happens with the backed prices, the marketed prices correspond to the CVaR of the estimated distribution of \(p_{\text{mark}}\), where the Low, Medium and High levels correspond to the confidence levels of the cost excess of 5%, 50% and 95%, respectively.

From the table it can be concluded that for a high-risk aversion level, solar technology is the least adequate technology for the marketing task, because its energy production is mainly done at the hours of

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**Table 1**

<table>
<thead>
<tr>
<th>Backed price calculation factors.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Coal</td>
</tr>
<tr>
<td>Solar</td>
</tr>
<tr>
<td>Wind</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Backed Price by risk aversion (US$/MWh).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Coal (20% ERNC)</td>
</tr>
<tr>
<td>Coal (30% ERNC)</td>
</tr>
<tr>
<td>Coal (40% ERNC)</td>
</tr>
<tr>
<td>Solar</td>
</tr>
<tr>
<td>Wind</td>
</tr>
</tbody>
</table>

**Table 3**

<table>
<thead>
<tr>
<th>Marketed price calculation factors.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Coal</td>
</tr>
<tr>
<td>Solar</td>
</tr>
<tr>
<td>Wind</td>
</tr>
</tbody>
</table>

**Fig. 6.** Generation profile by technology.
the day of the lowest spot prices, especially when there is a high ERNC inclusion.

It is worth noting that in both backed and marketed price calculations the Low risk aversion case (5% confidence level of the CVaR) is almost identical to a risk neutral case, given that it is an average considering 95% of the worst-case scenarios for the generator. On the other hand, we are assuming that the production risk and the spot risk are separable (reflected in the backed and marketed price respectively), being a simplification of the market dynamics; nevertheless this does not affect the general conclusions of the proposed mechanism.

4. Results

As mentioned before, for each ERNC inclusion scenario, both the case in which the 3 generation companies are required to supply the auctioned energy and the case where 2 generation companies can supply all the auctioned energy were considered. In addition, a third case was considered. It is similar to the second case, but assuming that there is an arbitrary support from the LSE to assign the backed energy to solar technology. In this manner, for each one of these “cases”, 81 auction simulations are obtained (given by [3 ERNC scenarios] x [27 risk aversion combinations]).

4.1. Case 1: the three companies are required to supply the auctioned energy

In this first case, we consider that each one of the three technologies mentioned before offers 876 GWh for 2030 (equivalent to 100 MW of mean power), and in turn, the demand is 2628 GWh with the daily profile shown in Fig. 5. As in this case all the energy offered is required to fulfill the auctioned demand, the total awarded energy to each generation company will be the energy that each one offers. In this case, the aim is to estimate the benefit that the proposed mechanism could bring to the LSE in a case where there is no excess of bids.

The resulting hourly assignment under the current mechanism is presented in Fig. 7. It can be observed that in this case, in each hour, each technology is in charge of supplying the same amount of energy.

On the contrary, Figs. 8 and 9 show the hourly assignment for two coal/solar/wind risk aversion combinations. In general, it can be observed that as more risk-adverse is a participant compared to its competitors, its energy assignment is increasingly similar to its generation profile.

In order to quantify the benefit or damage of the proposed mechanism, we will compare the result with the outcome of the current assignment mechanism, namely, where the hourly power assignment is made proportional to the energy awarded (as in Eq. (1)). For this, the chart in Fig. 10 presents the purchase cost savings for the LSE provided by the proposed mechanism compared to the current one, in function of the various risk aversion combinations of the participants and for the three ERNC inclusion levels. In this case, the purchase cost savings obtained by the LSE oscillates approximately between 4.7 and 107.3

Table 3
Marketed Price by risk aversion (US$/MWh).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal (20% ERNC)</td>
<td>90.75</td>
<td>106.81</td>
<td>222.51</td>
</tr>
<tr>
<td>Coal (30% ERNC)</td>
<td>93.90</td>
<td>111.31</td>
<td>226.25</td>
</tr>
<tr>
<td>Coal (40% ERNC)</td>
<td>97.18</td>
<td>117.60</td>
<td>226.32</td>
</tr>
<tr>
<td>Solar (20% ERNC)</td>
<td>107.79</td>
<td>124.13</td>
<td>265.00</td>
</tr>
<tr>
<td>Solar (30% ERNC)</td>
<td>111.37</td>
<td>130.92</td>
<td>282.77</td>
</tr>
<tr>
<td>Solar (40% ERNC)</td>
<td>117.29</td>
<td>142.18</td>
<td>290.60</td>
</tr>
<tr>
<td>Wind (20% ERNC)</td>
<td>68.70</td>
<td>83.17</td>
<td>190.63</td>
</tr>
<tr>
<td>Wind (30% ERNC)</td>
<td>69.89</td>
<td>85.44</td>
<td>196.51</td>
</tr>
<tr>
<td>Wind (40% ERNC)</td>
<td>70.47</td>
<td>89.07</td>
<td>199.28</td>
</tr>
</tbody>
</table>
It can be observed that the savings are quite notorious in those cases where solar technology has a high risk-aversion, because the actual mechanism “obliges” such technology to market a large portion of its energy. Also due to its characteristics, it will generate during the hours of the day in which the spot price is lower, resulting in a backup of its energy. Also due to its characteristics, it will generate during the hours of the day in which the spot price is lower, resulting in a backup of its energy.

It is worth noting that on each ERNC inclusion level there is a wide range of possible cost savings values, caused by a combination of two characteristics. In the first place, the considered power system has a large hydro share, which results in extreme opposite spot prices depending on hydrologic conditions. On the other hand, regarding the auction participants, all the combinations of risk aversion levels are being considered, giving place to extreme conditions such as where all the participants present high-risk aversion (or low-risk aversion). These two characteristics coupled together result in the mentioned wide ranges.

4.2. Case 2: two companies can supply all the auctioned energy

This case considers that each company (represented by the coal, solar or wind technology) offers 1314 GWh for 2030; equivalent to a mean power of 150 MW, while the auctioned demand that same year is 2628 GWh. In this manner, two generation companies could supply all the auctioned energy, considering that if a company is chosen for the awarding, all its energy must be bought. The aim of this constraint is to create a more realistic case, because if a generation company foresees that only part of its energy will be auctioned, this would be expressed in its bid prices.

With the mentioned assumptions, there are only three possible award combinations in terms of technology mix, being Coal/Solar, Coal/Wind and Solar/Wind. So, for each one of the 27 possible risk aversion combinations (given by the 3 risk aversions of the 3 technologies) on each inclusion level of ERNC, the resulting awarded technology combination will be one of the 3 mentioned before. Table 4 shows how many times each of the 3 technology combinations is awarded in the different scenarios, both for the actual and proposed mechanism. The table shows that while there are no significant differences between the two mechanisms in terms of technologies chosen (mainly being coal and wind the two awarded technologies), the slighter higher assignment that the solar generator has with the proposed mechanism is exclusively due to the greater freedom the LSE has when distributing the energies offered.

On the other hand, as there is more ERNC in the system, the coal generation dispatch is considerably reduced. Anticipating this condition, the coal generator would bid higher prices in the auction so that it can recover its investment costs, which in turn implies an increase of competitiveness for the solar generator and greater assignment to its offers under both mechanisms.

Fig. 11 shows for each risk aversion combination the savings in annual energy purchase costs for the LSE involved in using the proposed mechanism instead of the current mechanism. It can be observed that the annual cost savings when using the proposed mechanism is about 0.6 and 30.1 million US$ depending on the ERNC inclusion scenario and on the risk aversion combination.

Additionally, considerable savings are obtained when the wind generator has a high-risk aversion. This happens because the backed energy offered by such technology is very economic compared to the marketing cost, therefore the freedom the LSE has of being offered an assignment according to its generation profiles is of great benefit in this case.

4.3. Case 3: two companies can supply the auctioned energy and the solar technology has preference in the backed energy awarding

To be exact, this case is a sensitivity analysis of Case 2, because we assume that only two generation companies are required to supply the entire auctioned demand. However, we consider that there is a benefit given to solar technology, giving it priority in the awarding of its backed energy with respect to remaining participants. In addition, the assumption that the companies do not know their competitors is relieved. However, we still consider that each company attempts to make the most competitive bid under this new scheme. In this manner, the companies calculate their bid prices without knowing the competitors'
bid prices, but they are aware of the benefit for the solar generator when it is awarded the backed energy.

This could be similar to dedicate a special auction at the hours in which the solar generator is generating, because in this manner such generator could offer all its energy without marketing risks. Consequently, this would make the solar generator prices highly competitive in those hours, making the rest of the technologies to somehow give up winning in those hours, reflecting it in their prices.

To calculate the new bid prices we continue with the methodology described in 3.5.3. However, instead of considering that the LSE can request for an equiprobable supply in the 24 hours, we adjust such probability to allow a very low or nil probability of assignment during the hours in which the solar generator is producing, as applicable.

These two probabilistic profiles for the hourly assignment of supply for the 40% ERNC inclusion scenario are presented in Fig. 12. When observing this figure and comparing it with the generation profiles in Fig. 6, it can be observed that when increasing the ERNC inclusion level, the coal generation profile is more similar to the probability of assignment for case 3, hence allowing to have a larger proportion of the assignment of that technology being covered by its own generation.

In this manner, the bid prices for this case in particular are the ones presented in Table 5, where solar energy can present its most competitive bid in all the cases, namely, its backed price. It can be observed that there is an important increase in the bid prices both from the coal and wind technologies, while the solar technology maintains the same bid price independent of its risk aversion.

Fig. 13 shows the annual over cost that the solar technology support has for the LSE, both with the actual and proposed mechanisms of auction awarding. In the case of the actual mechanism, it can be observed that there are some scenarios where the solar technology preference brings savings for the LSE, although mainly there are over costs. In general these savings are present in scenarios where the wind generator has low risk aversion and the coal generator has high risk aversion, so coupled with a low bidding price for the solar generator (which does not have marketing risk) allows the LSE to award the auction to the solar and wind generators at a low clearing price.

In the case of favouring the solar technology while using the proposed mechanism, there are only over costs, but in average they are lower than in the case of the actual mechanism. These over costs are due to the solar technology preference removing flexibility from the proposed mechanism, thus limiting its ability to find the best award.

From the same figure we can deduce that the over costs variance is greater in the actual mechanism scenario than in the proposed one, making more difficult to predict the real effect that a transition to a solar support scheme of this kind will have.

Also, it is worth noting that in this case the over costs or savings that resulted are independent from the solar generator risk aversion, as from that generator’s perspective there is not a marketing risk.

5. Discussion

5.1. Arbitrary technology support

In both the first and second simulated cases, the results show a decrease in purchasing costs for the LSE when the risk aversion of the auction participants is explicitly considered in the awarding mechanism, which puts in evidence the necessity to consider such variable in the bidding rules definition for future auctions.

How to include this information in the auction mechanism may vary, but one must be careful at the time of the design and implementation. For example, in recent energy auctions conducted in the Chilean system, a portion (15%) of the total energy auctioned was offered in 3 independent time blocks (hours 23:00 to 07:59, hours 08:00 to 17:59 and hours 18:00 to 22:59), thus allowing technologies whose production profile fit with any of those blocks to only bid for the particular block, without acquiring the supply risk of the other blocks.

While this is an advance in the sense of giving more flexibility to the bidders, in reality the situation is not very different from Case 3 of the simulations presented, where certain technology is supported with a specific profile without worrying about the increased risk that this decision brings to the rest of the bidders. As we have seen, this is not necessarily a good decision, whose outcome will depend on the risk aversion of the participants.

In this direction, an important policy implication from our work is the importance to carefully consider all the participants of the auction when designing the mechanism, because otherwise you can move one step forward and two steps back, getting suboptimal results for the end consumers.

5.2. Strategic behavior of the generators

The exercise of market power or strategic behavior from the auction participants would condition the application of the proposed methodology, and thus we make an analysis of this issue.

In the first place, it is important to notice that the bid structure of the proposed mechanism allows us to obtain a single offer price for a generator $i$, as in the following equation:

$$p_{offer} = \frac{\sum_i (p_{back,i} q_i^M + p_{mark,i} q_i^M)}{q_i^{total}}$$

(10)

This price is a function of the backed and marketed price ($p_{back,i}$ and $p_{mark,i}$, offered by the generator) and the backed and marketed quantities ($q_i^M$ and $q_i^M$, assigned by the auctioneer). With this in mind, a generator could try to exercise market power exaggerating either its costs (represented by $p_{back,i}$) or its risk aversion (represented by...
both of which would imply offering a greater offer price than its true value. The issue of strategic behavior by generators has to be analyzed understanding that the proposed mechanism is a long-term energy auction, where generators offer a quantity and a single price, thus homologating it with existing long term energy auctions (moreover, being a simplification of the auctions already present in Brazil and Chile, which are multi-product).

Different references indicate conditions that limit market power exercise in such auctions and suggest approaches to tackle it. A good analysis is presented in the reference (Arellano and Serra, 2010), where they use a simple model composed of two generation firms with two available technologies, inserted in a 3 stages game. They tackle the problem of market power exercised by distorting the choice of the generating technology, assuming that the dispatch is cost based. The main conclusion from their work is that the larger the proportion of the total demand is auctioned in advance, then the lower are both the contract prices and the average spot price of energy. The reason for this is that the generator that wins the auction has an incentive to reduce its energy cost, therefore invest in baseload capacity, reducing the average spot price. On the other hand, the lower average spot price leads generators to bid lower prices in the forward auction. Their findings goes with the recommendation to pay attention to the design of the specific auction in order to mitigate market power and obtain good results, preferring a centralized process (simultaneous auctions for all consumers), offering long standing contracts and auction with enough anticipation to allow for new investors to bid, therefore increasing competition.

Reference (Villar and Rudnick, 2013) makes an assessment of market power exercise in a hydrothermal system, and concludes that market power exercise mitigates considerably when there is an increase in the level of contracting. Further on, they argue that the need of competing firms to develop long term contracts has an important mitigation effect on their market power.

Related recommendations are given in (Moreno et al., 2009) where they remark the importance of designing the auction process in order to lower the entry barriers, increasing in this way the number of competitors. On the other hand, the awarding mechanism can play an important role in order to avoid collusion and inefficient allocation. For example the Brazilian process is a very interesting one, being a hybrid mechanism where a uniform price first stage is followed by a pay-as-bid negotiation. Finally, from a concrete implementation, observations of both (Moreno et al., 2009) and (Cavaliere and Loureiro, 2010) show that the auction processes in Brazil have increased competition and lowered prices.

6. Conclusions and policy implications

- The increase of economic and intermittent energy technologies in modern power systems modifies the electricity market dynamics, increasing the level of uncertainty for all the participants in it. Due to this, the decisions that support the incorporation of such technologies must necessarily include changes in the auction methodologies used until today, because on the contrary, the costs benefits from such technologies will not be fully transferred to the end consumers simply due to a poor assignment process.
- In the case of the short term assigned hourly supply profile, it is necessary to recognize the capacity of the participants to manage risk, which must be remunerated in an efficient manner.
- A new auction mechanism is proposed to represent the short term hourly assignment issue in long-term energy auctions. It tries to clearly set out the short term risk management that the participants must necessarily have to make, and include that information in a market mechanism. In this sense, the mechanism requires auction participants to take responsibility for their own profile. Thus, risk transfers from the renewables to the conventional generators are avoided, assuming that there is not an intention to subsidize renewables by this mean.
- In the first example for the Chilean system, where all the energy...
offered is required to fulfill the LSE requirements, the proposed mechanism could result in cost savings in the ranges 4.7–80.9, 7.3–90.6 and 12.4–107.3 million US$ for ERNC inclusion levels of 20%, 30% and 40% respectively, compared to the base mechanism. Likewise, in the case where not all the offered energy is required, the mechanism could result in cost savings in the ranges 0.6–27.5, 0.8–29.5 and 1.3–30.1 million US$ for the same ERNC inclusion levels. On each one of these ranges the only thing that varies is the risk aversion of the auction participants, which highlights the importance of considering it explicitly as the proposed mechanism does.

– As we mentioned in the Discussion section, in recent auctions of the Chilean system, a portion of the energy has been auctioned in three different intraday time windows, adding a level of flexibility to the process. For this reason, the calculated benefits from the proposed mechanism will probably be less when compared to this newly implemented method. Nevertheless, the detailed profile and indifference curves in the proposed mechanism give more flexibility to the LSE in order to optimize the total allocation.

– In the presented examples, explicitly supporting the solar technology, by favouring its backed energy awarding, brings as a consequence an important increase in the bid prices of the other technologies, although this does not necessarily imply an over cost for the LSE. In the context of the actual award mechanism, there are some risk scenarios with cost savings benefits for the LSE given by the solar supporting scheme, but in average they are mainly over costs. On the other hand, in the context of the proposed mechanism the solar supporting scheme brings only over costs, although in average they are lower than in the actual mechanism context.

– The auction cost effects of a transition to a solar technology supporting scheme like the one considered in Case 3 are more predictable with the proposed award mechanism, so it could be useful when defining that kind of support policies.

– Regarding the short term risk due to the hourly assignment problem, at the light of the results it is convenient to explicitly consider the risk aversion of the participants in the auction mechanism design without missing the global perspective, that is to say, to carefully analyse the implications of favouring one technology over the others.

Acknowledgements

Thanks to Fondecyt 1141082.

Appendix A: Screening curves methodology

In the first place, each technology is represented by its unitary annualized investment cost and its variable operation cost, in order to represent its total annual cost as an affine function of the total hours of operation in the year (i.e. capacity factor), as can be seen in the upper graph of Fig. 14.

On the other hand, the system demand is represented by a cumulative probability function, like the one in the lower graph of Fig. 14, linking the probability (horizontal axis) with which the demand exceeds a particular value (vertical axis of lower graph) in the specific year.

Fig. 14 shows the screening curves technique scheme, which in essence is a lookup table that links the most cost effective technology to supply each MW of expected load according to the percentage of the year where that specific MW is active. The points where the cost functions of different technologies crosses are of special interest, given that their counterparts in the expected duration curve will give the information about how much capacity of each technology to install.

![Screening curves technique](image)

References


