Assessing the Complementarities of Colombia's Renewable Power Plants

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Comprehending the complementarities between a country's renewable power plants can help strategically plan for the future of its power system. Furthermore, complementarity can reduce the system's vulnerabilities and its dependency on a single energy source. The Colombian power system significantly depends on hydroelectricity, which meets approximately 65% of the country's electricity demand, making it vulnerable to droughts, particularly those caused by the El Niño–Southern Oscillation. Using either gas or coal power plants during a drought to back up the power system is expensive and polluting. This paper assesses the complementarities of Colombia's hydro, wind, and solar power plants, with the purpose of identifying the weaknesses and strengths of the system and suggest a way for redressal. Complementarity is assessed via Pearson's correlation analysis and Beluco et al. (2019) complementarity dimensionless indexes. The results suggest that the Colombian power system lacks complementarity, but it can be enhanced by investing in solar and wind power plants.

Keywords: complementarity, Colombia, renewable power plants, hydropower, wind power, solar power, El Niño–Southern Oscillation

INTRODUCTION

Colombia is renowned for its abundant water resources; consequently, its power system was built heavily dependent on water. Approximately 65% of the country's electricity consumption is derived from hydroelectricity, with the remaining 35% being sourced from fossil fuel-based power plants (primarily gas and coal). Hydropower accounts for 68% of the installed power capacity, distributed through 29 large-scale hydropower plants, which are centrally dispatched, and 115 non-centrally dispatched run-of-the-river hydroelectric plants (XM, 2019a).

Colombia's high dependence on water for its power system makes it vulnerable to droughts, especially those caused by the El Niño–Southern Oscillation (ENSO). ENSO is one of the significant catalysts influencing Colombia's hydroclimate, thus having a substantial impact on its power sector (Poveda et al., 2011). El Niño, ENSO's warm phase, is a natural phenomenon comprising abnormal warming of the sea surface over the eastern and central tropical Pacific, occurring every three to eight years and lasting for approximately 8–10 months (Poveda et al., 2006; Poveda et al., 2011). On average, El Niño reduces precipitation and runoff in Colombia, thus increasing electricity costs and power supply losses (Franco and Dyner, 2018).

In addition, Colombia also has abundant renewable resources, such as solar radiation and winds, particularly in the north, which can be used for electricity production (Henao et al., 2019; Henao and Dyner, 2020), although these have not yet been used to their optimal level. There is a 9.8 MW solar plant in western Colombia, an 18.4 MW wind farm in the north, and two new solar parks with 18 MW capacity. However, these alternative renewable power plants barely encompass 2% of the national demand.

Scholars have urged Colombia to complement its power system with alternative clean energy resources to minimize its vulnerability during dry periods and to decrease its fossil fuel usage (Zapata et al., 2018; Henao et al., 2019; Henao and Dyner, 2020). The complementarity between renewable energy sources has received increased attention since it can aid in the strategic planning for the future expansion of the power systems (Jurasz et al., 2020). However, it has not yet been studied in detail regarding Colombia, with few exceptions (Henao et al., 2020).

This paper assesses the complementarity between Colombia's existing hydro, wind, and solar power plants. The purpose is to identify which plants are essential, complementary-wise, and identify any requirements to enhance complementarity. We contrast Pearson's correlation coefficients and the complementary indexes of Beluco et al. (2019). Complementarity is evaluated by comparing pairs of renewable power plants, which include the 35 main tributaries that reach Colombia's hydropower plants, the Jepirachi wind farm, and Celsia's Yumbo solar plant.

The remainder of this paper is organized in the following manner: *Literature Review* briefly reviews the complementarity literature. *Material and Methods* presents the data and methodology. *Results and Discussion* demonstrates the results for Colombia and discusses their implications. Finally, *Conclusion* concludes and offers final remarks.

LITERATURE REVIEW

Complementarity between two renewable energy resources can be understood as the ability of one of the resources to compensate for the other's deficits, i.e., when the average energy availability of one resource is low, the energy availability of the other resource must be high (Beluco et al., 2008). In this regard, complementarity can occur between two (or more) energy resources of the same or different types, located at the same or different geographic places. The variations in energy availabilities can be due to seasons, differences in orography or location, or the physics-dynamics that make the weather variables to behave oppositely (Risso et al., 2018). Power networks can exploit complementarity by interconnecting energy resources located in different geographic regions that can complement each other. Thus, the literature recognizes the following types of complementarity:

- Temporal: It occurs between two energy resources located in the same geographic region during a specific season or period of the year (Beluco et al., 2008; Risso et al., 2018).
- Spatial: It occurs between energy resources located in different places over a vast region (Risso et al., 2018).
- Spatio-temporal: It takes place between energy sources of the same type over a vast region and during a specific period, or time of the year (Jurasz et al., 2020).

Correlation coefficients, such as Pearson's, Kendall's, and Spearman's, are the most commonly employed tools to assess complementarity (e.g., Cantão et al., 2017; Zhang et al., 2018). For

example, Ren et al. (2019) evaluated the complementarity of Chinese power plants combining wind and solar in the same place using Kendall's correlation coefficient. Han et al. (2019) developed and applied an index to assess complementarity in terms of the fluctuations and ramps of the energy resources. Li et al. (2019) used stochastic optimization to improve the operational performance of a hybrid power plant, using complementarity in their favor. Furthermore, Wang et al. (2018) evaluated a hydro-thermal-wind-photovoltaic plant, demonstrating that the generation of wind and solar generation can be increased together by taking advantage of complementarity.

Other metrics and approaches have also been proposed (see Prasad et al., 2017; Han et al., 2019; Canales et al., 2020a; Jurasz. et al., 2020). For example, absolute median deviation (Mohammadi and Goudarzi, 2018), portfolio models (Odeh and Watts, 2019), graphical representations and percentile ranking (Hoicka and Rowlands, 2011), critical time window (Berger et al., 2020), among others. Beluco et al. (2008) proposed the concept of energetic complementarity to assess the extent to which two energy resources can compensate for each other's energy availabilities. It combines three different characteristics: temporal-asynchronism, differences in average outputs, and differences in the range of variations. The concept encompasses not only the behavior of the variables over time and space but also the similarities of their average magnitudes and amplitudes of variations. For these reasons, Beluco's et al. (2008) approach was decided to be employed in this research.

Complementarity has been studied in numerous countries, including Brazil (Rodrigues et al., 2016; Silva et al., 2016), China (Zhang et al., 2018; Han et al., 2019), Poland (Jurasz et al., 2018a; Jurasz and Ciapała, 2017), Australia (Prasad et al., 2017), United States (Solomon et al., 2016), and the Iberian Peninsula (Santos-Alamillos et al., 2015). It has also been studied across countries. Miglietta et al. (2017), for example, evaluated complementarity between solar and wind energy using the Pearson correlation coefficient for the entire European continent. Chattopadhyay et al. (2017) evaluated the storage and backup requirements to supply a reliable energy service across Europe using renewables. Finally, François et al. (2016) demonstrated that integrating run-of-the-river, solar, and wind can increase the penetration rate of renewables regionally in Europe.

Most studies that explore complementarity to find ways to integrate different renewable resources to improve reliability on national power systems use simulation and optimization approaches. They are used to suggest ways to combine renewable resources (Moura and de Almeida 2010; Bezerra Leite Neto, et al., 2020), interconnect neighboring countries (Viviescas et al., 2019), or flatten the output of the renewable resources (Jaramillo et al., 2004). For example, in Poland, Jurasz and Ciapała (2017) developed an optimization model to reduce the variability of solar photovoltaics by combining it with a runoff power plant. And, Jurasz et al. (2018a) and Jurasz et al. (2018b) used simulation, optimization, and artificial neural networks to model the operation of a large-scale hybrid power plant.

The majority of the studies concerning complementarity in Latin America have focused upon Brazil. Risso et al. (2018), for example, used hexagonal-network-cells to quantify spatial complementarity and to map it. De Oliveira Costa Souza Rosa et al. (2017) used Pearson's correlation coefficients and a linear programming model to optimize the combination of three renewable energies. Borba and Brito (2017) developed a method to calculate the complementarity between at least two energy resources using hourly and daily time series. Cantão et al. (2017) developed hydro-wind correlation maps to record detailed complementarity analysis between two energy resources.

In Colombia, Henao et al. (2020) explored the complementarities between the hydro, solar and wind energy sources at the annual and interannual scales, using reanalysis information and Pearson's correlation coeficients. Paredes and Ramírez (2017) analyzed the wind/solar complementarity in different parts of the country, wherein water resources were feeding the power system. Pearson's correlation coefficient was used to estimate complementarity. Canales et al. (2020a) developed a temporal complementarity index that combines Pearson's correlation coefficient and compromise programming, and applied it in a follow-up paper across Colombia's territory using wind speed, solar radiation and surface runoff data from 2015 (see Canales et al., 2020b). The studies mentioned above have found evidence of high complementarity potential between solar radiation and runoff, and wind speed and runoff. Those studies, however, did not evaluate the complementarity between the actual renewable power plants that comprise the power system over an extended period. They estimated complementarity using climatic data in regions where actual plants do not exist.

This study assesses the complementarity between the renewable power plants in Colombia using 20 years of monthly data. We apply both Pearson's correlation coefficient and the dimensionless indexes of Beluco et al. (2019); Beluco et al. (2008). We assess the extent to which two power plants complement each other in terms of their energy output contributions. Our analysis facilitates the identification of crucial renewable assets, complementarity-wise (i.e., power plants that complement the most in relation to the rest of the other plants), and ascertains how to enhance complementarity to reduce the power system's future vulnerabilities.

MATERIALS AND METHODS

Data
The time-series data used for this research consists of 20 years of monthly observations (2000–2019) of water availabilities, expressed in energy terms, of the 35 main tributaries that feed the Colombian hydroelectric power plants. Additionally, the energy availabilities of the Jepirachi wind farm, located in the north, and Celsia's Yumbo solar plant, located in the west, were also employed. These data can be retrieved from XM's Portal-Bi database (XM, 2020a). XM is the electricity market operator who offers historical data related to the operation of the national power system free of charge. The water availabilities appear under

the Spanish name of "*Aportes mensuales*" (XM, 2020b), while the energy availabilities of Jepirachi (wind) and Yumbo (solar) can be found under the Spanish name "*Generación por recurso*" (XM, 2020c).

The names of the 35 tributaries used of the Colombian hydroelectric power system are the following: San Lorenzo, Alto anchicaya, Amoya, Bata, Betania, Bogotá NR, Calima, Carlos Lleras, Cauca Salvajina, Chuza, Concepción, Cucuana, Desv. EEPPM (Nec, Paj, Dol), Dev. Guarino, Dev. Meek, dev. San Marcos, Digua, El Quimbo, Florida II, Grande, Guadalupe, Guatape, Guavio, Magdalena Betania, Miel I, Nare, Other Rivers (Estimated), Porce II, Porce III, Porce2 Cp, Prado, San Carlos, Sinu Urra, Sogamoso and Tenche. **Figure 1** illustrates the location of the tributaries.

Figure 2 depicts the monthly total energy availabilities of the national power system with standard deviation (**A**), and the average contribution of each power plant (**B**). The former shows the bimodal cycle of Colombia's rainy/dry weather (Poveda et al., 2011). The energy availability peaks during May–June, and again in October–November, while the least contributions from power plants occur during January–March. **Figure 2B** highlights the power plants contributing the most to the national power system: Nare, El Quimbo, Sogamoso, Grande y Porce II.

Methodology
The complementarity between two energy resources or, in this case, two power plants is calculated in the following manner.

First, Pearson's correlation coefficient is calculated over the monthly averages emerging from the observations of the two energy variables. The correlation coefficient ranges from −1 to +1, where negative values are interpreted as complementary. Synchronism is assumed when correlation results are positive. Finally, values close to 0 indicate that the two plants are neither complementary nor synchronic.

Second, the energetic complementarity indexes (Beluco et al., 2019) are calculated based on the monthly averages of the data described in *Data*. Beluco et al. (2019) proposed three complementarity indexes: temporal (K_t), energy (K_e), and amplitude (K_a).

The temporal complementarity index K_t is calculated according to **Eq. 1**. Where m_1 and m_2 represent the months where the minimum energy availabilities of the first and second energy resources occur, these values range between 1 and 12. Thus, K_t shows how distant in time, the two minimum values occur. K_t equals one when the two minimums are six months apart, and it equals zero when the two minimums occur in the same month. In terms of complementarity, two minimum values occurring in different months, ideally six months apart, are desired.

$$K_t = \min\left\{\frac{|m_1 - m_2|}{6}; \frac{12 - |m_1 - m_2|}{6}\right\} \qquad (1)$$

The energy complementarity index K_e is estimated according to **Eq. 2**, where e_1 and e_2 are the average energy availabilities for the first and second energy resources. K_e equals one when the average
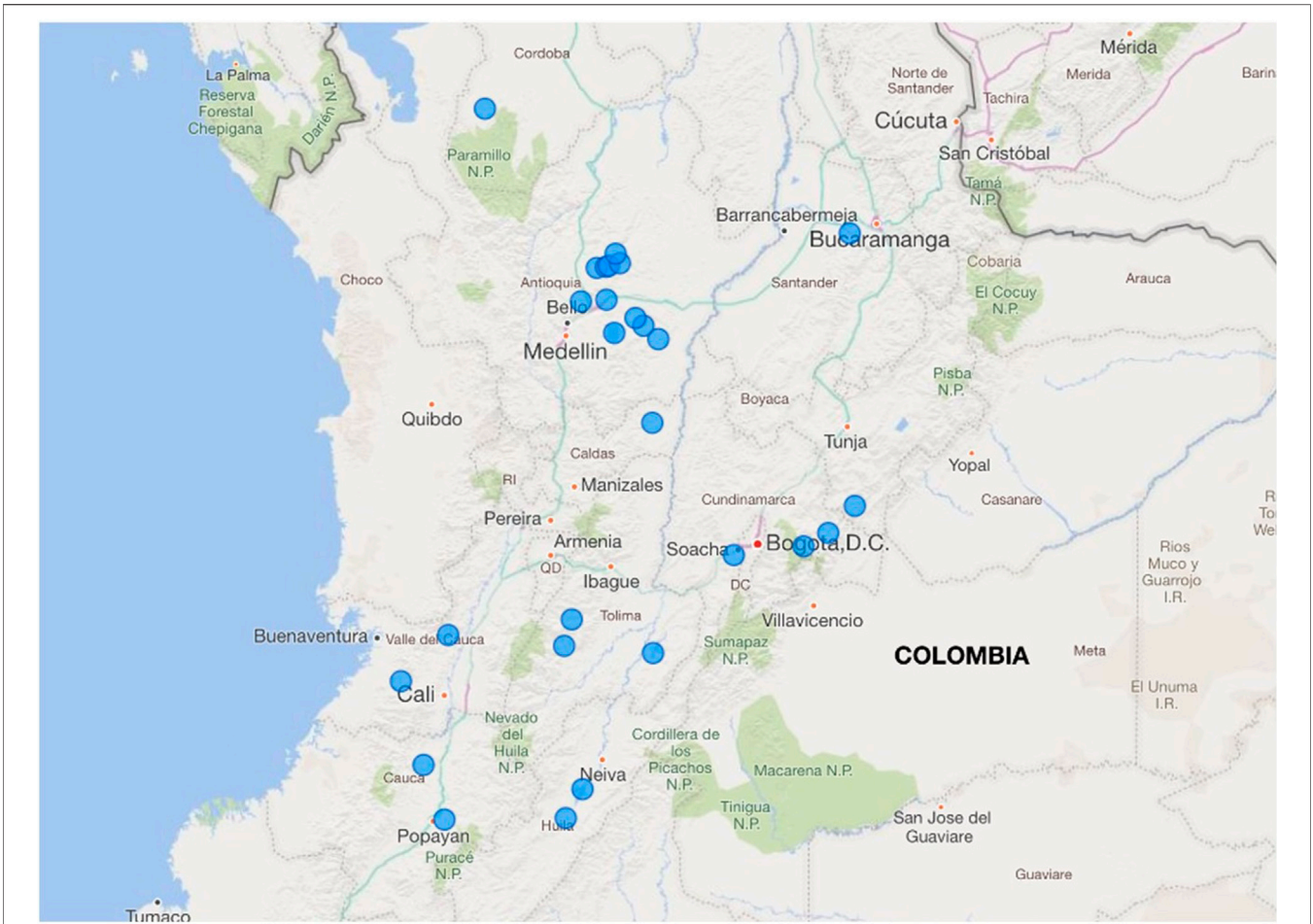
FIGURE 1 | Location of the 35 main tributaries that feed the Colombian hydroelectric power system.

values are the same, and it is close to zero when one value is much larger than the other. For complementarity, equal average amounts are desired.

$$K_e = 1 - \frac{|e_1 - e_2|}{e_1 + e_2} \qquad (2)$$

The amplitude complementarity index K_a is calculated according to **Eq. 3**. Where δ represents the difference between the maximum and minimum energy availabilities to the average value e. In both cases, if the minimum and maximum values are the same, δ equals one, and if this occurs with both energy resources, K_a also equals one. For complementarity, the variation in both resources should be similar.

$$K_a = \begin{cases} 1 - \left(\dfrac{\delta_1 - \delta_2}{1 - \delta_2}\right)^2 \dots \text{if } \delta_1 \le \delta_2 \\[2em] \dfrac{(1 - \delta_2)^2}{(1 - \delta_2)^2 + (\delta_1 - \delta_2)^2} \dots \text{if } \delta_1 > \delta_2 \end{cases} \qquad (3)$$

$$\text{where } \delta = 1 - \frac{(\max - \min)}{e}$$

A complementary index K is calculated by multiplying the time, energy, and amplitude complementarity indexes: $K = K_t * K_e * K_a$. Here, values close to one indicate that the two power plants complement each other in time, output, and intermittence; whereas, values close to zero indicate that at least in one of these three characteristics, one power plants fail to match the other.

RESULTS AND DISCUSSION

Figure 3 displays the correlation coefficients calculated by comparing pairs of power. The plants appearing along the x and y axes and are listed in alphabetical order. The correlation values are represented on a color scale, where negative values are red (complementarity); positive values are blue; and values close to 0 are white. As observed, blue predominates, meaning that the energy availabilities of most power plants are synchronized or fluctuate similarly. The plants Grande, Bogotá NR, and Nare show a significant coupling with the others, that is, with little complementarity. Note that the solar and wind power plants, appearing at the bottom and on the right-hand side, show a high
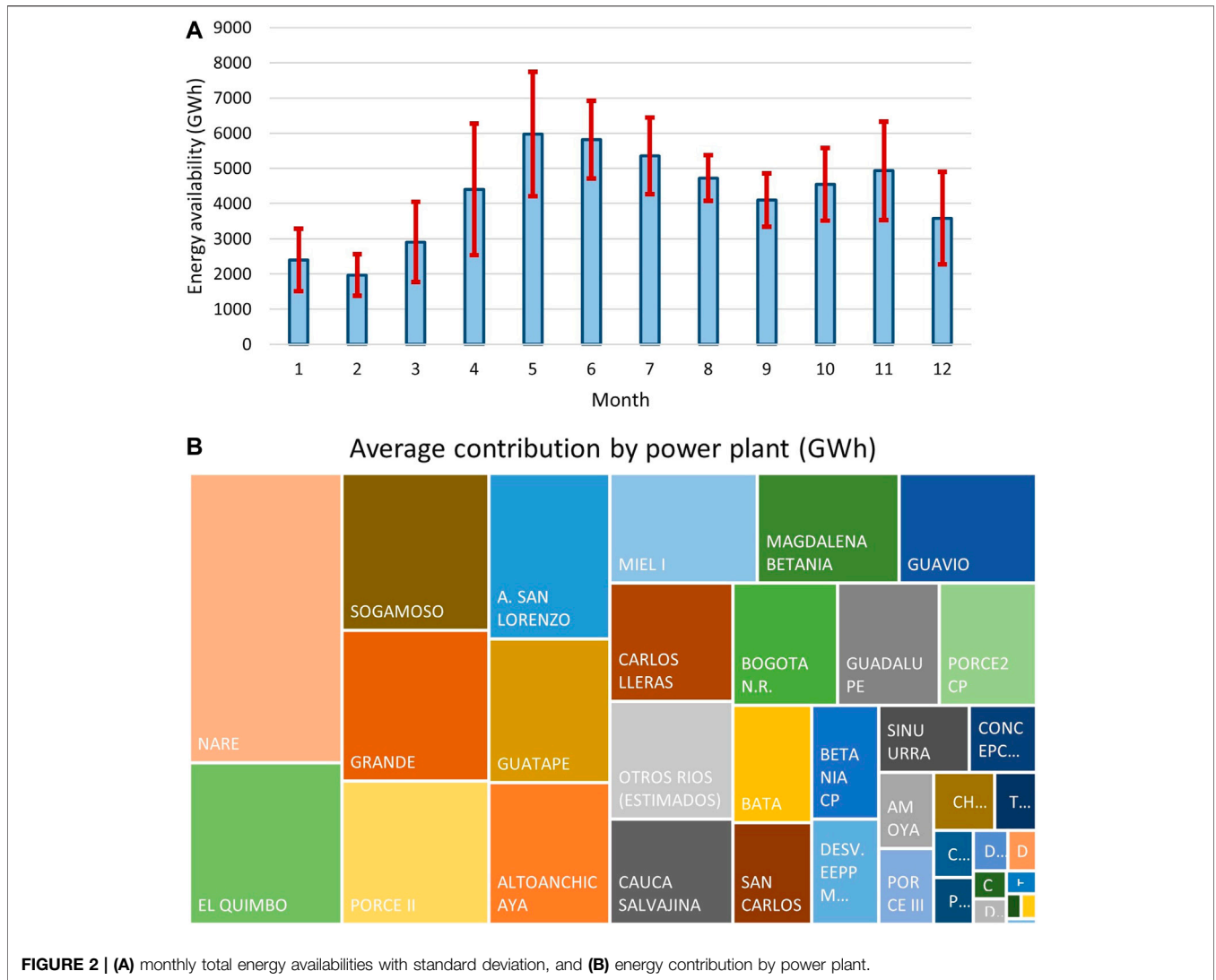
FIGURE 2 | (A) monthly total energy availabilities with standard deviation, and **(B)** energy contribution by power plant.

degree of complementarity with the rest of the power plants (see the red colors along the bottom and right edges in **Figure 3**).

Figure 4 displays the three complementarity indexes, K_t, K_e, and K_a. The renewable power plants are lined along the x and y axes in the same alphabetical order presented in **Figure 3**, and the diagonal corresponds to the comparison of a power plant with itself. K-values range from 0 to 1, where 0 indicates no complementarity between plants, and one indicates strong complementarity. Here, the K-values close to 0 appear in white and light blue, whereas K-values close to one are in dark blue.

Figure 4 (left) depicts the results of K_t. As can be observed, white and light blue predominate, suggesting that most of the power plants are synchronic or have little complementarity with the rest of the power plants in terms of time. Only a few blue stripes are shown, indicating that they behave oppositely, including Miel I (a hydro located in the central-west), Calima (a hydro situated in the west), Alto Anchicaya (a hydro situated in the west), Yumbo Solar (a solar farm located in the west), and

Jepirachi (a wind farm located in the north). The minimum energy availability of these plants occurs within six months difference from the rest of the plants.

The K_e matrix (**Figure 4**, middle) shows mixed results, i.e., blue and white. Blue indicates a significant group of plants, particularly hydroelectric plants, sharing similar average energy availabilities. These plants can eventually compensate for the deficits of their counterparts during a drought. The white and light stripes, in the center and on the right-hand side, represent power plants that are significantly bigger (or smaller) than the rest, making it difficult for them to be covered in case of deficits (or to cover plants with deficiencies). Among the smallest plants are Yumbo Solar, Jepirachi, Desv. San Marcos, Florida II, and Desv. Guarino. These plants show low complementarity because their sizes are minimal vis-à-vis the others.

Figure 4 (right), which represents the K_a index, depicts mostly blue, suggesting that most energy resources fluctuate with the same intensity, i.e., their energy availabilities deviate similarly from their average value.
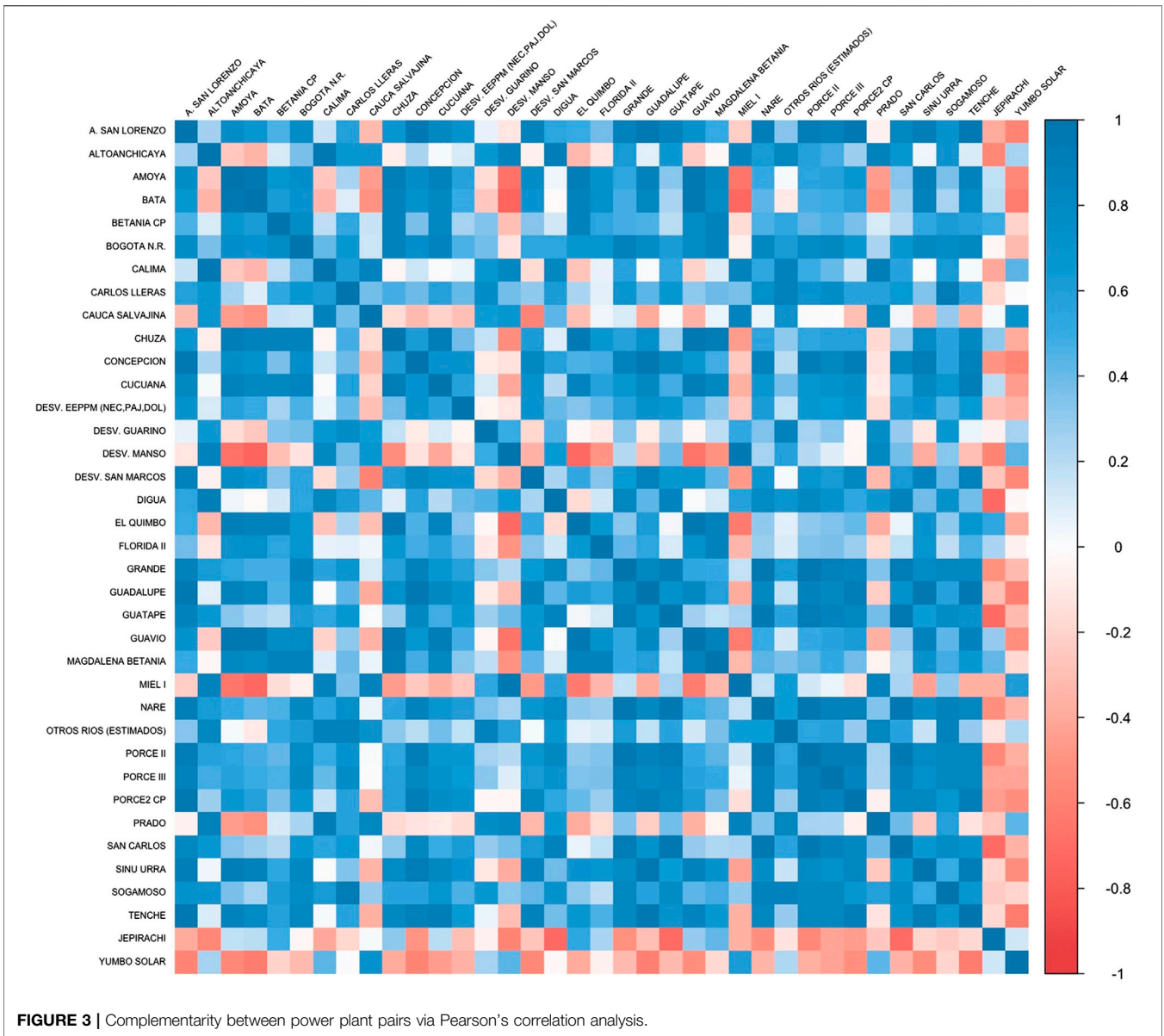
FIGURE 3 | Complementarity between power plant pairs via Pearson's correlation analysis.
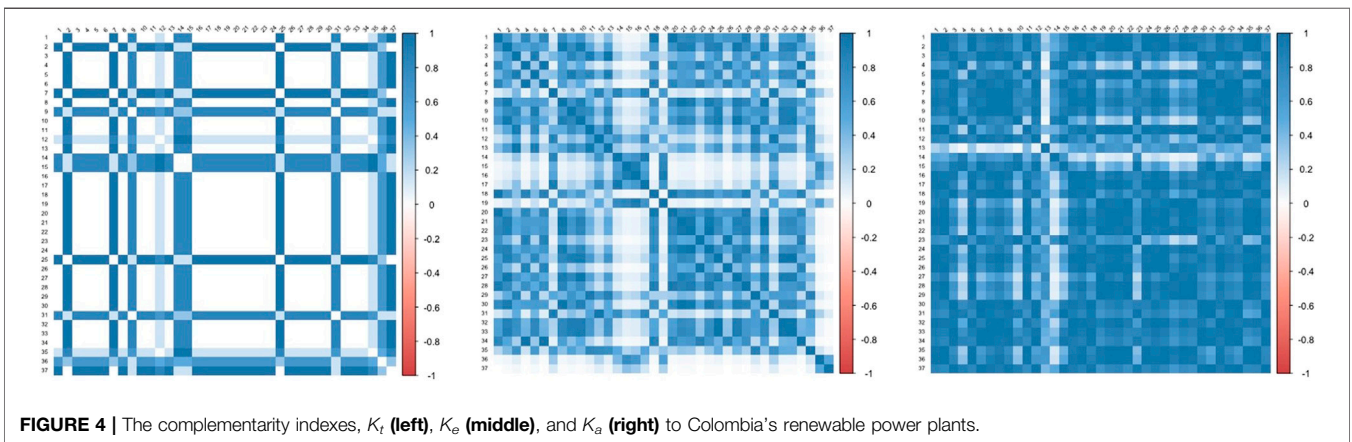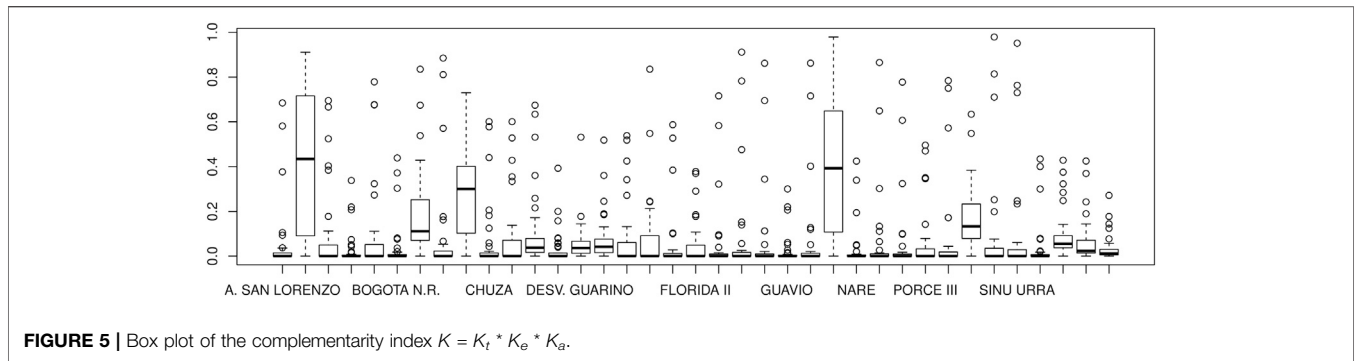

FIGURE 4 | The complementarity indexes, K_t **(left)**, K_e **(middle)**, and K_a **(right)** to Colombia's renewable power plants.

FIGURE 5 | Box plot of the complementarity index $K = K_t * K_e * K_a$.

For the K complementary index, values close to one represent full complementarity between power plants, i.e., their minimum values are 6 months apart, they have similar average energy availabilities, and their energy resources fluctuate with the same intensity. Values close to zero mean that the two power plants do not match in at least one of these three factors.

Figure 5 presents a box plot with the final K complementary index of all power plants. The figure shows that the final K index of most power plants is close to zero, indicating no complementarity with the rest. This suggests that the power plants are either synchronic, or if asynchronous, they cannot compensate for the deficits of the others due to their small size. These results demonstrate that the Colombian power system was built without considering the volatility and complementarity of the overall portfolio of energy resources comprising the system.

Only two hydropower plants (number 2 Alto Anchicaya, and number 25 Miel I) have decent middle-range complementarity values. In terms of planning, it is ideal to have several power plants (boxes) close to 1, with little dispersion or variability, in order to reduce the system's vulnerability via complementarity.

Figure 6 summarizes the results of Pearson's correlation analysis and the final K index to all pairs of renewable power plants, showing mixed results. The cases appearing in sector (indicated by the red dot) one are those where both methods suggest complementarity. The cases in sector two are those where both methods indicate no complementarity. Moreover, in sectors 3 and 4, the methods contradict each other: one suggesting complementarity and the other not suggesting any complementarity. Next **Figure 7** illustrates such cases with specific examples and deconstructs them in detail.

Figure 7A illustrates a case in sector one (case 1) by comparing the monthly average energy availabilities of the Sinú Urra and the Miel I power plants. As can be observed, both plants indicate complementarity, particularly from May to October. In this case, Pearson's correlation coefficient was negative, with a value equal to −0.43, suggesting complementarity. Similarly, the K index, equal to 0.95, suggests complementarity (K_t, equal to one; K_e equal to 0.99; and K_a equal to 0.96) indicate that both plants are entirely complementary in terms of time, average energy availability, and amplitude of variation.

Figure 7B illustrates case 2, showing the Guavio (hydro) and Bata (hydro) plants. Here, both plants behave similarly over time, indicating that they are coupled or synchronous. Pearson's correlation coefficient was positive and high (0.956),

**FIGURE 6 |** The complementarity K index (Beluco et al., 2019) and Pearson's correlation analysis.
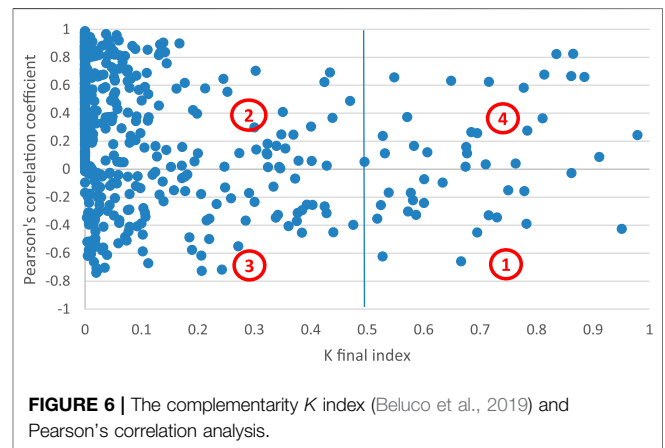
suggesting synchronism between both plants, while the K index was zero (0.0038), indicating no complementarity. Here, complementarity is not achieved because K_t was equal to 0 and because the minimum energy availabilities in both plants occurred in February.

Figure 7C, case 3, is illustrated with San Lorenzo and Bata. Ostensibly, the two plants appear complementary, particularly from May to October, i.e., Pearson's correlation coefficient was −0.69. However, the K_t index was 0, indicating low complementarity in terms of time, because their minimum values occurred both in February. The, complementarity appears to occur just during the middle of the year and the rest of the time the two plants are synchronized.

Finally, case 4 is illustrated via Alto Anchicaya and Guadalupe (**Figure 7D**). The K index is 0.92, reflecting an apparent complementarity behavior from May to November. However, Pearson's correlation indicates otherwise, reporting a value of 0.09. The correlation value approximates zero because both plants synchronize after month 11, i.e., from month 12 to month four of the following year. Therefore, Pearson misses detecting the partial complementarity happening from months 5–11 due to the synchronism occurring from months 12 to four of the next year.

The same degrees of complementarity illustrated in **Figure 7** can also be visualized by contrasting the time-series of the power plants' energy availabilities. **Figure 8** compares the time-series of such power plants to illustrate the same four specific case examples discussed above. Case 1 contrasts the time series of
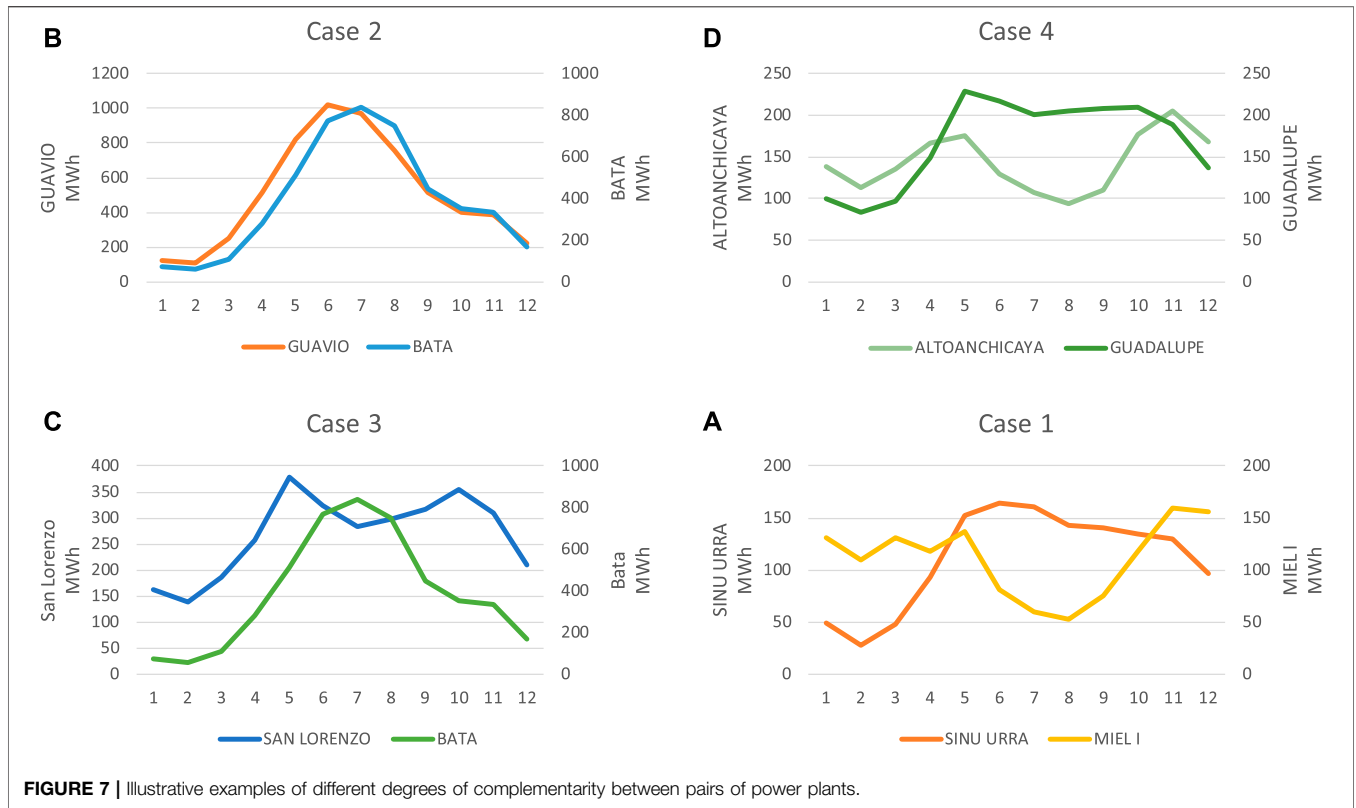
FIGURE 7 | Illustrative examples of different degrees of complementarity between pairs of power plants.

Sinu Urra vs. Miel I. This case shows the most evident complementarity of all, depicting two time-series that are asynchronous or in opposite phases (i.e., when one variable increases, the other decreases) (**Figure 8A**). Case 2 (**Figure 8B**) is on the opposite side of the spectrum. It shows two power plants (Guavio vs. Bata) that are almost perfectly synchronized (i.e., both variables increase and decrease simultaneously). The other two cases, cases 3 and 4, present partial complementarity characteristics. They have moments where the two variables appear to move in opposite directions (e.g., see case 4 around April–September 2011), and moments where the two variables appear to be synchronized (e.g., see case 4, around October 2003–March 2004). Therefore, rather than being a binary state, complementarity appears to be a continuum where two variables could be either asynchronous or synchronous or have partial complementarity characteristics.

As previously mentioned, the El Niño is an interannual climatic phenomenon that reduces runoffs in most of the tributaries that feed the national power system in Colombia (Poveda et al., 2006; Poveda et al., 2011). This occurs regardless of the tributaries' degree of complementary with others. **Figure 9A** shows the anomalies caused by the El Niño and La Niña events, from 2000 to 2019, on the time-series of the tributaries in the four cases analyzed above (blue lines). It also depicts the Oceanic Niño Index (ONI) in red, which indicates when an El Niño or La Niña event takes place. When ONI values are above (below) +0.5 (−0.5), over five consecutive overlapping seasons, an El Niño (La Niña) event is taking place (NOAA,

2020). The anomalies to study this phenomenon were calculated following **Eq. 4**.

$$z_{i,m} = \frac{x_{i,m} - \mu_m}{\sigma_m} \qquad (4)$$

Where: $x_{i,m}$ represents the i-th observation of month m, μ_m is the mean value of month m, σ_m is the standard deviation of month m, and $z_{i,m}$ represents the standardized anomaly associated with the i-th observation of month m.

Figure 9A shows that the tributaries of the four cases above experienced negative anomalies, below their monthly average levels, during El Niño, and positive anomalies during La Niña. It means that although a pair of tributaries could complement each other on regular times (e.g., see **Figure 8A**), this feature is likely to be curtailed during ENSO. The same anomalies pattern presented in **Figure 9A** has been observed in other tributaries and the aggregated water inputs the entire power system. As a result, different scholars have called to complement Colombia's hydropower sector with alternative energy sources, such as wind and solar, to strengthen the power system to face future ENSO events (Henao et al., 2020). In this regard, **Figure 9B** compares the Jepirachi wind farm's anomalies with those of the national power system's water inputs. As can be seen, the two energy resources behave complementarily during regular times and ENSO events, i.e., when one resource experiences negative anomalies, the other experiences positive anomalies, which is a feature highly desired for the Colombian power sector during El Niño.
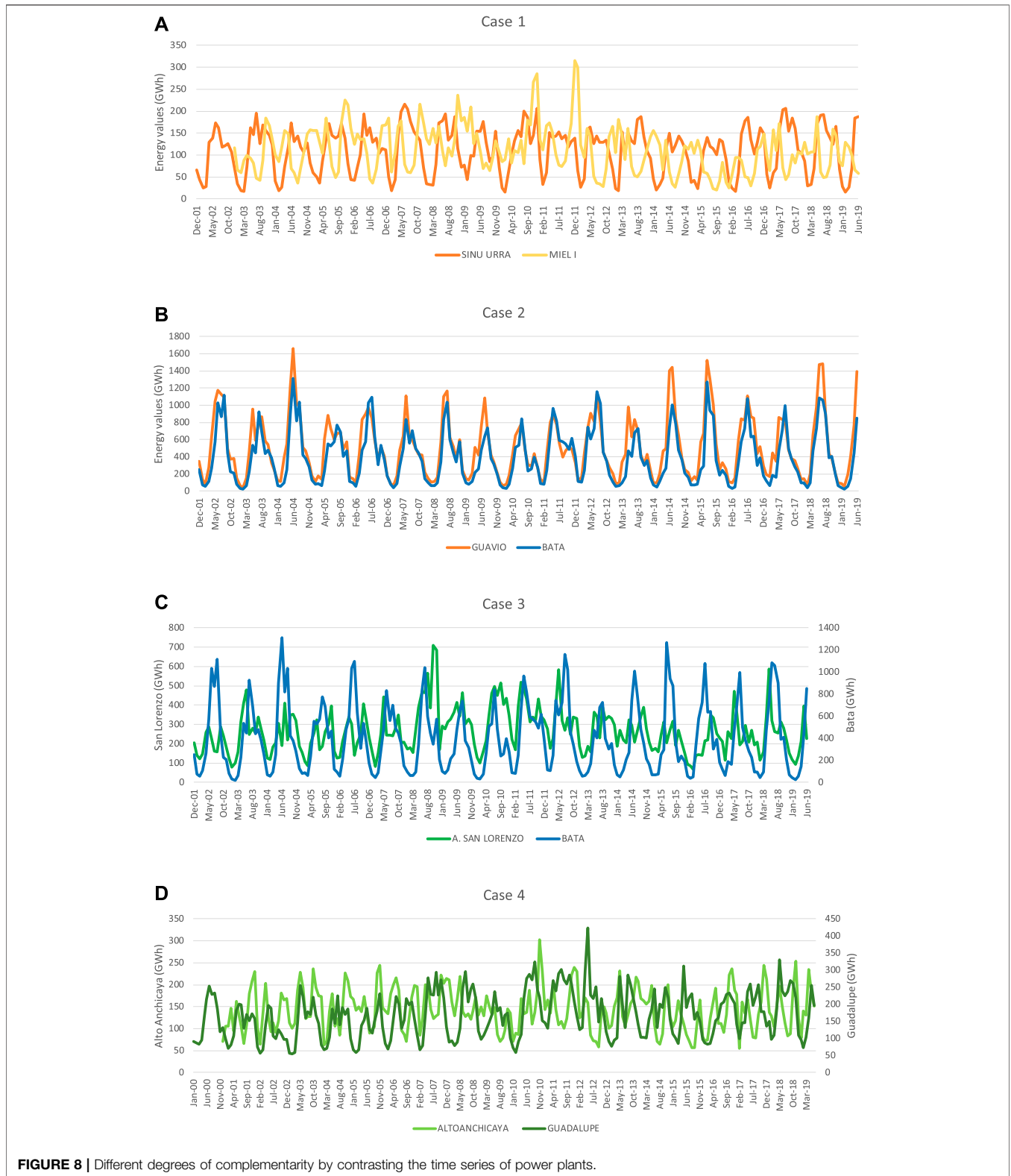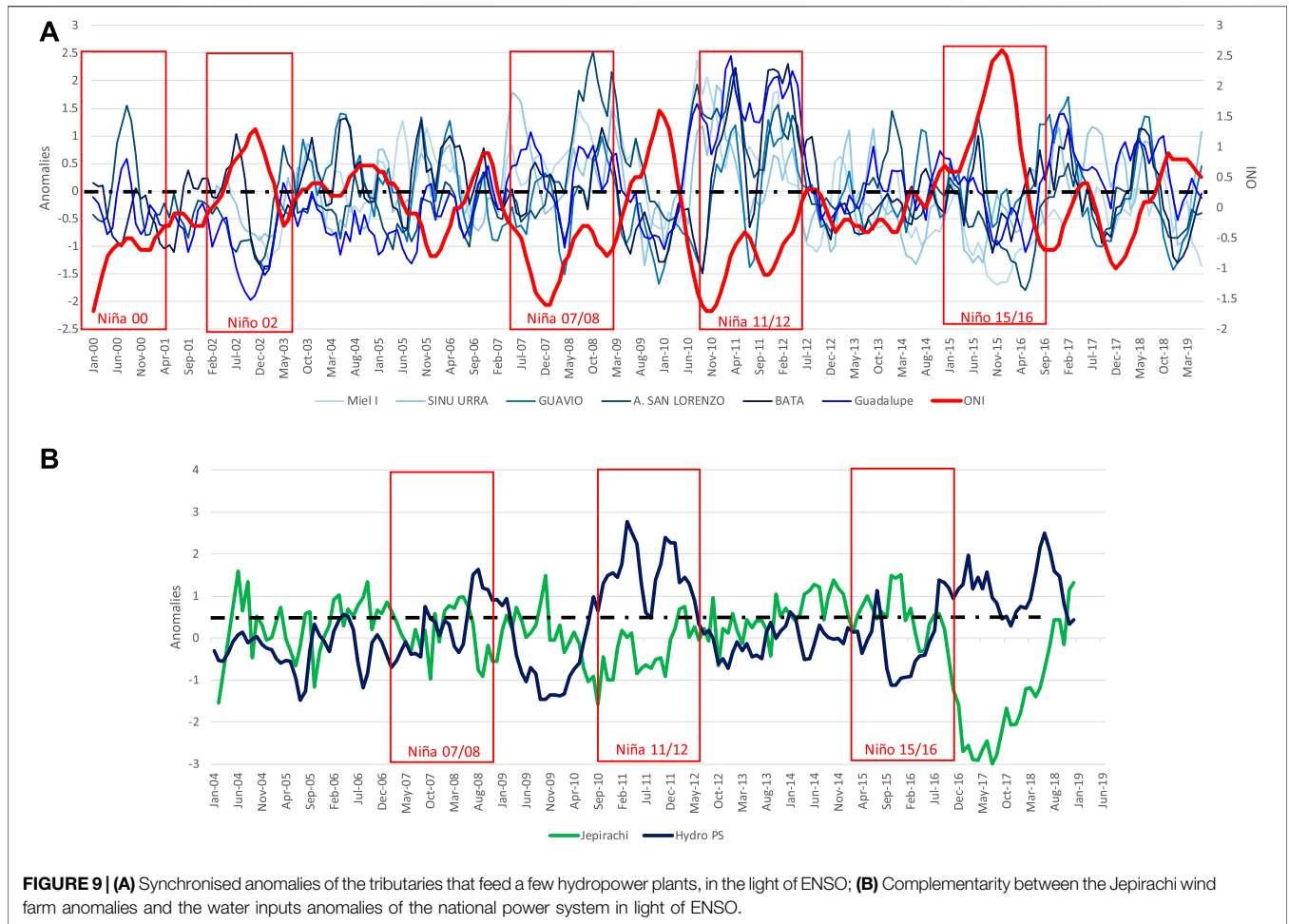
FIGURE 8 | Different degrees of complementarity by contrasting the time series of power plants.

In summary, the complementarity between two renewable power plants entails different characteristics beyond the asynchronous temporal behavior of the weather variables that feed those plants. The complementarity methodology of Beluco et al. (2019) considers three aspects of the weather variables: temporal behavior, average output, and amplitude. Pearson's

FIGURE 9 | (A) Synchronised anomalies of the tributaries that feed a few hydropower plants, in the light of ENSO; **(B)** Complementarity between the Jepirachi wind farm anomalies and the water inputs anomalies of the national power system in light of ENSO.

correlation analysis, which is tantamount to the K_t index, assesses complementarity only in terms of time. It misses the other two characteristics and fails to detect partial temporal complementarities, e.g., case 4 (**Figure 7**).

Regarding the power plants, the alternative renewables Jepirachi (wind) and Yumbo (solar) have both, for example, shown temporal and amplitude complementarities with most of the hydroelectric plants of the national power system. However, their final K index was low due to significant differences in size (Ke) with the other plants. These results suggest that the alternative renewable sources wind and solar have a high potential to complement Colombia's hydropower system if used more substantially. Therefore, future capacity generation investments should consider installing new solar and wind power plants in locations nearby Jepirachi and Yumbo, to improve the system's capabilities to compensate for the deficits of the hydropower plants during El Niño events.

On average, the water inputs that feed the national power system can experience significant reductions, up to 0.8 standard deviations, in power generation capacity, during an El Niño event. This equates approximately 1,000 GWh/month or 20% of the national demand. Hence, based on the average performance of Jepirachi or Yumbo power plants, for example,

it can be estimated that roughly an extra 9.5 GW of solar power or 6.4 GW of wind power, or a combination of the two, would be needed to compensate for such El Niño reduction effects in hydropower generation capacity. It is important to note, however, that power capacity expansion modeling requires the development of simulation or optimization models, which goes beyond the scope of this paper, to indicate the exact generation and transmission capacity investments that a system would need into the future (e.g., Henao and Dyner, 2020). These models, which usually consider future electricity demands, fuel prices, technology costs, and other technical elements, rarely include complementarity concepts (e.g., Da Luz and Moura, 2018). In this regard, we argue that energy planning would significantly benefit from complementarity concepts to guide future power capacity expansion choices.

CONCLUSION

In this paper, the existing complementarity between the renewable power plants (hydro, wind, and solar) in Colombia was assessed. Complementarity was quantified through Pearson's correlation coefficient and Beluco et al. (2019) complementarity

dimensionless indexes. Our study indicates the degree of complementarity within Colombia's power system. It also highlights the plants that are strategic, complementarity-wise, and others to be installed in the future to enhance complementarity.

The main findings of the study are as follows:

- The Colombian power system evidenced an overall low complementarity behavior between its renewable power plants;
- Most hydro-based power plants present similar temporal and amplitude characteristics, which makes the power system vulnerable to droughts;
- Wind and solar power plants have a high potential to complement Colombia's hydroelectric system, which suggests that more power capacity is needed to enhance such complementarity;
- Beluco et al. (2019) methodology provides a more holistic view of the complementarity concept than the widely-used Pearson's correlation coefficient;
- Beluco et al. (2019) method obtain similar results to Pearson's in terms of the temporal perspective, while offering two additional aspects and detecting partial temporal complementarities.

To conclude, from a practical point of view, this study recommends more ambitious investments in alternative renewables to diversify Colombia's energy matrix, and consequently reduce its drought vulnerability. Energy planning should start considering complementarity concepts alongside energy cost criteria to guide future power capacity choices. Also, the recent technological advances concerning artificial intelligence and sensor controls, among others, should be used to empower costumers and make the demand more responsive during critical dry seasons. Finally, in terms of methodology, Beluco et al.'s (2019) approach is recommended since it offers a broad perspective toward complementarity. The ideas above provide a vast number of opportunities to undertake future energy-related research, where the complementarity between renewable resources take a more dynamic role in energy planning and decision-making.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: http://portalbissrs.xm.com.co/Paginas/Home.aspx.

AUTHOR CONTRIBUTIONS

FH contributed by writing the manuscript and conceptualizing the work; LP contributed by searching at background literature and writing the manuscript. SG contributed by collecting the data and undertaking the empirical estimation. CM contributed by searching at background literature and writing the manuscript.

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