An Intraday Market Design for Colombia’s Energy Transition

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ABSTRACT The massive promotion of intermittent renewable resources as a decarbonization strategy for economies has led to the need to reconsider current market designs in order to facilitate the integration of this kind of production technology. The intraday market has established itself as an efficient mechanism for these purposes, as has been seen in diverse international experiences, principally Europe. The Colombian electricity market is no stranger to the needs of these reforms, as the National Energy and Mining Planning Office of Colombia (UPME in Spanish) estimates that by 2034 almost 30% of the electricity generation matrix will be comprised of intermittent renewable resources. This paper develops several elements to be considered for the implementation of an intraday market in Colombia, backed with quantitative information, contrary to previous studies that have based their recommendations on qualitative elements. The number of discrete intraday sessions, the effect of changing from a sequential energy and reserve allocation scheme to a co-optimized one, as well as the adjustment mechanism – or a balance mechanism – after the gate closure are, among other aspects, analyzed in this study. The computational simulations executed with real data from two operating months with different characteristics in terms of prices, unavailable assets – a liquidity factor for the new market – and system contingencies support the design elements developed in this study. That is, the proposed design – four sections, co-optimization of energy and reserve, and an adjustment mechanism that is not based only on the use of reserves – tested with real data confirm that this proposal is more convenient than the other kind of design from an operating cost and unavailability management perspective. The results reveal market design elements that must be considered in Colombia and serve as input for other countries – particularly Latin American countries – that are in the process of updating their electricity market designs as part of the current energy transition.

INDEX TERMS Electricity market reform, Colombian electricity market, intraday electricity market design, renewable energy penetration.

NOMENCLATURE To facilitate the understanding of the model, in the digital version of this article, the variables of a continuous nature that must comply with a positive condition – except the power flow and change in volume – are presented in red, binary variables are in green, slack variables are in blue, and the parameters of the model are in black.

A. SETS
\begin{align*}
Ω_t & \quad \text{Set of optimization periods} \\
Ω_U & \quad \text{Set of generation units} \\
Ω_{UT} & \quad \text{Set of thermal generation units} \\
Ω_{UH} & \quad \text{Set of hydraulic generation units}
\end{align*}
B. Parameters

\[ P_{r,t}^{DE} \] Energy generation offer price declared by resource \( r \) for period \( t \).

\[ P_{r,t}^{UP} \] Start-Shutdown offer price declared by resource \( r \) for period \( t \).

\[ PR_{r,t}^{up} \] Cost deviation above the reference schedule applied to resource \( r \) in the period \( t \), i.e., \( PR_{r,t}^{up} = P_{r,t}^{DE} \).

\[ CP_{r,t}^{dn} \] Cost deviation below the reference schedule applied to resource \( r \) in the period \( t \), i.e., \( CP_{r,t}^{dn} = \max \left( 0, P_{r,t}^{DE} - P_{r,t}^{DE} \right) \).

\[ PR_{r,t}^{DN} \] Offer price for allocation of secondary energy reserve to be lowered, declared by resource \( r \) for period \( t \).

\[ PR_{r,t}^{UP} \] Offer price for allocation of secondary energy reserve to be increased, declared by resource \( r \) for period \( t \).

\[ PR_{r,t}^{UP} \] Offer price for allocation of tertiary energy reserve to be increased, declared by the Economic Dispatch by resource \( r \) for period \( t \).

\[ PR_{r,t}^{DN} \] Offer price for allocation of tertiary energy reserve to be lowered, declared by resource \( r \) for period \( t \).

\[ cRac \] Rationing cost

\[ \bar{P}_{g,t} \] Effective net capacity declared by unit \( g \) at the end of period \( t \).

\[ \bar{P}_{r,t}^{UP} \] Upper limit of secondary reserve to be increased, allocated to resource \( r \) in period \( t \).

\[ \bar{P}_{r,t}^{DN} \] Upper limit of secondary reserve to be lowered, allocated to resource \( r \) in period \( t \).

\[ \bar{P}_{r,t}^{UP} \] Lower limit of secondary reserve to be increased, allocated to resource \( r \) in period \( t \).

\[ \bar{P}_{r,t}^{DN} \] Lower limit of secondary reserve to be lowered, allocated to resource \( r \) in period \( t \).

\[ \bar{P}_{r,t}^{DN} \] Upper limit of tertiary reserve to be increased, allocated to resource \( r \) in period \( t \).

\[ \bar{P}_{r,t}^{DN} \] Lower limit of tertiary reserve to be increased, allocated to resource \( r \) in period \( t \).

\[ \bar{P}_{r,t}^{DN} \] Lower limit of tertiary reserve to be lowered, allocated to resource \( r \) in period \( t \).

\[ \bar{P}_{r,t}^{DN} \] Requirements of secondary reserve to be increased in period \( t \).

\[ \bar{P}_{r,t}^{DN} \] Requirements of secondary reserve to be lowered in period \( t \).

\[ R_{r,t}^{up} \] Requirements of tertiary reserve to be increased in period \( t \).

\[ R_{r,t}^{dn} \] Requirements of tertiary reserve to be decreased in period \( t \).

\[ u_{g,0} \] Initial condition state of unit \( g \).

\[ P_{g,0} \] Power injected by unit \( g \) in the initial condition.

\[ T \] Number of optimization periods.

\[ TU_{g} \] Minimum time of firm generation of unit \( g \).

\[ TD_{g} \] Minimum time of non-firm generation of unit \( g \).

\[ TD_{R} \] Remaining time in which the unit \( g \) must remain in a firm generation state, i.e., \( TD_{R} = \max \left[ 0, (TU_{g} - TU_{g}^{0}) u_{g,0} \right] \).

\[ SF_{g,i} \] Ramping up rate of unit \( g \) in its minimum value of segment \( i \).

\[ SF_{g,i} \] Ramping down rate of unit \( g \) in its minimum value of segment \( i \).

\[ NAP_{g} \] Number of starts permitted per day of unit \( g \).

\[ NAO_{g} \] Number of starts that occurred during the day of unit \( g \).

\[ BigM \] Big number.

\[ D_{d,t} \] Forecasted demand at node \( d \) at the end of period \( t \).

\[ \gamma_{PTDF} \] PTDF associated with the generators, i.e., sensitivity factor that considers the change in flow for line \( l \), due to a variation in the injection in node \( b \), considering the topology of the system at instant \( t \).

\[ \gamma^{PTDF}_{d} \] PTDF associated with the demand nodes, i.e., sensitivity factor that considers the change in flow for line \( l \), due to a variation in withdraw in node \( b \) of the system, considering the topology of the system at instant \( t \).

\[ F_{l} \] Maximum power flow for line \( l \).

\[ \psi_{l,c} \] Matrix that maps the generation units \( g \) with respect to the system nodes.

\[ K_{l} \] Permitted maximum transfer of power through the transmission element \( l \) due to a fault in another system element.
C. VARIABLES

| Symbol | Description |
|--------|-------------|
| $u_{g,t}$ | Firm generation state of unit $g$ during period $t$ |
| $v_{g,t}$ | Entry to firm state of unit $g$ in period $t$ |
| $w_{g,t}$ | Output to firm state of unit $g$ in period $t$ |
| $V_{r,t}$ | Exit to firm state of resource $r$ in period $t$ |
| $p_{g,t}$ | Power above the programmed technical minimum of unit $g$ for the end of period $t$ |
| $\hat{p}_{g,t}$ | Total power injected by unit $g$ at the end of period $t$ |
| $\hat{P}_{r,t}$ | Total power injected by resource $r$ at the end of period $t$ |
| $f_{l,t}$ | Power flow through transmission element $l$ at the end of period $t$ |
| $r_{g,t}^{3+}$ | Allocated tertiary reserve to increase to unit $g$ at the end of period $t$ |
| $r_{g,t}^{2+}$ | Allocated secondary reserve to increase to unit $g$ at the end of period $t$ |
| $r_{g,t}^{3-}$ | Allocated tertiary reserve to decrease to unit $g$ at the end of period $t$ |
| $r_{g,t}^{2-}$ | Allocated secondary reserve to decrease to unit $g$ at the end of period $t$ |
| $P_{r,t}^{2+}$ | Power allocated to unit $g$ in period $t$ to upload secondary energy reserve |
| $P_{r,t}^{2-}$ | Power allocated to resource $r$ in period $t$ to download secondary energy reserve |
| $P_{r,t}^{3+}$ | Power allocated to resource $r$ in period $t$ to upload tertiary energy reserve |
| $P_{r,t}^{3-}$ | Power allocated to resource $r$ in period $t$ to download tertiary energy reserve |
| $\Delta_{r,t}^{up}$ | Positive deviation with respect to the reference generation schedule of resource $r$ in period $t$ |
| $\Delta_{r,t}^{dn}$ | Negative deviation with respect to the reference generation schedule of resource $r$ in period $t$ |
| $q_{l,r}^{0}$ | Amount allocated by the Day-ahead Market (DAM) for resource $r$ in period $t$ |
| $q_{l,s}^{r}$ | Amount allocated by the intraday session $s$ for resource $r$ in period $t$ |
| $Vq_{0}$ | Volume in MW of those resources that, for period $t$, changed their programmed value for the schedule of the next intraday session in relation to the scheduled dispatch (or DAM) |
| $d_{r,t}^{rac}$ | Power curtailed demand in node $b$ at the end of period $t$ |
| $A_{r,t}^{2UP}$ | Binary variable that signals the activation of the increase in the secondary energy reserve for resource $r$ in period $t$ |
| $A_{r,t}^{2DW}$ | Binary variable that signals the activation of the decrease of the secondary energy reserve for resource $r$ in period $t$ |
| $A_{r,t}^{3UP}$ | Binary variable that signals the activation of the tertiary energy reserve to be increased for resource $r$ in period $t$ |
| $A_{r,t}^{3DW}$ | Binary variable that signals the activation of the tertiary energy reserve to be decreased for resource $r$ in period $t$ |

I. INTRODUCTION

One of the principal challenges to reduce greenhouse gases in the decarbonization process of economies is the electrification of distinct economic sectors. For said reason, promoting renewable energy resources is extremely relevant as part of the energy transition, as clean generation will allow electrified sectors – particularly that of transport – to contribute significantly to the decarbonization process. In this regard, the design of an electricity market, in countries where there is a competition-oriented model, must promote the deployment of clean technologies without compromising the reliability of the electricity supply. Examples of designs that promote this integration are found in the United States and Europe [1].

The integration of renewable energy sources whose power delivery to the grid presents a stochastic characteristic implies great challenges for the operation of the system as a consequence of uncertainties caused close to real time. Markets that allow trading in moments before the real-time operation have proven to manage the uncertainty caused by these resources efficiently. This is because these markets, called intraday or real-time, incorporate a better forecast of the production of stochastic renewable resources in their processes, any unavailability caused during the intraday market operation, an update of the offers or bids-by-resource etc. This is evidenced through different international experiences. For instance, in Europe, the intraday transnational market functions under the XBID management [2], a platform that allows for continuous transactions between European countries through which the participants maintain their balanced positions. It’s a platform that has registered more than 2 million transactions according to its website. This platform complements the Day-Ahead Market (DAM) [3], [4]. Likewise, in Europe, the intraday market is complemented by an adjustment market, or balance, so that the transmission system operators guarantee the frequency of the system within established limits [5]. In the United States, there are instances within the trading day which permit agents to adjust their positions for unforeseen conditions in the DAM. These markets are known as real-time markets and, generally, are implemented through various optimization processes linked between them. That is, the output of one process provides input for the next process. This concatenation allows to commit resources not scheduled in the DAM to manage unpredictable events and renewable resources. The real-time market, as well as the DAM, are liquidated at nodal prices [6], [7].

Though the DAM and the real-time market are the two predominant energy markets in the United States, [8] proposes to establish additional intraday sessions that generate intermediary settlements between the day-ahead market and the real-time market in order to facilitate the penetration of distributed energy resources in the United States. Likewise, it is noted that the intraday market would reduce exposure to real-time price volatility. A similar recommendation is developed in [7], in which a system of multiple settlements...
is proposed – similar to those obtained in an intraday – with prices established during the trading day.

The intraday markets have also been analyzed under an academic perspective. In [9], a review of different intraday market designs in Europe, along with an extensive synthesis of academic studies, has been executed. The authors specify that the academic trend focuses on the design of bidding strategies for the intraday market. Likewise, a future line of investigation is being followed that focuses on price-prediction methods that are formed in the intraday market. Something worth noting, that is pointed out in the review, is the need to develop simulation tools of the intraday market. This point, at least for the Colombian case that is detailed in Section III, is a contribution of this paper. A particular case study of the intraday market and of special interest for this paper is found in [10]. There, the Spanish market is analyzed and is useful as the first intraday design recommendations in Colombia adopted aspects of this market. The article points out intraday benefits, though it highlights several factors that – according to the authors – have distorted the market, among them dispatch prioritization rules and renewable support schemes. These distortions could impact operation costs of the system. For said reason, for the implementation of an intraday in Colombia it considering these warnings is recommended.

Conversely, and when the intraday provides enough information, [11] proposes a mechanism for the creation and analyses of wind energy generation scenarios that allows for, along with an intraday instance, offers to be formulated to maximize generator profits. In [12], a two-stage stochastic algorithm is formulated that permits wind resources, through instances of an intraday market, to establish optimal management of deviations. The article concludes that this management is more efficient because of the existence of an intraday. In [13], the potential of the participation of solar plants in the intraday market is shown, including the possibility to provide complementary services. The impact of forecast errors of intermittent sources is another aspect analyzed in [14], in which the relationship between the errors and the intraday market price are presented. This study highlights the relationship derived between the size of the renewable resource – in terms of energy – and the price established in the intraday.

Three papers are worth mentioning from an academic perspective for this paper. In [15] a trading market simulator is presented so that market participants can simulate different strategies to assess the expected cash flow for different electricity markets. The article simulates four European electricity markets – Bilateral market, day-ahead market, intraday market, and balancing markets –. The steps to perform market trading simulations are a useful high-level overview for this paper. An uncertainty predictive control model for residential buildings to participate in intraday markets is in [16]. The paper shows how residential buildings can actively participate in an intraday market so that – and aligned with the interest of this paper – future aggregators might be able to execute market commitment even though residential buildings are often inflexible-price demands. An investigation on the impacts of low probability and high-intensity events on wind power generators’ market participation is in [17]. The paper considers the existence of an intraday market so that the profitability of wind-generation power plants is assessed under extreme events that might occur in Colombia, as most of these types of generation are in the influence zone of the hurricane season.

On the other hand, and relating to the design aspects, although they are not applied to the Colombian context, the following papers provide quantitative evidence of useful attributes for the designs developed in this paper. One of the first articles to mention the advantages of co-optimization is [18], in which the advantages of including complementary services – ancillary services – in the optimization process along with energy are shown numerically. In [19], different implementations of market models are reviewed and analyzed, and, for the purpose of this paper, a description of the sequential and co-optimized allocation is made, and those markets – which at the date of the publication of the article – that use each one of these allocation schemes. In North American markets, a preference to a co-optimized allocation emerges, whereas [20], [21], suggest a sequential allocation in European markets. In [22] due to the strong dependence between reserves and energy, a process of co-optimized allocation is recommended over a sequential one, as the latter is generally implemented via rules of thumb that entail a loss of wellbeing. In [23], an interdependence between energy and reserve are analyzed for different massive penetration scenarios of intermittent resources, in one case inspired by the system in Central-western Europe. The authors find an increase in the differential cost between a co-optimized allocation and a sequential one when there is a greater penetration of renewables, the sequential allocation being more costly. For the sake of this paper, this conclusion is useful, as the Colombian electricity market is expected to experience a significant penetration of intermittent resources.

Considering the intraday market designs, in [24], several relevant aspects are significant for this paper. The first one corresponds to the need to establish discrete intraday sections, stressing the fact that the frequency of these are a “driver”, based on the need to trade in specific moments. The study also underscores that, “The key question is not if auctions need to be introduced, but rather when to introduce them and how many are needed.” This clearly indicates the importance of discrete intraday sessions. In the same line of thought, [25] indicates the benefits of having discrete intraday sections for reasons of liquidity, depth, and the reduction of the volatility of the price. The two aforementioned references lead to the conclusion that the benefits of an intraday market with discrete sessions are not under discussion; on the contrary, determining, according to the particularities of each market, how many and at what moment these sessions are needed. These are areas that will be developed in this paper.

In a more specific context, Colombia is familiar with promoting renewable resources due to the success of two long-term contracting auctions for these kinds of technologies,
which will increase the participation of these resources by approximately 30% of the country’s installed capacity by 2034 [26]. This increase implies several challenges, one of which is to reform the current design of the market that facilitates the integration. The reform – motivated by elements described in Section II – entails the creation of an intraday market that facilitates the management of a considerable volume of intermittent energy. And though the reforms are described in [27], [28], [29], and [30], these lack quantitative evidence to determine which is the intraday design that best adjusts to the conditions of the country. For instance, the number of sessions and allocation mechanism – co-optimized or sequential – are recommended based on international experiences, which are useful, but not backed by quantitative support. For said reason, this paper shows a computational analysis tool developed to determine the principal design elements that the intraday market should consider for Colombia’s circumstances. The number of intraday sessions, the effect of a co-optimized allocation of energy and reserve, the energy and reserve volumes programmed in each section of the intraday, the effect of offer changes, among other factors, are analyzed in this paper. Though other important design aspects exist, it is essential to define these first elements as they constitute the foundational aspects of the market.

Note that the above state-of-the-art review is divided into three sections. The first is conformed of academic papers showing how market participants can establish their participation strategies based on an intraday market design. The second section focuses on quantitative aspects of an intraday market design; however, they are applied in contexts different from Colombia. Finally, a third section is conformed of those articles and government analyses that propose intraday market design elements in Colombia based on qualitative aspects. Of the three sections, note that, for Colombia’s case, no article exists that proposes foundational elements developed from quantitative elements. That is, this article fills the gap of not having a market design backed up by quantitative analysis. Though the importance of this paper focuses on Colombia, it also serves as a reference for other countries, in particular in Latin America, that are in the process of reforming their electricity market – as part of the energy transition – and that face a considerable penetration of stochastic renewable resources [31]. While the market design adjusts to technological aspects specific to each country, these kinds of studies make it possible to incorporate good practice elements.

Finally, this article is organized as follows: Section II describes the principal aspects – along with the necessity to facilitate the integration of renewables – that motivate market reform and the creation of an intraday market in Colombia. Section III describes the platform and mathematical model with which the DAM and intraday market are simulated to establish the principal design aspects of that market. Section IV shows the main numerical results with which the proposal of the design for Colombia is based. Conclusions and their applicability to other contexts are detailed in Section V.

II. DESIGN CHANGE OPPORTUNITIES OF THE COLOMBIAN ELECTRICITY MARKET

One of the main flaws of the current Colombian electricity market design is the impossibility of changing positions – changes in the offers of energy or reserve – of a participant during the operating day. Participant, as understood in this paper, is a market agent – generator or aggregator – with the capacity to formulate an energy and/or reserve offer and, for now, in Colombia, these are mainly focused on generation resources. This impossibility implies that the positions of the participants based on new information that originates after the gate closure of the DAM cannot be balanced. Although the current design considers changes in the generation schedule, they don’t originate as a consequence of new offers; on the contrary, they are produced when a set of previous established causes – for instance, a system component failure or unexpected maintenance [32] – occurs. This process of changing the generation program is known, in the country, as redispetch. Another shortcoming that justifies the presence of an intraday market corresponds to the fact that the forecasts of the production of intermittent renewable resources of the current design will have to be made – for some operating periods – with a temporal horizon of more than 24 hours. This is because the gate closure of the DAM in the Colombian market is established at 8:00 am of the previous day. These time horizons are considerable for these kinds of resources, as there are significant forecasting errors expected, affecting the cost of operating the system, principally due to an intense use of the reserves.

The existence of an intraday market allows for the incorporation of forecasts of production of stochastic resources close to the real-time operation with a reduction in the use of the system’s reserves. Likewise, an intraday market allows agents to balance their positions based on a better forecast of production with which they can assume the excesses or deficits of their resources in a market instance.

Another element of the current design of the Colombian electricity market is that it doesn’t have price signals in real time due to the fact that these are calculated ex-post. For said reason, the participants do not have timely information to formulate new offers or bids, in other words, balance their positions. This aspect can be rectified as long as the intraday market provides precise signals, preferably binding signals.

Other elements unique to Colombia that might be rectified in an intraday market, with respect to the current market design, are the following:

1. It would allow for the better management of possible floodwater in the reservoirs in that, confronting this situation, a generation agent can make the decision to change their position – substantially lowering their offer – in such a way that a new generation schedule permits the increase of its production, and, thereby, avoid discharges of water. This aspect is not a small matter in a country where 70% of electrical generation is hydraulic.
2. It would allow for a more adequate management of the declared availability of resources by plants smaller than 20 MW. The current market design requires that plants with a capacity inferior to 20 MW declare their available capacity for the following operating day, without an offer. Nevertheless, the declared capacity is a forecasting exercise since many of them are riverrun generators that must make forecasts with periods greater than 24 hours. The intraday will allow these forecasts to be made closer to the operation in real time, achieving fewer deviations and, with that, less use of reserves, resulting in lower operating costs.

3. An intraday market would allow for the implementation of new energy and reserve allocation schemes. The current design presents an energy and reserve sequence allocation scheme, one that is equally applied in other markets [5]. However, the intraday would allow for the establishment of a new, co-optimized allocation scheme between energy and reserve, resulting in lower operating costs, as evidenced in Section IV.

4. It would establish binding dispatches – that are not present today – so that the deviations of the commitments acquired by the DAM are assumed by the causative agent and not assumed – pro rata – by the demand.

5. It would establish new business opportunities and, in turn, the emergence of new market agents that other markets have experienced [33].

Improvement opportunities described in this section constitute the main aspects that currently drive the creation of an intraday market in Colombia. Some of these have been described in diverse studies from [27], [28], [29], and [30] and in the energy transformation study led by Colombia’s Ministry of Energy and Mines [33]. These studies are descriptive in their recommendations, but the numerical evidence that stipulates the best way to implement reforms is scarce. Based on these needs, this article has determined, through a detailed modelling of the Colombian market, the principal elements of the design of the intraday for Colombia.

III. ANALYSIS TOOLS

A. INITIAL CONSIDERATIONS

The intraday market is a market that occurs after the gate closure of the DAM and the real-time operation. It allows participants to formulate new energy and reserve offers and bids to adjust, or balance, their positions, taking into consideration new information that arises after the gate closure of the DAM. Although the intraday market implies defining various aspects – whether it is continuous or discrete in nature, detection and mitigation schemes of possible market power, etc. – this article analyzes the foundational aspects to be considered that are most relevant for the design, among them, the number of discrete sessions, the energy and reserve allocation scheme, and the adjustment mechanism or balance. These factors are analyzed from an economic and operational perspective. This last aspect is of particular importance for the system and market operator because with it, it is possible to determine the technological requirements that must be met to withstand the implementation of this market.

From an operational perspective, the changes in MW of the operating programs are determined. These changes are calculated as the difference between the program established by the DAM and the one established by each intraday section, details in section IV. The operator must manage the magnitude of these changes – or volumes in terms of MW – either manually or through an automatic control of the generation resources. The magnitude of the volume allows to determine the technological requirements, and though this paper does not go into depth in sizing, the results of the analysis reported here are being run to revise the current technological capacity of the operator.

For numerical analysis purposes and design conclusions, the following subsection describes the analysis platform developed along with the mathematical model with which the short-term energy market is simulated. It is worth noting that these analyses incorporate the greatest quantity of the Colombian system for which the results reflect, with a high degree of certainty, the possible impacts of the implementation of an intraday market.

B. DESCRIPTION OF THE ANALYSIS PLATFORM

Fig. 1 shows the flowchart implemented by the intraday market analysis platform. The leftmost part simulates the DAM taking agent offers and bids, the transmission network parameters of generation resources, and electrical restrictions, among other aspects, as input. This input is taken directly from the system and market operator (XM in Spanish) transactional tools in order to perform computational exercises with real values.

The results of this first stage correspond to a generation program that allocates energy and reserves through the optimization model described in Section C of Numeral III. Subsequently, the intraday market simulates each one of the sessions. The allocation model described in Section III.C is performed for each session, taking new data from the system operation as input, including the inflexibility of resources scheduled in the DAM or a previous intraday session, new demand forecasts, etc. Likewise, and if the case study considers it, the changes of position – new offers – are incorporated by the market participants. Each session delivers a new energy and reserve allocation program with which several variables of interest can be calculated for this paper that are described in the numerical analysis. Note that the flowchart describes a sequential process of discrete intraday sessions, as it is the expected path for the implementation of this market in Colombia.

Finally, this analysis platform is notable because it is constructed modularly, in such a way that new design elements can be incorporated as needed in the future.
C. ALLOCATION MODEL

The allocation model is a security constrained unit commitment that includes, among other aspects, the following noteworthy elements:

1. Restrictions associated with the technical characteristics of hydraulic and thermal generation resources. These restrictions include – for thermal generation – startup/shutdown time, ramping up/down rates, minimum up/down time, minimum generation levels, etc.

2. Restrictions associated with a set of contingencies to guarantee the system operates within security limits.

Fig. 2 conceptually shows the model developed for the purposes of computational simulations. This model is used to execute the DAM and intraday sessions indicated in Fig. 1 and is close to the one implemented in the operation of the system and electricity market in Colombia. Because of this, the conclusions that are drawn from this model reflect real conditions.

To analyze case studies that will be detailed in the section IV, four objective functions are presented. The first of them, equation (1), shows an objective function with which the co-optimized allocation of energy and reserve for the DAM and any intraday session is calculated. Equations (2) and (3), on the other hand, correspond to objective functions of a sequential allocation process in which first the reserve is allocated and after, the energy, a situation that corresponds to the current design of the Colombian market. Equation (4) corresponds to the objective function that minimizes differences between intraday session schedules, which is used to balance the system in scenarios after the gate closure of an intraday session. The usage details of these different objective functions are shown in the numerical results section. It is important to clarify that the allocation model only uses one of the four objective functions depending on the case study.

To facilitate the understanding of the model, in the digital version of this article, the variables of a continuous nature that must comply with a positive condition – except flow – are presented in red, binary variables are in green, slack variables are in blue, and the parameters of the model are in black.

\[
\min FO = \sum_{t \in T} \sum_{r \in R} \left( P_{DE}^{r,t} P_{r,t} + PR_{UP}^{r,t} P_{r,t}^{2+} + PR_{DN}^{r,t} P_{r,t}^{2-} + PR_{3UP}^{r,t} P_{r,t}^{3+} + PR_{3DN}^{r,t} P_{r,t}^{3-} \right)
\]  

\[
\min FO = \sum_{t \in T} \sum_{r \in R} \left( P_{DE}^{r,t} P_{r,t} + PR_{UP}^{r,t} P_{r,t}^{2+} + PR_{DN}^{r,t} P_{r,t}^{2-} + PR_{3UP}^{r,t} P_{r,t}^{3+} + PR_{3DN}^{r,t} P_{r,t}^{3-} \right)
\]  

\[
\min FO = \sum_{t \in T} \sum_{r \in R} \left( P_{DE}^{r,t} P_{r,t}^{+} + PR_{UP}^{r,t} P_{r,t}^{2+} + PR_{DN}^{r,t} P_{r,t}^{2-} + PR_{3UP}^{r,t} P_{r,t}^{3+} + PR_{3DN}^{r,t} P_{r,t}^{3-} \right)
\]  

\[
\min FO = \sum_{t \in T} \sum_{r \in R} \left( P_{DE}^{r,t} P_{r,t}^{+} + PR_{UP}^{r,t} P_{r,t}^{2+} + PR_{DN}^{r,t} P_{r,t}^{2-} + PR_{3UP}^{r,t} P_{r,t}^{3+} + PR_{3DN}^{r,t} P_{r,t}^{3-} \right)
\]
Once the thermal units are turned on, and to preserve their integrity, they must remain for a minimum production time, defined as minimum generation time. Likewise, once turned off, they must remain a minimum time out of generation, defined as time offline. Equations (8)-(11) guarantee that both times are met for the thermal units.

\[
\sum_{t=1}^{T} u_{g,t}^r \geq T U_{g,T}^r \quad \forall g \in \Omega_U,
\]
\[
\forall t \in \Omega_t | T U_{g,T}^r + 1 \leq t \leq T - T U_{g,T}^r + 1
\]

(8)

\[
\sum_{t=1}^{T} (1 - u_{g,t}^r) \geq 0 \quad \forall g \in \Omega_U
\]
\[
\forall t \in \Omega_t | T - T D_g + 2 \leq t \leq T
\]

(9)

Equation (18) restricts the changes based on the initial value of the power at the beginning of the programming period.

\[
-S F_{g,t}^{dn} \leq P_{g,t+1} - P_{g,t} \leq S F_{g,t}^{up} \quad \forall g \in \Omega_U,
\]
\[
\forall t \in \Omega_t | t < t_f
\]

(17)

\[
-S F_{g,t}^{dn} \leq P_{g,t_0} - P_{g,t} \leq S F_{g,t}^{up} \quad \forall g \in \Omega_U
\]

(18)

Equation (19) relates the power of a generation resource with the units that it is made of. This value is relevant as the response of the allocation model in Colombia’s case is by resource, for which, independent of the value at which the units are dispatched, the reference value on which the analyses are executed in this paper is based on the result indicated by (19). Equation (20) shows that a resource is on if at least one unit of the resource is turned on.

\[
\hat{P}_{r,t} = \sum_{g \in r} \hat{P}_{g,t} \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(19)

\[
\sum_{g \in r} (v_{g,t}^r) \leq \text{BigMV}_{r,t} \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(20)

The secondary reserve requirements for the system in each period is specified in (21) and (22), and the distribution of the allocation of this kind of reserve in each one of the resources is defined in (23) and (24). The allocation of the secondary reserve is limited by (25) and (26).

\[
\sum_{r \in \Omega_r} p_{g,r,t}^{2+} = R_{g,t}^{2up} \quad \forall t \in \Omega_t
\]

(21)

\[
\sum_{r \in \Omega_r} p_{g,r,t}^{2-} = R_{g,t}^{2dn} \quad \forall t \in \Omega_t
\]

(22)

\[
\hat{P}_{g,t}^r = \sum_{g \in r} r_{g,r}^2 \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(23)

\[
\hat{P}_{g,t}^r = \sum_{g \in r} r_{g,r}^2 \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(24)

\[
-P_{g,t}^{2+,A_{r,t}} \leq P_{g,t}^{2+,A_{r,t}} \leq P_{g,t}^{2+,A_{r,t}} \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(25)

\[
-P_{g,t}^{2-,A_{r,t}} \leq P_{g,t}^{2-,A_{r,t}} \leq P_{g,t}^{2-,A_{r,t}} \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(26)

The tertiary reserve requirements for the system in each period is specified in (27) and (28), and the distribution of the allocation of this kind of reserve in each one of the resources is defined in (29) and (30). The allocation of the tertiary reserve is limited by (31) and (32).

\[
\sum_{r \in \Omega_r} p_{g,r,t}^{3+} = R_{g,t}^{3up} \quad \forall t \in \Omega_t
\]

(27)

\[
\sum_{r \in \Omega_r} p_{g,r,t}^{3-} = R_{g,t}^{3dn} \quad \forall t \in \Omega_t
\]

(28)

\[
-R_{g,t}^{3+,A_{r,t}} \leq P_{g,t}^{3+,A_{r,t}} \leq R_{g,t}^{3+,A_{r,t}} \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(29)

\[
-P_{g,t}^{3-,A_{r,t}} \leq P_{g,t}^{3-,A_{r,t}} \leq P_{g,t}^{3-,A_{r,t}} \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(30)

\[
-P_{g,t}^{3+,A_{r,t}} \leq P_{g,t}^{3+,A_{r,t}} \leq P_{g,t}^{3+,A_{r,t}} \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(31)

\[
-P_{g,t}^{3-,A_{r,t}} \leq P_{g,t}^{3-,A_{r,t}} \leq P_{g,t}^{3-,A_{r,t}} \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(32)

Equation (33) represents the global balance of the system in which the rationing variable is included, that,

\[
\sum_{t=1}^{T} v_{g,t}^r \leq \text{BigMV}_{r,t} \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(33)

\[
\sum_{t=1}^{T} v_{g,t}^r \leq \text{BigMV}_{r,t} \quad \forall r \in \Omega_r; \forall t \in \Omega_t
\]

(33)
when activated, guarantees the convergence of the model. Equation (34) limits the quantity of rationing per system node.

\[
\sum_{g \in \Omega_G} \hat{p}_{g,t} = \sum_{d \in \Omega_D} (D_{d,t} - d_{d,t}^{rac}) \quad \forall t \in \Omega_t
\]

\[
d_{d,t}^{rac} \leq D_{d,t} \quad \forall t \in \Omega_t
\]

Finally, the model of the transmission network is a DC model represented by the PTDF – denoted as \(\Gamma_{l,b,t}^{PTDF}\) and \(\Gamma_{l,d,t}^{PTDF}\). Equation (35) establishes the flows for different contingencies to execute a security constrained unit commitment optimal is established in (37) using the LODF – denoted as \(\phi_{l,c}\).

\[
f_{l,t} = \sum_{b \in \Omega_b} \Gamma_{l,b,t}^{PTDF} \Gamma_{k,b}^{PTDF} \hat{p}_{g,t} - \sum_{d \in \Omega_D} \Gamma_{l,d,t}^{PTDF} (D_{d,t} - d_{d,t}^{rac}) \quad \forall l \in \Omega_L; \forall t \in \Omega_t
\]

\[
\hat{f}_{l,t} \leq f_{l,t} \leq \hat{F}_{l} \quad \forall l \in \Omega_L; \forall t \in \Omega_t
\]

\[
-K_{l} \leq \hat{f}_{l,t} + \sum_{c \in \Omega_L} \psi_{l,c} \hat{f}_{c,t} \leq K_{l} \quad \forall l \in \Omega_L; \forall t \in \Omega_t
\]

Note that the previous problem is mixed integer linear programming that guarantees the feasibility of adding the slack variable \(d_{d,t}^{rac}\) in the objective function and in the constraints (33)-(35). This variable is penalized with a high value – denoted as \(cRac\) – and that activates – when its value is different from zero – in extreme cases to specify the demand quantity that cannot be met but will guarantee the feasibility of the model. The value of \(cRac\) must be greater than the highest energy and reserve offer formulated by any agent. And for computational effects, the model was implemented in GAMS, solved with CPLEX, with a stop criterion of a gap of 0, which guarantees the optimality [34].

Finally, an important factor that should be avoided in the process of co-optimization are multiple solutions that can arise when two or more resources formulate energy and reserve offers of an equal value. From the optimization point of view, this means that given the same input values, the results of the allocation model could be different for each execution. For the market, this situation is not admissible because two or more resources with equal economic conditions would have different allocations leading to different incomes in each execution of the model. From an operational point of view, it is also not admissible, because it introduces high volatility in the operating programs. Although the problem of multiple solutions can be resolved in many ways, for purposes of this study, a tie-breaking process was implemented, described in the appendix to this article, which worked successfully in all reported computational tests of this paper. In fact, the solution was recommended to the market designer in Colombia for implementation purposes.

### IV. COMPUTATIONAL RESULTS

The numerical results presented in this section that quantitatively establish the principal design aspects of the intraday market in Colombia are developed in four parts. The first, Section IV.A, determines the number of discrete intraday sections based on an analysis of unavailability due to the fact that these will be one of the liquidity drivers of this new market. That is, having binding commitments in the DAM, the agents must adjust their commitments in the intraday sessions in case one of their generation assets has technical difficulties – becomes unavailable – and with which they cannot honor their binding commitment. In this case, the unavailability becomes one reason to resort to the intraday section, giving liquidity to this market. The second part, Section IV.B, determines that the co-optimized allocation scheme is more efficient, in regards to costs, than the sequential allocation scheme, which is currently in use. The analysis determines the allocation costs as well as establishes the quantity of MW that move because of each of these allocation schemes.

Movements of MW is understood as the difference between the generation program established by the DAM and the one established by an intraday section. These variables are of importance for the system operator because, with them, the operator can establish technological requirements that are necessary for the efficient management of these movements. The third part, section IV.C, carries out an additional analysis of the sensitivity of movement of the MW, but with a change in offer of the extra-marginal resource. The usefulness of these section is that it provides an expected value in the changes of the MW based on a change in the position of an agent, which, and together with the results of section IV.B, allows for determining the technological requirements. The last part of the numerical analysis, section IV.D, establishes if an adjustment mechanism after the closing of the gate of an intraday section, and implemented through various optimization processes, is more efficient, in terms of costs, than the use of reserves.
A. Determining the Number of Intraday Sections

The first analyzed factor is the number of discrete intraday sessions that should be implemented in the intraday market. In [30], the authors propose that this market be implemented with two intraday sessions to familiarize the participants with the new design. Though the idea is plausible, the findings below indicate it is possible to begin with four sessions.

Fig. 3 exemplifies the existing uncertainty between the DAM gate closure and the intraday sections gate closure with the operation in real time. The further from the gate closure of both markets, the greater the uncertainty – the vertical axis – the operator must manage. That is, the existence of a gap implies that the operator must have the tools to manage any event after the gate closure. These tools are generally reserves or a mechanism – or even a market – of adjustment or, called in some markets, a balance mechanism. Fig. 4 shows the size of the gap of Fig. 3, measured by the number of hours that elapse between the gate closure and the beginning of each of the programs established by the intraday, assuming this type of market is implemented with four or two sessions.

The execution period is the one the operator takes to run the unit commitment with the respective electrical analysis and the gate closures are the ones that might be possible in Colombia with the current technological capability. Fig. 4 is an infographic of the time distribution of four and two discrete intraday sessions with the purpose of specifying the number of hours over which the balance mechanism acts.

Observe that the four-session intraday market manages less uncertainty than the two-session market. To clarify, the gate closure of sessions 2 and 3 at periods 1 and 7 of the four-sessions intraday market capture more information or observed values of the random variables (uncertainty) that are not possible in a two-session intraday market. In terms if Fig. 3, the gap between the intraday market gate closure and real-time is always shorter in a four-session market than two-session.

To confirm the advantages of the four-session intraday, the number of events managed by an intraday market of two and four sessions are analyzed. By managed event, it is understood that the unavailability of a resource or network element enters as a restriction of the model described in Section III.C because it took place before the gate closure of the respective session. Fig. 5 shows the percentage of events that the intraday market of four and two intraday sessions would not manage. This figure is constructed with 2,267 registered unavailability requests during an operating year and the number of those events that happen before each one of the gate closures is counted – illustrated in Fig. 4 – for each intraday session. These unavailability requests are incorporated as restrictions to the allocation model of the corresponding section. That is, each generation unavailability that happens in the system implies that the agent must resort to an intraday session to adjust their position to comply with the binding commitment acquired in the DAM. Note that Fig. 3 and Fig. 4 correspond to a conceptualization that is required for the construction of Fig. 5.

Note that in Fig. 5, for a two-session scenario, between 36% and 90% of the requests would not be managed for an intraday market session, as illustrated by the red line, as these are generated after the gate closure. On the other hand, the blue line shows that for a scenario of a four-sessioin intraday, the events the intraday session cannot manage fall between a range of 36% and 64%, a decrease compared to the two-sessioin case. Nevertheless, these percentages imply that a number of unavailability requests must be taken on by a mechanism after the gate closure of distinct sessions of the intraday market, as is detailed in section IV.D.
B. ANALYSIS OF THE EFFECTS OF A CO-OPTIMIZED ALLOCATION AND SEQUENTIAL ALLOCATION

Another important factor of the design is determining if a co-optimization is more efficient in terms of allocation costs than the current sequential practice. This section compares co-optimization and sequential allocation costs. It also calculates the changes in energy and reserve between the operating program defined in the DAM and an intraday session. These MW changes are relevant for the system operator as input to define the technological requirements to run the system under the new market design. Historical data were taken from two operating months for analysis purposes. The first month presented an average number of generation unavailability and energy market prices; it is, therefore, a representative month. The second month exhibited high generation unavailability and high market prices. It was a month that the system and the market were under stress. The analyses conducted in two months with distinct characteristics permit a broader study.

For the purpose of this section, the change of volume is defined as the sum of the changes in the generation schedule or reserve schedule of all the generation resources – changes that are established with respect to the DAM schedule for each period as indicated in (38). Note that this variable determines the variation in terms of power of these resources that do not formulate a new offer in the intraday and whose utility comes from measuring only the allocation changes due to effects not attributable to a change in position.

\[ V_{q,t}^{up} = \sum_{r \in \Omega} (q_{t,r}^i - q_{t,r}^0) \quad \forall t \in \Omega_t; \quad \forall s \in \Omega_S \]  

(38)

1) RESULTS MONTH 1

Fig. 6 shows the change in volume for each period (horizontal axis) made by each intraday session. Consider, for instance, the blue bar of the first period (p01). The height of this bar indicates that a co-optimized allocation process of the first intraday session changes the generation schedule around 300 MW in relation to the DAM. In other words, as a result of the unavailability and topological changes that are recorded before the close of the first session – that occurs for simulation effects at 19 o’clock (7:00 pm) the previous day according to Fig. 4 – the effect of the allocation of energy and reserve through a co-optimized mechanism change, for Period 1 of the entire month being studied, a total of 300 MW. Observe period 07 where two bars are shown. The blue-colored bar demonstrates that the first intraday session – for purposes of the co-optimization – moves close to 300 MW, and the orange bar moves close to 500 MW for this period. The difference in height between the two bars is because of the gate closure of the second session, that occurs at 1:00 am in the operating day, captures a greater quantity of outages and generation unavailability in than the first session.

From Fig. 6 two factors can be concluded: 1) A increase in the size of the bars for those sessions whose gate closures are further from the beginning of the trading day is evidenced, with an increase in the last intraday sessions and 2) Changes above 1500 MW occur in periods of great demand in the country (p19 and p20) only because of the effect of the program changes performed for each intraday session. These changes represent close to 15% of the power demand for which the operator must rely on technology that allows them to efficiently manage at least the magnitude of these changes that occur because of unavailability or outages.

Fig. 7 compares the average volume per period of a sequential allocation with a co-optimized allocation. The sequential allocation corresponds to the model of Section III.C with the objective functions (2) and (3), whereas the co-optimized allocation employs the objective function (1). Each boxplot is constructed with the average volume per period displaced for one allocation scheme regardless of the intraday session, considering only the unavailability and outages for the month of study. An interesting aspect of this figure is that the co-optimized allocation moves a similar quantity of MW compared with the sequential allocation. However, numerical results show that the average production cost is lower by 1.5% for a co-optimization allocation compared with the sequential one.

Another important factor that is analyzed regarding the effect of co-optimization is the reallocation of the reserve of each session compared the allocation established in the DAM. That is, in each intraday session, the model reallocates – if such is the case – the secondary or tertiary reserve for the system. Fig. 8 shows the secondary reserve changes in MW to increase – positive values – or decrease – negative values – as a consequence of the co-optimization. By contrast with a co-optimized allocation, the sequential allocation does not make changes to the reserve allocation since the current design prioritizes the reserve allocation to the most economical resources, so unless a resource is declared unavailable, there should be no changes in the allocation of a sequential allocation.

2) RESULTS MONTH 2

Fig. 9 shows the effects of the co-optimization for the second test month in which price and availability conditions above historical averages were presented. Unlike the first simulation month, a greater quantity of volume changes and in a different pattern, as indicated in Fig. 6, are reported as a consequence of unavailability. For instance, observe how the second intraday session for month 2 moves a different quantity of MW than in month 1 because of a different behavior of unavailability. And though the patterns of the changes of volume are different between both months, it is significant that in Fig. 6 and Fig. 9 the magnitude of changes does not exceed 2500 MW. That is, when facing unavailability conditions, only changes of volume around this value are expected. This value, then, becomes a reference point from which the operator establishes technological requirements that must be available to adequately manage these magnitudes.

On the other hand, Fig. 10, shows the boxplot that compares the changes of volume as a consequence of a sequential allocation scheme with a co-optimized one and the second test month. It is noteworthy that the co-optimized allocation...
scheme moves a slightly smaller quantity of volume with respect to the sequential one. This aspect confirms, from an operational point-of-view, the convenience of this allocation scheme. In fact, the average production cost as a result of a co-optimized allocation is less than 1.3% compared with a sequential one, which favors this design proposal.

With regard to the change of the secondary reserve allocation to be increased and lowered because of the effect of co-optimization, Fig. 11 shows results indicating a different pattern as compared to Fig. 8; however, these changes have similar orders of magnitude for which – independent of the behavior of unavailability – changes of this order of magnitude can be expected if there are no changes in the generator’s offers.

3) CO-OPTIMIZATION CONCLUSIONS
Based on the results of the two simulation months, the following aspects can be concluded:

1. The co-optimization option has lower production costs than sequential allocation, i.e., around 1.5% less in the first month and 1.3% in the second month.
2. The co-optimized option displaces a lower quantity of MW than the sequential one for energy allocation for the second month and a similar quantity for the first month.
3. The co-optimized option displaces a greater quantity of MW than the sequential one for reserve allocation. This is expected because the current market design prioritizes reserve allocation over energy allocation.

Finally, note that the third conclusion is not necessarily desirable, but the first two compensate for this circumstance. Therefore, it is preferable to have a co-optimized allocation of energy and reserves for the new market design.

C. ANALYSIS OF THE EFFECT OF A CHANGE IN POSITION OF AN EXTRA-MARGINAL RESOURCE
In this section, the effect of a change in the position of the agents – a predictable situation – with respect to the schedule established by the DAM is analyzed. As it is not possible to determine how the offer of the agents will be to allow for adjustments in their changes of position under this new market scenario, a scenario in which the first extra-marginal generator decreases the offer by 10% for the following intraday session is simulated. This situation could be realistic due to the fact that the generation resources that were not scheduled in the DAM or in an intraday session, as a strategy, could lower their offer, to be scheduled in the next session in case they have commitments through contracts.

Fig. 12 shows the changes in volume as a result of a change in the offer for the different sessions and for distinct periods. These changes correspond to a co-optimized allocation, as indicated in the previous section, this is a more efficient allocation than a sequential one. Important changes are noted when this result is compared with those shown in Fig. 6 and
Fig. 9, for which it is expected that changes of the position of the agents will change the DAM schedule, substantially. From the operator’s point of view, this implies having access to technology to manage these movements that are introduced by intraday sessions efficiently and – in comparison to the DAM – close to 30% of the maximum power demand of the system with only one resource to change the offer. This implies that a movement in MW can be expected between the values of 10% – only for effects of unavailability and outages, results of section IV. A – or 30%, only if the extra-marginal resource lowers its offer.

**D. ANALYSIS OF ADJUSTMENT MECHANISM**

As is indicated in Fig. 3, events after the gate closure must be managed by the operator through an adjustment mechanism – denominated balance in some markets – or through the use of a reserve. With the purpose of establishing which is the most convenient option to be implemented along with the intraday market in Colombia, both options are analyzed from the point of view of operating costs. The adjustment mechanism corresponds to the energy and reserve allocation model described in Section III with the objective function indicated by (4). That is, the mechanism is that which, in the event of an unavailability after the gate closure, establishes the minimum deviation from the current generation schedule, the one established by the latest intraday session, complying with the restrictions indicated by the session III model. The result of the mechanism is the allocation of deviations with which the unavailability is covered. The other option is to activate the use of the reserve.
With available data in Session IV.C, the costs of the operation of the adjustment mechanism are compared to those that imply the operation of the system with three possible corresponding tertiary reserve values of 500 MW, 1000 MW, and 1500 MW. The computational results show that the system costs increase 7%, 15%, and 26%, respectively, for the three tertiary reserve values. In other words, from an economic point of view, it is more efficient to operate the system after the gate closure with an adjustment mechanism through an optimization model than rely on a reserve with which unforeseen events must be managed after the close of the intraday.

V. CONCLUSION

This paper determines design elements supported by quantitative analyses that must be the foundational elements of the new intraday market in Colombia for its correct implementation as part of the energy transition. A market motivated primarily to facilitate the diversification of the electricity generation matrix that will have a penetration of non-conventional, i.e. intermittent resources (solar and wind), of at least 30% by 2034.

Based on unavailability analyses, this study demonstrates that four discrete intraday sessions are advised for Colombia, as opposed to two sessions that have been suggested in other studies. Unavailability is expected to be a significant liquidity factor for the market because the day-ahead market will establish binding commitments; hence, any unavailability needs to be offset in an intraday section. Similarly, based on historical unavailability and energy price data from two months with distinct characteristics, this paper shows that a co-optimized energy and reserve allocation scheme is more efficient in terms of allocation costs and changes in MW compared to the current sequential practice. Changes in MW is especially important for the operator, as it specifies the MW that the operator must be capable of managing only as a consequence of unavailability of generation or network elements. The same exercise of changes in terms of MW was executed when the extra-marginal resource modified its offer. Numerical results show that significant variations in the generation schedules can be expected because of this modification. Regardless of the reasons that cause changes in generation schedules of each intraday session – because of unavailability or participant offers – the scale that is determined in this study is very useful for the operator to determine technological requirements needed to implement this new market.

This article also establishes that the management of events that occur after the gate closure be made through an adjustment mechanism, based on an allocation of minimum deviations, as opposed to recommendations that indicate events after gate closure be managed with the use of the reserve. The recommendation is established based on operating costs involved in the implementation of both alternatives in which the adjustment mechanism is the most economical option.

Finally, this kind of analysis constructs a reference for countries – in particular Latin American countries – that are in the process of a massive penetration of intermittent renewable resources, as the article provides not only mathematical models of allocation which are generally not easy to access in these countries, but also shows the type of analysis that leads to determining the foundational elements of an intraday market that most likely will be part of the ongoing energy transition.

APPENDIX

MECHANISM TO AVOID MULTIPLE SOLUTIONS

The development of this annex came from the possibility that the mixed integer-linear model presented in section III.C might present multiple solutions for the causes described below. Multiple solutions do not come from a nonlinearity, as these are not present in this model and are, instead, a result of the offers for reserve and energy.

Having strategies to avoid multiple solutions is a common practice in the ISOs, to ensure that the energy and reserve allocation is optimal and reproducible in any execution of the model. Thus, this section initially describes the reason for which multiple solutions originate in the process of a co-optimized allocation process and the guidelines to avoid this situation, which is not desirable, as stated in the last paragraph of Section III.C. Without loss of generality, the demonstration is executed for one period – denoted as \( t_i \) – and the analysis of the effect of the tertiary reserve is ignored since, if it is included, the rules can be easily extended to consider the effect of this reserve.

Consider that the effective capacity of a resource for the instant \( t_i \) – denoted as \( Q_{r,t_i} \) – can be disaggregated as \( Q_{r,t_i} = \hat{P}_{r,t_i} + P_{r,t_i}^2 + Q_{r,t_i}^{ND} \), where \( \hat{P}_{r,t_i} \) and \( P_{r,t_i}^2 \) are defined in the variables of the model of Section III.C and \( Q_{r,t_i}^{ND} \) is the non-programmed capacity of the resource. Fig. 13 shows, graphically, how the effective net capacity of a resource is
distributed for a period of time. Note that the allocation of energy obtains – if such is the case – the secondary reserve \( P^{r+}_{r,t} \) for which this component is not included in an explicit manner in the allocation equation of the resource. The delta variable \( \Delta_{r,t} \) is the difference between the energy allocation and the reserve to be lowered and is used for subsequent analysis.

Equation (1) – the objective function that co-optimizes – can be rewritten as indicated in (A.1) in which the energy allocation term \( \tilde{P}_{r,t} \) is left in function of the effective net capacity and the secondary reserve allocations to increase and decrease. For purposes of discussion in this appendix, this function is denoted as the reduced objective function, and, for facility, the start-up, shutdown, and penalization costs for power not supplied are ignored.

\[
\text{Reduced OF} = \sum_{r \in \Omega} P^{DE}_{r,t} \left( Q_{r,t} - Q^{ND}_{r,t} - P^{r+}_{r,t} \right) + \sum_{r \in \Omega} PR^{UP}_{r,t} P^{2+}_{r,t} + \sum_{r \in \Omega} PR^{DN}_{r,t} P^{2-}_{r,t} \quad \text{(A.1)}
\]

The above equation can be re-organized for analysis purposes as is shown in (A.2).

\[
\text{Reduced OF} = \sum_{r \in \Omega} P^{DE}_{r,t} \left( Q_{r,t} - Q^{ND}_{r,t} \right) + \sum_{r \in \Omega} \left( PR^{UP}_{r,t} - P^{DE}_{r,t} \right) P^{2+}_{r,t} + \sum_{r \in \Omega} PR^{DN}_{r,t} P^{2-}_{r,t} \quad \text{(A.2)}
\]

Consider the following two cases derived from (A.2):

Case 1: The undispatched capacity of the resource is equal to zero, that is, \( Q^{ND}_{r,t} = 0 \). In said case, (A.2) can be rewritten as indicated in (A.3).

\[
\text{Reduced OF} = \sum_{r \in \Omega} P^{DE}_{r,t} Q_{r,t} \quad \text{(A.3)}
\]

For this case:

1. The first term \( \sum_{r \in \Omega} P^{DE}_{r,t} Q_{r,t} \) is constant, so it has no effect on the multiple solutions.
2. The second term \( \sum_{r \in \Omega} PR^{UP}_{r,t} P^{2+}_{r,t} \) denotes that the energy offer must be different from the secondary reserve offer to go up for all resources and in all periods, otherwise, the value inside the parenthesis is set equal to zero with which any value could be assigned to \( P^{2+}_{r,t} \), being one of the causes that originates multiple solutions. In other words, the value of \( P^{2+}_{r,t} \) is irrelevant for the minimization process – any value is valid – if the offers make the value within the parenthesis be equal to zero.
3. The second term also implies that the differential \( PR^{UP}_{r,t} - P^{DE}_{r,t} \) must be different between two resources, that is, \( PR^{UP}_{r,t} - P^{DE}_{r,t} \) for the resource \( i \) must be distinct to \( PR^{UP}_{r,t} - P^{DE}_{r,t} \) of the resource \( j \).
4. The third term \( \sum_{r \in \Omega} PR^{DN}_{r,t} P^{2-}_{r,t} \) implies that the reserve offers –i.e., \( PR^{DN}_{r,t} \) – must be different for all resources in every period \( t \), since equal values would imply that multiple solutions can occur.

Case 2: The undispatched capacity of a resource is different than zero, that is, \( Q^{ND}_{r,t} \neq 0 \). In this case, (A.2) can be rewritten in the form indicated in (A.4)

\[
\text{Reduced OF} = \sum_{r \in \Omega} P^{DE}_{r,t} \left( PR^{UP}_{r,t} + PR^{DN}_{r,t} \right) P^{2-}_{r,t} + \sum_{r \in \Omega} P^{DE}_{r,t} \Delta_{r,t} \quad \text{(A.4)}
\]

For this case:

1. The first term implies that the sum \( P^{DE}_{r,t} + PR^{DN}_{r,t} \) must be different between two resources, that is, \( P^{DE}_{r,t} + PR^{DN}_{r,t} \) for the resource \( i \) must be distinct to \( P^{DE}_{r,t} + PR^{DN}_{r,t} \) for the resource \( j \).
2. The second term \( \sum_{r \in \Omega} PR^{UP}_{r,t} P^{2+}_{r,t} \) implies that the reserve offers –i.e., \( PR^{UP}_{r,t} \) – must be different for all resources and in every period \( t \), because equal values would imply that multiple solutions can occur.
3. The third term \( \sum_{r \in \Omega} P^{DE}_{r,t} \Delta_{r,t} \) implies that energy offers must be different for all resources and in every period \( t \) because equal values would imply that multiple solutions can occur.

Based on cases 1 and 2, and to avoid multiple solutions, the following requirements must be met:

1. \( P^{DE}_{r,t} \) different for all resources
2. \( PR^{UP}_{r,t} \) different for all resources
3. \( PR^{UP}_{r,t} - P^{DE}_{r,t} \) \neq \( PR^{UP}_{r,t} - P^{DE}_{r,t} \)
4. \( PR^{DN}_{r,t} + P^{DE}_{r,t} \) \neq \( PR^{DN}_{r,t} + P^{DE}_{r,t} \)
5. \( PR^{DN}_{r,t} + P^{DE}_{r,t} \) \neq \( PR^{DN}_{r,t} + P^{DE}_{r,t} \)

Based on the above, this study proposes a tiebreaker scheme in which a random number from a uniform distribution is added to all reserve and energy offers that have an equal value. The limits of this distribution are 0.000001 and 0.5, which were established after several computational exercises to prove their effectiveness. They are convenient with the order of magnitude in Colombian pesos – the country’s national currency – that energy and reserve offers are sent daily to the market operator. The random generated numbers with six decimal places are added to the integer part of the offer that needs a tiebreak. In other words, the tiebreaker offer conserves the integer indicated by the agent along with a decimal place of six digits, randomly generated to break the tie. If all the of offers are untied, then these, evidently, comply
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DISCLAIMER
Opinions or conclusion expressed in this study are personal and do not necessarily reflect the views or positions of our employees.

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