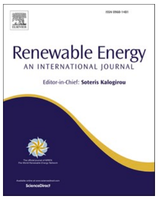
Renewable Energy 232 (2024) 121073

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



Effect of the intermittency of non-conventional renewable energy sources on the volatility of the Colombian spot price

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ARTICLE INFO

Keywords:
Non-conventional energy sources
Vector error correction
Spot price
Time series
Price volatility
Financial risk

ABSTRACT

This paper explores one of the side effects and challenges that integrating non-conventional renewable energy sources poses to the Colombian electricity market, the spot price volatility which is directly related to financial risk. We propose a vector error correction model that allows an integrated and dynamic modelling of the offer-side of the spot market by considering bid prices, available energy, renewable energy production and the spot price. To validate the model, we performed statistical tests on the residuals of the model and back-testing. The results show that given a one standard deviation shock in renewable energy production from non-conventional sources, the spot price volatility increases from 12.7 % to 14.5 % in a 365-day horizon, which represents a relative increase of 14.2 %. Also, when evaluating different renewable energy integration scenarios and the official system expansion, we see that assuming 100 % fulfilment of the non-conventional sources integration plan, the volatility goes up to 31.2 % vs. 12.3 %. It is also worth noting that if the plan is fulfilled up to 25 % there is no significant increase in spot price volatility, which can be justified by the simultaneous expansion of conventional sources that compensate for the effects of non-conventional renewable sources.

1. Introduction

There is a widespread interest worldwide in incorporating renewable energy into large power systems. The main renewable energy sources are developed around solar and wind technologies, used in CO2 emissions reduction goals, and show a reduction of their levelized costs during the last few years. One of the more staggering examples is the European Union (EU), a trading bloc that set the goal of reducing greenhouse emissions by 80–95 % in 2050 compared to 1990 emissions [1]; another example is the Senate Bill SB-100 in California USA, which states that by 2045, 100 % of the electricity of the state will come from clean sources [2]. Despite the previous examples, a successful transition to cleaner energy sources must go beyond the definition of a regulatory framework that assures the financial viability of such projects. The transition must consider other aspects like the acceptance of these projects by the communities directly affected to avoid social resistance and not-in-my-back-yard (NIMBY) manifestations [3,4].

Laws 1715 of 2014 [14], 1955 of 2019 [15], and 2099 of 2021 [49] show Colombia has the same interests and concerns as the rest of the world regarding its energy security, fossil fuel dependence, and greenhouse emissions. Moreover, the law defines renewable energy as only solar, wind, and small-scale hydropower generation, and they refer to it as non-conventional renewable energy sources (NCRES). These acts establish a set of incentives for the incorporation of NCRES into the energy mix of the country through various policy instruments and define them for the Colombian context as solar photovoltaic, wind, small hydro power (less than 20 MW). Colombia is principally powered by hydro generation, which constitutes 90 % of its energy mix. The reliance of almost solely one type of energy can prove catastrophic in case of inevitable droughts or other extreme events. This issue is ever-more pressing given the ongoing global climate change.

Given that the energy production from NCRES (solar, wind and small-scale hydro) is determined by the climate, variability and intermittence are the main characteristics of these sources, thus posing difficult and important challenges in the response-mechanism design, usually market-oriented, that allows power systems to keep operating under well-established reliability and security standards in systems with high shares of NCRES [5]. The EU was a pioneer in this matter with the

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https://doi.org/10.1016/j.renene.2024.121073
Received 21 February 2022; Received in revised form 17 May 2024; Accepted 22 July 2024

adoption of several bills by its member states, most notably in Germany with the Renewable Energy Sources Act (Erneuerbare Energien Gesetz). Most of the previous studies dealing with the impact of NCRES integration on electricity prices have been carried out/conducted regarding European markets.

Previous studies that have analysed the dynamics of the Colombian spot price have focused on questions such as how do short- and long-term prices behave? How volatile are the prices and what drives their volatility? In Ref. [6], several univariate time series models are assessed to measure spot price volatility. The authors conclude that there is high kurtosis with volatility clusters associated with exogenous climate variables. The best model they found was an exponential generalized autoregressive conditional heteroscedastic -EGARCH model [1]. In a related study [7] a methodology to obtain spot price forecasts from autoregressive integrated moving average -ARIMA-type models is developed; the authors conclude that extreme events are frequent in the Colombian system and are usually related to climate and regulatory changes, both of which should be considered as input variables to the models.

In [8], artificial neural networks (ANNs) are used to obtain long-term forecasts of the spot price, and their results are compared with mainstream econometric models. The input variables for ANN are reservoir levels, available energy declared by market participants, and electricity demand. The main conclusion of this study is that ANNs are more precise than econometric models when these input variables are used.

A more recent study is presented in Ref. [9], where the authors, through a counterfactual analysis, model the impact of the integration of NCRES into the spot market. They propose a structural model where strategic bids by agents are represented. The authors found that, in the spot market, NCRES integration could bring a price decrease of around 12.75 COP$/kWh, 10 % of the average spot price in 2018.

In this paper, we propose a specific model for the Colombian spot price of the electricity market, which can be used to analyse and plan the effects of spot price volatility associated with the integration of NCRES. We used a multiple time series approach [10], which allows us to consider the dynamic behaviour and interactions among different variables. To do this, we first propose a recursive ordering of the market variables and validate it; the variables of the model are NCRES energy production, hydro power plants' bid price and their available energy; with the data associated with these variables, we built a Vector Error Correction model (VEC). Then, with this model and considering the scenarios defined in the system expansion plan [11], we ran an impulse-response analysis and measured spot price volatility.

The main results of this work indicate that using a VEC representation the model captures the relationships between spot price volatility and NCRES energy production. Also we found that under the current market and system conditions, a one standard deviation shock in NCRES electricity production increases the spot price volatility from 12.7 % to 14.5 % for an in-sample forecast using the last 365 daily data points. When testing different NCRES integration scenarios, we observe that with complete fulfillment of the system expansion plan, the spot price volatility goes up to 31.2 % vs. a 12.3 % level for the whole sample data; it is also worth noting that if the plan is fulfilled up to 25 %, there is not a significant increase in spot price volatility.

The other sections of this paper are organized as follows: in Section 2 we make a brief review of the NCRES integration in Colombia. In Section 3 we explain the relationship between spot price volatility and NCRES integration. In Section 4 we propose a model for that relationship. Section 5 presents the main results. Finally, Section 6 includes conclusions and future developments and applications of the model. All the analyses were performed using the software R [45] and the vars package [46]; the code and data can be found in the GitHub repository [50].

2. 2. Non-conventional energy sources in Colombia

The first regulation regarding the integration of NCRES into the Colombian system can be traced back to the Law 697 of 2001 [12]; this is one of the first explicit references in the legal system to NCRES and establishes its promotion as a matter of national interest. Despite that, the focus of the Law was Rational and Efficient Energy Use (URE by its Spanish acronym), and aspects related to energy production were not developed.

More than ten years later, laws 1665 and 1715 of 2013 and 2014 were promulgated. Through the first, Colombia approves and adheres to the Statute of the International Renewable Energy Agency (IRENA) and automatically commits to greater participation of NCRES in the energy mix [13]. After that, Law 1715 establishes the mechanisms and policies to be employed to fulfil its commitments [14]. Then in the Law 1955 of 2019, some of the mechanisms defined in 2014 were changed, and market-related aspects were incorporated mainly by establishing that at least 10 % of household electricity consumption should come from NCRES [15].

In the last revision of the system expansion plan [11], one of the proposed scenarios establishes that by 2030, NCRES would have a share of 23 % of the energy matrix, with 12 % as wind turbines in the north of the country. Although this may seem like a positive aspect given the COP21 goals regarding greenhouse emissions, the high dependency of NCRES on hydrometeorological factors, the difficulties producing accurate weather forecasts in the tropical zone [17], and the structural changes of El Niño Southern Oscillation (ENSO) [18] pose significant challenges to both the system operation and the electricity market to efficiently and safely integrate NCRES.

In 2019, the Ministry of Mines and Energy implemented an important incentive to develop NCRES projects in Colombia through long-term auctions [19]. These auctions seek to lower cash-flow uncertainty during the financial viability assessment of this kind of project; using standardized long-term contracts with energy retailers, in 2019, 1298 MW of NCRES capacity were allocated. Also, in the last reliability charge auction, 1398 MW worth of NCRES capacity were assigned through firm energy obligations [20]. These two situations point to strong contractual incentives and market interest in developing NCRES projects in Colombia.

Regarding the planning of the electrical energy supply and the probable additions to generation capacity, it is important to point out that Colombia has a public entity, UPME (Unidad de Planeación Minero-Energética), which, in an indicative, permanent, and coordinated manner is in charge of planning which energy resource is used. In addition, it is in charge of modelling and analysing the information regarding the country's energy potential. An official document containing this information is the System's Reference Expansion Plan [11], published regularly and publicly available. Another document, the National Energy Plan [16], provides a broader perspective of the energy sector and includes other energy sources plus the transport sector. In summary, the procedure followed by UPME in their analysis is as follows: firstly, several scenarios are determined based on different macroeconomic assumptions, the current and expected network infrastructure, and the availability of primary energy sources like coal, natural gas, oil, solar radiation, rainfall, and wind speed. In the case of the availability of the primary energy for NCRES, historical data are evaluated and from them synthetic series are produced and assigned to each scenario. These scenarios are the input to least-cost energy planning models, producing the cost-optimal expansion plan for each of them. The resulting data are published in Ref. [11] (in Spanish). Here, it is important to clarify that, since our goal is to measure the probable effect the incorporation of NCRES could have over the spot price's volatility under the current market arrangement, the assessment of the country's NCRES potential is beyond the scope of our work and we use the data from UPME.

3. Spot price volatility and NCRES

An effect of NCRES' intermittence is the price volatility associated with sudden changes in available energy, thus having a direct effect on the financial risk of the spot market. This behaviour of electricity prices and some technical challenges are studied by researchers worldwide regarding the effects of NCRES integration.

In [21], the authors conclude that the EU power systems would require an increase in operation flexibility if the goals of reducing greenhouse gases are to be accomplished. As a result of this research, they found that, under the current scenario, in 2050, countries like Germany or the United Kingdom could face hourly variations in residual demand of up to 50 %–100 %, respectively, compared to 2011 levels. Another study concerning the EU [22] applies univariate time series models to the Italian market price. With regard to price volatility, the authors concluded that an increase of 10 % in photovoltaic and wind energy generation would decrease prices by 0.34 % and 0.36 %, and increase volatility by 0.67 % and 0.76 %, respectively, for each technology. Nevertheless, they also point out that the balancing mechanisms required for NCRES integration (e.g. ancillary services) could offset the price reduction in the tariff paid by end-users.

In [23], the authors analyse the determinants of price volatility in Iberian markets (Spain and Portugal) and its relationship with NCRES integration. They propose a GARCH model through which the merit order effect (displacement of technologies in the unit-commitment) corresponding to NCRES electricity production is measured. Their main conclusion is that higher NCRES integration is associated with a more significant merit order effect.

Most research regarding price variations and NCRES integration studies the European markets; however, in Ref. [24], an analysis of the New Zealand market is presented. Using Fourier regressions, the authors identify the correlations between market prices, NCRES availability, and system demand. Their main conclusion is that due to the seasonal patterns that affect hydro plants plus the variability of wind energy, the market prices are highly correlated with NCRES integration.

In [25], the merit order effect associated with photovoltaic and wind generation on the Californian market is measured. The authors conclude that there would be variations of between 5 % and 12 % in the day-ahead and real-time market prices.

In [26], given the tight relationship between volatility and risk, the author proposes different techniques and models to measure volatility in energy markets. The suggested approach is to model price returns using a stochastic process and implicit volatility measurements, as is widely done in highly developed financial markets.

Using implied volatility requires mature and developed derivatives markets. In Colombia, there are forwards and futures; with mechanisms like the one described in Ref. [27], the system is advancing towards reliable derivatives markets. However, given the current depth and liquidity of these markets, they should not be used as an efficient price signal.

Currently, the most common approach to understanding price dynamics and volatility is based on univariate models. We can see that most of the current research proposes univariate models over the spot price (or some transformation of it) and then look for a correlation with exogenous time series. This approach overlooks the interaction and feedback mechanisms between the series, if not adequately treated [28].

Another issue is the lack of consensus about which is the best option – from a methodological perspective – for analysing the spot price. This topic, along with others, is dealt with in Ref. [29]; they conclude that since electricity markets become more complex than other commodities due to their physical properties and the fact that they constitute an essential service, it is difficult to develop general models, and most would be contingent upon the analysed system.

Based on previous research, in this paper we propose a specific model for the Colombian spot market for electricity, which can be used as an analysis and planning tool to measure the impact of NCRES (solar photovoltaic, wind, small-scale hydro power [less than 20 MW]) integration over the spot price volatility, as it allows system operators, generators and even policymakers to assess the effect these new technologies will have on the market.

4. 4. The colombian electricity market and Non-conventional energy sources (NCRES)

The Colombian regulation establishes electricity as an utility, which defines four business activities: generation, retail, transmission and distribution, and two markets – wholesale and retail. Generators use their power plants to produce energy, which they sell to retailers in the wholesale energy market (MEM, by its Spanish acronym). This wholesale market is again divided into two parts: the spot market and the forward market; then retailers buy energy from the wholesale market and sell it to customers in the retail market. Transmission deals with long-distance transportation and high-voltage infrastructure, and distribution entails delivery to customers and low-voltage networks. Generation and retail activities are market-based with competing agents, while transmission and distribution are regulated monopolies. The general structure can be found in Fig. 1.

The Colombian spot market is marginalist with an hourly settlement – that means each power plant declares their hourly available energy and submits a bid price for the whole day, which includes their costs and perception of risk; the bids are used to construct a supply curve for each hour and then matched with demand. Power plants receive an hourly generation schedule, which is limited by the amount of available energy they declare. Small-scale power plants (less than 20 MW of installed capacity) are considered price takers and do not submit bid prices or available energy, and they produce energy according to the availability of their primary source. The installed capacity from each energy source is presented in Fig. 2.

Regarding renewable energy, law 1715 of 2014 establishes the framework for the Colombian energy transition and defines the following NCRES for the Colombian electricity market: small-scale (<20 MW) hydro power plants, photovoltaic (PV) power plants, wind turbines and geothermal (although this technology is in the feasibility stage in Colombia). The law also includes tax breaks and other economic incentives for new NCRES projects, which are emphasized and expanded in Law 1955 of 2019. Additionally, Law 2099 of 2021 simplifies the regulation and bureaucracy to help obtain those incentives.

In relation to distributed energy sources (DERs) the regulator issued: Resolution 174 of 2021, which defines small- and large-scale self-supply activities; Resolution 098 of 2019, which allows battery energy storage systems for grid support and congestion management; and Resolution 101–001 of 2022, which defines the requirement for advanced metering infrastructure (AMI).

Through Resolution 40678 of 2019, the Colombian government defined an auction-based mechanism of long-term forward contracts exclusively for new NCRES projects. The first auction allocated 10.2 GWh-day, of which 82.6 % come from wind and 17.4 % from PV. The average pure energy price of the auction was 95.7 COP$/kWh (excluding capacity payments and public transfers). Also, in a private tender during April 2022, eleven PV projects with an installed capacity of 796.3 MW were allocated; the average price was 155 COP$/kWh. Until 2020, NCRES energy production was dominated by run-of-river small-scale power plants of less than 20 MW; however, installed capacity and energy from PV sources started a steep increase in 2020 and it is expected that wind production will also increase once the required transmission lines in the north of the country are built. Fig. 3 shows the evolution of energy production from NCRES from 2018 to July 2022.

Spot price is primarily determined by large hydro power plants (>20 MW) and their bid prices, as can be seen in Fig. 4; this happens because their variable cost is much lower than that of fuel-fired power plants and depends only on rainfall; so the bid price of these power plants can be considered an opportunity cost. Bid prices in the figure are weighted by the available energy declared by each hydro power plant for that specific day, while the spot price is weighted by the hourly demand of the system.

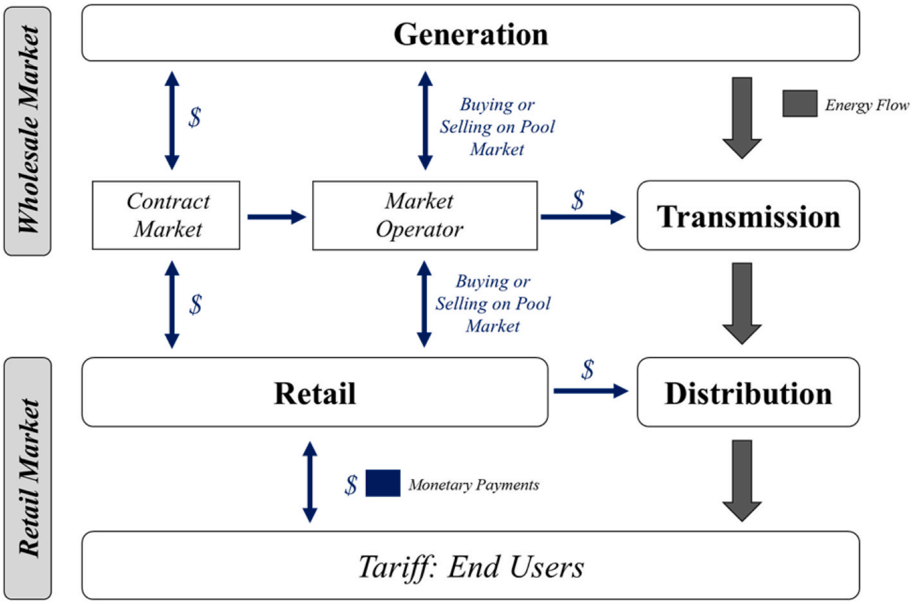

Fig. 1. Colombian electricity market. Source [47]:

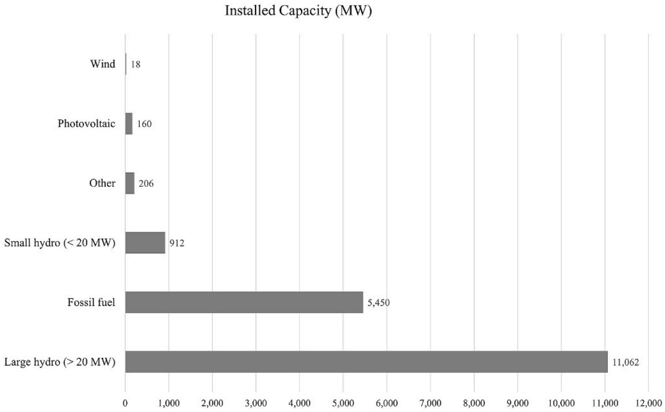

Fig. 2. Installed capacity. Source: Sinergox [32].

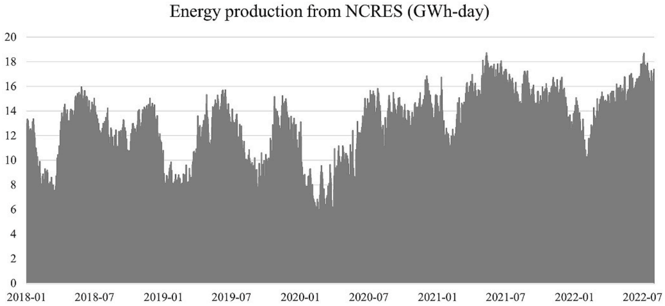

Fig. 3. Energy production from NCRES. Source: Sinergox [32].

Bid prices of thermal power plants are rather stable as they depend on the fuel prices negotiated by the plants' operators. Their main revenue source for thermal power plants is the capacity mechanism of the Colombian market defined in Resolution CREG 071 of 2006, which works like a call option [48] and enforces them to produce energy in case the spot price exceeds a predefined level.

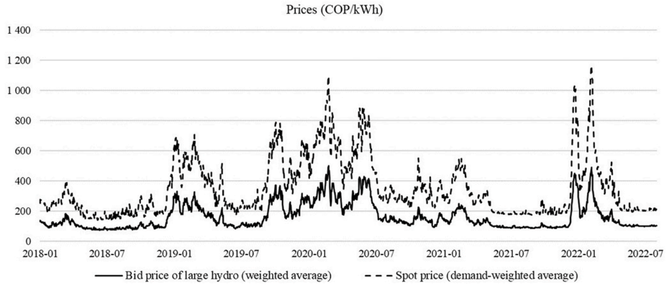

Fig. 4. Spot and bid prices. Source: Sinergox [32].

5. 5. Proposed model

We propose a multiple time series model to measure how changes in NCRES energy production might affect the spot price of the Colombian market. Multiple time series models allow researchers to simultaneously analyse the interaction between different time-varying variables [10]. To obtain a model specification we used the following procedure based on [42]: 1) define the set of time series to use based on the results from the previous section; 2) analyse the stationarity of each series independently; 3) test for the existence and quantity of cointegration relationships; 4) estimate the cointegration equations and perform model validation.

5.1. Input data and time horizon

For our analysis, we used publicly available data from Refs. [11,16,32], which are also available in the paper's GitHub repository for the reader's convenience. Considering that our model has a daily time step and most of the operational data of the Colombian system is hourly defined, we performed the following procedure for each of the variables used in the model. With respect to the available energy, we aggregated the hourly historical data into daily values for the existing capacity, and to obtain, in energy values (MWh), the new additions to the system we used the results from UPME regarding the system's expansion, which are in power units (MW), and applied a load factor to each of the technologies [36], the resulting value is then multiplied by 24, which results in the expected daily energy availability of each source, corresponding to the new power plants considered in the system's expansion plan. In the case of NCRES, the energy availability is called energy production because these sources are always in the base of the merit order dispatch and the existing regulation incentivizes that they produce whatever they have available at any given moment. For the spot price we calculated a demand-weighted daily average, and for the hydro bid price we used a capacity-weighted average considering the prices from all the resources that correspond to this technology.

From the analysis in the previous section, it follows that the Colombian power system is dominated by large (>20 MW of installed capacity) hydroelectric sources; also, despite the short-term inelasticity of the demand [43], and not finding it statistically significant in the explored specifications, we considered it important to represent demand seasonality in our model, in particular with respect to Sundays and holidays. to achieve this, we included a dummy variable to the VEC model, which is one when the day is either a Sunday or a public holiday, and zero otherwise. The list of variables used in our model is presented in Table 1 and their descriptive statistics can be found in Table 2.

Our aim was to have a model that quantifies the effect NCRES generation might have on the spot prices. We included the hydro bid price and availability because this is the dominant technology in the Colombian system and we needed to differentiate its effect from that of NCRES. Further, we did not consider climate variables as our goal was not to model NCRES but their influence over the spot price.

We used data from January 2018 to July 2022 despite having price information since 1995, as important regulatory modifications in 2009 [31] fundamentally changed the spot price formation, specifically with regard to the payment of start-up and shutdown fixed costs of thermal generators; additionally, in the last year the Colombian system has seen a large increase in both installed capacity and generation from NCRES; especially in PV installations and more recently in wind. The raw data have an hourly resolution and were downloaded from the public interface of the Sinergox system [32].

5.2. *Structural definition*

Considering that the spot price in Colombia is largely determined by the hydro power plants, we built our model focusing on those sources; we discarded the climatological aspects as our goal is to measure the effect of NCRES generation on the spot price and not the variability of NCRES generation or hydro power plants' availability due to climate factors. Following our description of the Colombian power system, we suggest the following ordering of the variables: we start with NCRES generation, which is only dependent on installed capacity of NCRES, and their capacity factors, which are not considered in our model; then we have hydroelectric power availability which is contingent on climatological circumstances and the storage capacity of the reservoirs; then we consider the hydro power plants' bid price, which depends on their available energy and climate expectations; finally, in our model, the spot price is determined by the interaction between the different variables (NCRES energy production and hydro power plants' availability and bid price). Demand was not statistically significant in any of the specifications we tried, which is consistent with the market's short-term inelasticity [43]; however, its seasonality is represented in the data, as explained in the previous section. We want to emphasize that our goal was to represent the effect NCRES generation shocks may have on the spot price; also in addition, we considered the hydro power plants' bid prices and quantities to isolate the effects from these sources and NCRES, as both are contingent to climate factors.

Table 1
Variables (daily values).

Variable	Units	Identifier	Description
Available Energy from Large Hydro Plants	GWh	*hydro_avail*	Energy offered by hydro power plants (>20 MW)
NCRES[a] Generation	GWh	*ncres_gen*	Energy produced by NCRES (non-conventional renewable energy sources)
Average Hydro Price	COP/kWh	*hydro_price*	Weighted average bid price from hydro power plants
Average Spot Price	COP/kWh	*spot_price*	Weighted daily average of the spot price
Holiday Dummy	Binary	*aux_dummy*	One if the day is a holiday or a Sunday, and zero otherwise

[a] Non-conventional renewable energy sources.

According to that, we propose the recursive order of the variables defined in (1).

$$Y_t = \begin{bmatrix} nces\_gen_t \\ hydro\_avail_t \\ hydro\_price_t \\ spot\_price_t \end{bmatrix} \tag{1}$$

After defining the variables, the next step is to choose a model specification; for this we test if any of them has a unit root using the augmented Dickey-Fuller statistic [38] and the iterative procedure described in Ref. [37], which suggest starting testing with a high number of lags and decrease it until the absolute value of the statistic is close to 1.6. The results are presented in Table 3., which indicates that all of the variables have a unit root for a test unit root with the indicated number of maximum lags; it is worth mentioning that this does not correspond to the lag order of the model but the maximum number of lags used to perform the unit root test.

To determine the lag order of our model we considered the following information criteria: Akaike (21 lags); Schwarz (3 lags); Hannan–Quinn (7 lags); and final prediction error (FPE) (21 lags). Since both Akaike and FPE point to 21 lags we used that order in the estimation. Then, we applied the Johansen's procedure [33] to identify possible cointegration relationships between our variables; the results are presented in Table 4.

Based on the results we concluded, with a confidence of 95 %, that there are up to three cointegrating relationships, and after applying [33] we have the following cointegration equations:

$$ncres\_gen_t + \left(5.54 \times 10^{-2}\right) spot\_price_t = 0 \tag{2}$$

$$hydro\_avail_t + \left(1.12 \times 10^{-1}\right) spot_{price_t} = 0 \tag{3}$$

$$hydro\_price_t - (1.00) spot_{price_t} = 0 \tag{4}$$

Multiple time series models usually come from one of two of families, vector autoregressive (VAR) or vector error correction (VEC); with regard to residuals and forecasts, both tend to produce similar results, and their main difference lies in model identification, where the VEC specification explicitly considers the structural relationships among input variables, if any [10,41]. These relationships are omitted under the VAR specification and a researcher must resort to techniques like structural VAR specifications to enforce them using specific domain knowledge and testing different specifications.

Considering that we identified explicit cointegration relationships from the data, we use the following VEC specification:

$$\Delta Y_t = \Pi Y_{t-1} + \sum_{i=1}^{20} \left(\Gamma_i \Delta Y_{t-i}\right) + \varepsilon_t \tag{5}$$

$$\Pi = \widehat{\alpha}\widehat{\beta^T} \tag{6}$$

where β corresponds to the long-term (equilibrium) relationships specified in (2–4), α represents short-term deviations from the equilibrium, Γ_i corresponds to the coefficients between the lagged differences of the variables, and ε_t are the residuals of the model. The complete estimation can be found in the Appendix.

Table 2
Variables – Descriptive statistics.

	Min value	First quartile	Median	Average	Third quartile	Max value	Std. Dev.
Available Energy from Large Hydro Plants	171.9	212.8	223.1	221.9	231.3	250.1	13.0
NCRES[a] Generation	5.65	10.9	13.4	12.9	14.9	18.7	2.8
Average Hydro Price	73.0	98.8	126.5	161.4	202.0	500.0	85.8
Average Spot Price	64.9	106.5	153.3	189.9	251.0	685.5	106.5

[a] Non-conventional renewable energy sources.

Table 3
Unit root tests.

	Lags Evaluated	Statistic	p-Value
NCRES[a] Generation	358	−1.62	0.71
Available Energy from Large Hydro Power Plants	296	−1.62	0.74
Average Hydro Price	358	−1.80	0.66
Average Spot Price	362	−1.64	0.73

[a] Non-conventional renewable energy sources.

Table 4
Cointegrating relationships.

Relationships	Statistic.	Crit. Value 5 %	Crit. Value 1 %
≤3	8.17	8.18	11.65
≤2	23.53	17.95	23.52
≤1	43.33	31.52	37.22
= 0	77.79	48.28	55.43

5.3. *Model validation*

To validate the model, we used the Portmanteau [35] and Breusch-Godfrey [39,40] tests for serial correlation. In both cases we got a p-value higher than 0.01, which means that we cannot reject the null hypothesis of no serial correlation in the error term of the model. Fig. 5 shows the residuals of all the variables and Fig. 6 their autocorrelation function [44]. We can see that the values are within the confidence interval for all the lags up to the order of the model (21) and Fig. 7 presents the one-step forecast of the spot price compared to the real values for the complete data set; the forecast has a root mean squared error of 20.44 and mean absolute percentage error of 8.2 %.

The highlighted periods in Fig. 5 correspond to volatility clusters that cannot be accounted for in our model and suggest the possibility of exploring other alternatives that explicitly deal with heteroscedasticity in the error term in case the model were to be expanded to a probabilistic setting. Finally, the spot price volatility obtained from the model's one-step forecasts for the whole dataset is 12.3 %, while the one from the real data is 12.1 %. The definition of volatility used in this work corresponds to the one used in financial markets: the standard deviation of the natural logarithm of price returns [30].

6. Results

With the selected model, we made an impulse-response (IR) analysis [10] that measures the change of the spot price as a response to shocks in NCRES generation, hydro power plants' bid price and their availability; we also measured the volatility of the spot price considering different integration scenarios for NCRES; these are based on the official capacity expansion plan published by the Colombian energy planning unit [11].

6.1. *Impulse-response analysis*

In Fig. 8, we present the effect on the spot price of an increase of one standard deviation in NCRES generation; the confidence intervals are calculated using the bootstrap described in Ref. [34] with 200 samples and confidence intervals at the 99 % level; the analysis was performed with the complete estimated model, so it can be interpreted as if the

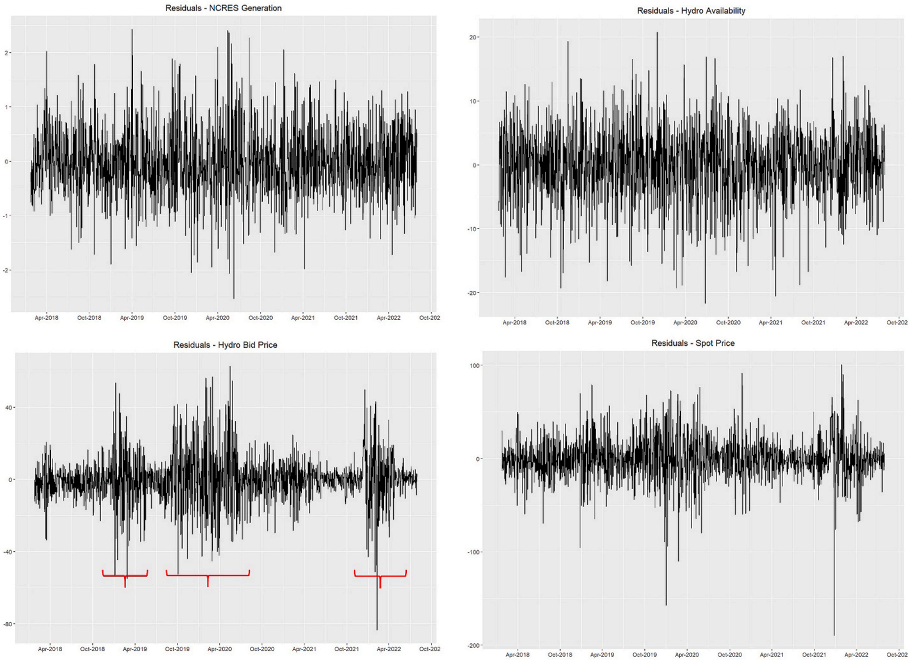

Fig. 5. Residuals.

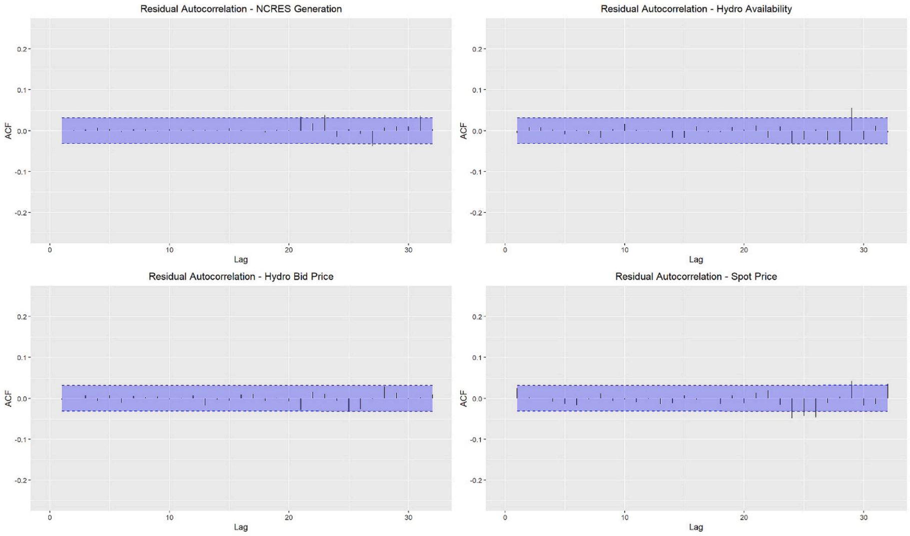

Fig. 6. Residuals autocorrelation.

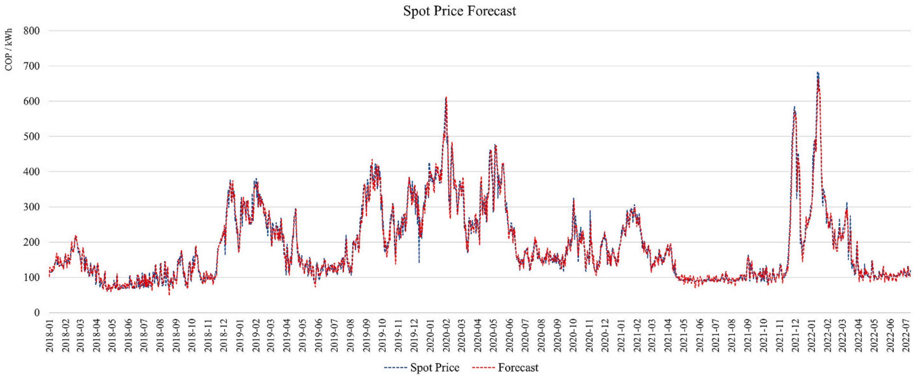

Fig. 7. Spot price forecast.

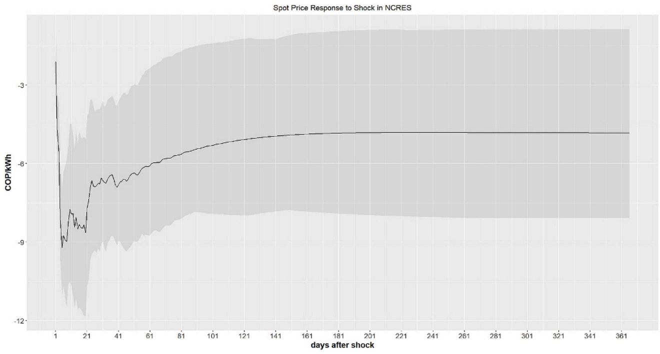

Fig. 8. Spot price response to shock in NCRES generation.

increase occurred on any of the days in the data set, and the response would be the variation of the spot price in the following year due to that increase. From the results, we conclude that shocks of these magnitudes can decrease the spot price by up to 9 COP$/kWh; this behaviour is supported by the supply law, as one sudden increase in the offer (in this case NCRES generation) decreases the price in a market; at this point it is worth remembering that NCRES do not offer their available energy to the market and they produce whatever they have available as they operate as a baseload resource as long as grid constraints are met, producing the previously mentioned merit order effect.

In Fig. 9, we present the effect on the spot price of one standard deviation shock in the hydro power plants' bid price, where we can see a direct relationship with the spot price increasing up to 15 COP$/kWh. This is in accordance with the normal behaviour of the Colombian system as hydro power plants are the de facto marginal resources in the Colombian market.

In Fig. 10, we show the effect on the spot price of a shock of one standard deviation increase in the available energy from large hydro; the behaviour is similar to the shock in NCRES generation, but of lower magnitude (5 COP$/kWh); the reason for this is that large hydro

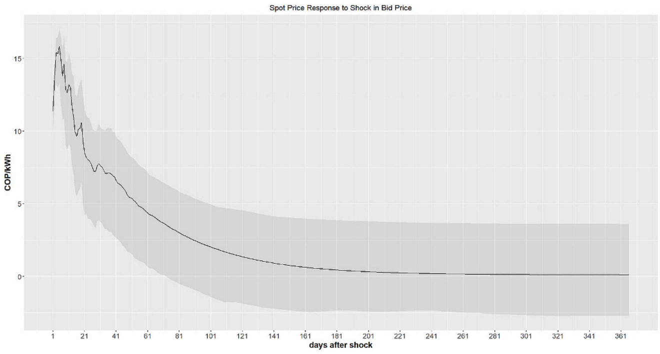

Fig. 9. Spot price response to shock in hydro bid price.

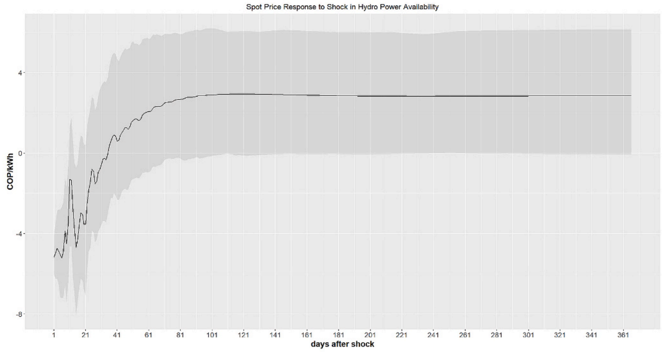

Fig. 10. Spot price response to shock in hydro power availability.

availability has a lower standard deviation in relative terms compared to NCRES generation because of the storage capacity of hydro power plants. Also note that the confidence intervals for shocks in bid price and hydro power availability are narrower than those for a shock in NCRES generation.

6.2. Volatility analysis

To analyse the effect of shocks in NCRES generation on spot price volatility under the current energy mix, we used the following procedure: first, we generated *in-sample* dynamic forecasts of the spot price for the last 365 days of the data set, August 2021 to July 2022, and obtained a daily volatility of 12.7 %. Then we added the response of a one standard deviation shock in NCRES generation in Fig. 8 to those forecasts and obtained a volatility of 14.5 %, which means an increase of 1.8 % in absolute terms and 14.2 % in relative terms. Then we proceeded to perform the same analysis under various levels of NCRES integration.

6.3. Scenario evaluation

Our goal was then to measure how would the volatility of the spot price change under different levels of fulfillment of the expansion plan with respect to NCRES, and how would a shock in the energy produced by these sources affect the spot price. To measure volatility changes under different NCRES integration scenarios we scaled the generation and availability variables in the data set to match the energy mix considered in the system expansion plan. For NCRES generation we used the historical load-factor, which we calculated with the installed capacity and actual generation and scaled to the new capacities suggested in each scenario; the expansion plan takes into consideration 5.9 GW of photovoltaic, 4.1 GW of wind, 0.5 GW of small-scale hydro and 1.7 GW of large hydro.

Then we designed three scenarios, which correspond to different degrees of fulfilment of the expansion plan with respect to the expected installed capacity for NCRES: 25 %, 50 %, and 100 %; for large hydro power we assumed a 100 % fulfilment of the expansion plan because these are tied to the capacity mechanism of the Colombian market (reliability charge) and we applied the same procedure as in the previous section; the results are presented in Table 5. The column *Base Volatility* refers to the volatility of the spot price when performing a dynamic forecast after scaling the variables to match the fulfillment of *NCRES integration* according to the expansion plan, for example, if the system expansion plan were to indicate a 1000 MW of additional NCRES, the 25 % level would mean that we perform dynamic forecasts considering only 250 MW. The *Volatility after shock* column measures the spot price volatility, if a shock of one standard deviation were to occur to the NCRES generation variable (after scaling to the corresponding level of fulfillment of the expansion plan) this is done to represent the variability of these energy sources due to their dependence on the weather. Finally, column *Relative change* measures the relative difference between the *Base Volatility* and the *Volatility after shock*.

Table 5
Scenario evaluation results.

NCRES integration	Base volatility	Volatility after shock	Relative change
25 %	7.6 %	7.2 %	5.5 %
50 %	21 %	22.7 %	8.1 %
100 %	31.2 %	35.7 %	14.2 %

As expected, the higher the NCRES integration, the higher the daily volatility of the spot price and the sensitivity to NCRES generation shocks. Considering that the base volatility for the whole data set is 12.7 %, we see that under a 100 % fulfilment of the plan, volatility more than doubles increasing up to 31.2 %; it is also worth noting that a fulfilment of up to 25 % does not translate into increases in volatility. This result emphasizes the importance of having hedging mechanisms to adequately manage spot market risk.

7. Conclusions and future work

In this work, we developed a model that aims to evaluate the probable effect the plan for integrating NCRES could have on the volatility of the spot price under the current market arrangement. In our approach, we started from the results published by UPME concerning capacity expansion. Then we applied and expanded a multiple time series modelling technique used in econometric analysis, VEC, and then backtested and evaluated different scenarios. The model and data are publicly available for replicability and extension purposes.

From the results, the proposed model adequately represents the main drivers of the offer-side in the Colombian wholesale electricity market, which determines the spot price. A contribution of this work is that it represents the structure of the system, so the results follow the economic principles and its physical behaviour – specifically, the offer law as illustrated by the inverse relation in the cointegration equations between spot and bid prices and available energy.

Another contribution of our study is that it allows the evaluation of the impact of different NCRES integration scenarios on the spot price. According to the results, if the current market structure remains unchanged, spot price volatility can almost triple, increasing financial risk; to effectively integrate NCRES in the Colombian electricity market, we need a regulatory framework that promotes development of financial instruments that help to mitigate it.

Accordingly, we see that higher NCRES integration translates into a spot price more sensitive to shocks in generation from these sources and the current market structure can tolerate around 25 % of the planned capacity increase in NCRES without significant changes in volatility.

On the system operation side, the results confirm the importance of accurate forecasts of both: the availability and energy production of NCRES; and a need to improve existing models of climate variables that directly affect these sources. In addition, market participants need efficient signals with regard to the impact NCRES will have on prices. More accurate NCRES operation models will help the development of adequate hedging mechanisms, reduce uncertainty, and promote the entry of participants with different risk profiles; also, market-oriented mechanisms like ancillary services or swing contracts, however these would require deep reforms to the Colombian regulation.

Our results also highlight the relevance of regulatory adjustments in electricity markets to better incorporate NCRES, as current mechanisms are highly dependent on short-term prices, which tend to increase their volatility, and therefore the risk, of what are already volatile commodities, one option, at least in the Colombian case, could be regulating the market participation of energy storage at the grid scale, as this would help stabilize the prices, and dampen the variability of these sources.

In future work, different structural formulations should be tested. One important improvement would be to use the actual capacity factors of solar and wind, once more operational data is gathered. Also, a more detailed representation of the error term must be done considering alternatives like the multivariate general auto-regressive conditional heteroscedasticity (MGARCH) formulation; so, the model could be used in a probabilistic setting where spot price distributions can be generated.

Another aspect is the inclusion of the long-term bilateral market, so we can measure the impact NCRES will have on the forward market and evaluate whether a higher level of long-term contracting helps to mitigate spot price volatility.

CRediT authorship contribution statement

David Cardona-Vasquez: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **John Garcia-Rendon:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Adriana Arango-Manrique:** Investigation, Methodology, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors would like to thank Universidad EAFIT for supporting this research through the Research Assistantship grant from project 952–000003. This research has also been developed in the framework of the “ENERGETICA 2030” Research Program with code 58864 in the “Colombia Científica” initiative funded by The World Bank through the call “778–2017 Scientific Ecosystems” managed by the Ministry of Science, Technology and Innovation (Minciencias).

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