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Variable Renewable Energies and Their Contribution to Energy Security:

Complementarity in Colombia

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Abstract

The Energy Division of the Infrastructure and Environment Sector (INE/ENE) of the Inter-American Development Bank support the efforts of its member countries to improve their energy security through diversification and increased use of endogenous sources of renewable energy. Electricity does not exist as a natural resource; it must be generated from primary sources—fossil fuels and Variable Renewable Energies (VRE). This monograph describes the linkages between the concept of *capacity* in energy markets and the characteristics of VRE—hydro, solar, and wind.

We live in a carbon-constrained world challenged by climate change. This document provides practical ways for member countries to increase their energy security and to assess the complementarity between variable renewable energies such as wind or solar. The publication assesses the complementarity between variable renewable energies such as wind or solar and one of the most abundant renewable resources in Latin America, hydropower, taking the Colombian electricity system as a case study.

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Introduction

The region comprising Latin America and the Caribbean is facing a series of challenges to its energy security. Because energy consumption and economic growth go hand in hand, countries must provide sufficient capacity for their electricity systems—the generation, transmission, and distribution of energy to end-users. Without sufficient capacity, countries cannot ensure their energy security. The region must also become more energy-efficient by increasing the share of renewable energy in its energy mixes. Secure, efficient, and renewable energy, all three, are central to the region's future. Together they can form a pillar for a competitive and productive region.

The integration of renewable energy into this sector faces significant hurdles, however. Surmounting them will require not only regulatory changes but also a detailed knowledge of the resource, its variability, and its potential to meet the region's energy needs.

Compared with traditional fuel sources like coal, oil, and natural gas, electricity produced with wind or sun is almost free from carbon emissions. Their capital cost was once an insuperable hurdle, but costs have plummeted in the past decade. Their economic feasibility is now a selling point to governments and out-of-sector investors. Electricity produced on sites with abundant wind and solar is now competitive with fossil fuels; for isolated regions, wind and solar are already the cheapest and cleanest fuel for the generation of energy.

But wind, solar, and hydropower are variable resources, making the electricity generated by wind turbines, solar panels, and run-of-river hydropower plants variable as well. This variability can make it difficult to dispatch energy on demand, in contrast to conventional power plants, which are able to store and process fossil fuels almost immediately, providing baseload capacity. Two options are available to mitigate the variability of renewable resources and provide on-time demand: (1) energy storage and (2) electrical interconnections.

Hydropower's first option is water stored in reservoirs or behind dams. Used for millennia by farmers and millers for irrigation and food production, dams and reservoirs are now invaluable in the generation of electricity. Few technologies are available, however, for the storage of large amounts of solar heat or electricity—at least at competitive prices without having to resort to subsidies. But with the dramatic decline in battery costs (and the advent of mass-production of advanced battery systems), countries now have a viable option, in the near future, for storing large amounts of electricity.

Countries also have the option of sharing surplus renewable energy. In Scandinavia, the Nordpool market can send surplus wind energy from Denmark, which sometimes runs at 140 percent of demand, via submarine cables to Norway for consumption in that country. This spares Norway the cost of generating energy from water stored in its dams, freeing it for later use.

But insufficient storage and the lack of interconnecting electrical grids raise a number of questions around capacity. Can renewable energies provide baseload capacity for countries that rely on conventional energy systems? What percentage of the baseload capacity can be replaced by renewable energy? Does that percentage correspond to the nominal power of the renewable energy plants? This paper will address these and other questions by describing basic concepts and international experiences and providing regional case studies.

This monograph describes how variable renewable energies (VRE) such as wind or solar might contribute to Latin America's energy security. The first section will cover energy security concepts (such as reliability, affordability, and complementarity), especially as they relate to VRE; national studies and scientific work will be cited in support of the theory. Besides of the spatial complementarity, the temporal complementarity between different VRE resources is one of the most relevant advantages that these resources can offer to cover electricity demand effectively; examples from Brazil, Uruguay, and South America's Pacific coast are given. In the second section, the complementarity of wind, solar, and hydropower in Colombia are described in depth; this fact could constitute a feasible alternative to diversify a very high hydro dependent energy matrix, making it more resilient to natural variability and climate change.

Energy security and complementarity

According to the IEA, energy security is the "uninterrupted availability of energy sources at an affordable price." Energy security over the longer term must be based on reliable energy sources that are priced as competitively as possible and stable over time. It is also essential to understand that the concept of energy security has gained greater relevance in the past few years as new social, economic, and environmental dimensions need also to be considered in energy policy and planning exercises.

The use of VRE has direct implications in the energy security of the countries. VRE use native and local resources that reduce the region's dependence on imports and lower greenhouse gas (GHG) emissions, while lowering water consumption per unit cost of electricity. In addition, distributed VRE-generated electricity has the potential to cut energy losses in transmission and distribution lines and to create systems that are more resilient in the face of natural disasters.[1] Technical improvements in these areas may allow countries to postpone (or avoid altogether) spending on transmission and generation infrastructure.

Many of the benefits identified above could translate into lower direct costs for the system. In addition, with lower subsidies for fossil fuels, governments realize advantages, which, depending on the tariff scheme, might benefit end users. The community enjoys indirect economic benefits through improvements in air and water quality, the generation of jobs, and stronger supply chains for industry.

Finally, this paper will focus not on the economic aspects of energy but rather on the conceptual and technical relationships between VRE and conventional energy sources and their contribution to energy security.

Reliability

The reliability of energy supply can be considered across several timeframes in comparing generation technologies based on fossil fuels with those based on VRE.[2] With regard to the reliability of VRE, we want to acknowledge fears expressed around the increased penetration of variable renewables into electricity networks. To wit: that systems are rendered more vulnerable to blackouts or other extreme events. In our view, these fears run contrary to the experience in countries with high percentages of variable energy. In fact, we have observed that even with an increased penetration of variable renewables, the systems remain stable. Similarly, the likelihood of outages and unavailability remains stable and is in fact lower than in systems based almost solely on fossil fuels or nuclear. Although a causal relation cannot be established between a higher percentage of variable renewables and network stability, these operational observations support arguments in favor of wind or solar plants and stable electricity networks.

One indicator for the reliability of an electricity system is its index of average interruption-duration, or SAIDI (figure 1, p. 16). Countries with lower SAIDI scores (or higher system reliability, like Germany and Denmark) have larger shares of VRE in their energy mix. In Germany 19.2 percent of the electricity consumed in 2015 was generated from wind or solar, while in Denmark, wind power alone reached a 42 percent share throughout the year (Graichen 2016).

In 2013 Spain and Italy had VRE share percentages above 30 percent in their energy mix, and better reliability indexes than countries possessing lower penetrations of variable renewables, like France and the United States. Interconnected electrical grids are also critical in managing the variable capacity and characteristics of solar and wind power. In the case of Europe, such interconnectedness guarantees the region's short-term ability to deliver surplus energy to a neighboring country dealing with a shortfall of renewable resources.

As for the long term, measured on a yearly scale, fossil fuels offer the desired reliability in terms of delivery, provided firm power-supply contracts are in place throughout the useful life of the generation plants, in addition to any other mechanism ensuring a constant supply of fuel to the plants. Coal, oil, and natural gas can all be stored, so their supply can be guaranteed through the use of economic contracts, at least as long as the effects of their depletion are not noticed; the planet has only a finite supply of these resources.

The reliability offered by fossil energy sources will therefore depend more on geopolitical or environmental variables.[3] When countries need to import fossil fuels, they become dependent on the market or the producing country. If an ideal geopolitical environment ensures the supply of these fuels, then energy security will depend to a greater or lesser extent on how diversified the power generation mix is and the degree to which it is dependent on external agents.

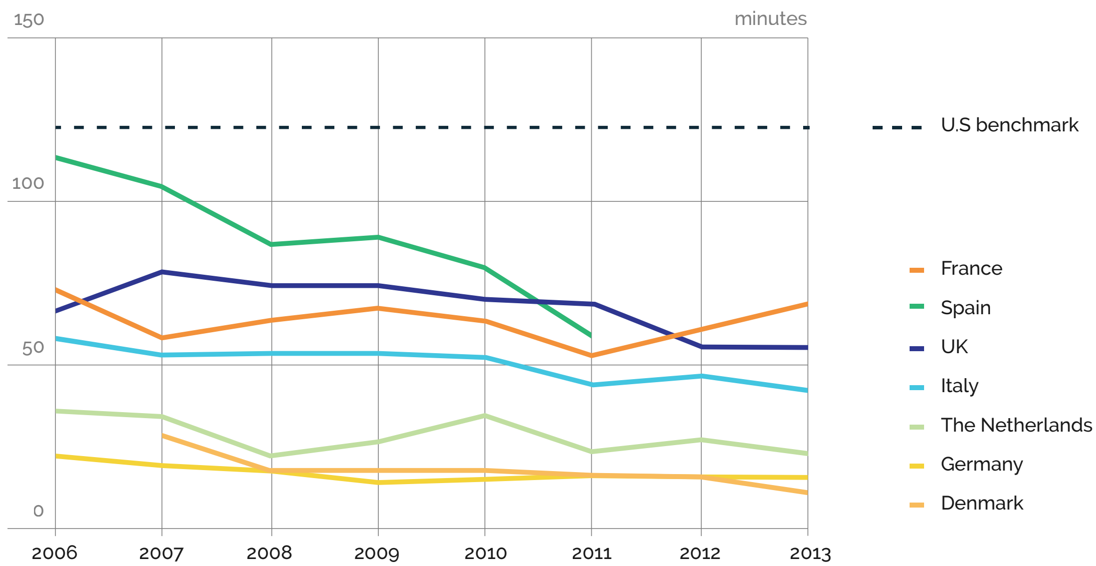
Renewable energy sources guarantee a long-term supply, provided they are managed sustainably. Sustainability may also be relevant for biomass or geothermal resources, where the consumption of

[1] Assuming the design of decentralized generation based on local renewable resources is adequate (and siting meets vulnerability criteria), the probability of major blackouts decreases when those disasters affect large generation units.

[2] The short- and medium-term challenges of VRE (which is to say, the per-minute or hourly scales used to measure electricity) deserve a more in-depth discussion. Please refer to the 2013 IDB Regional Policy Dialogue (Batlle 2014).

[3] Among the most relevant of environmental variables is the Paris Agreement—ratified by the UN General Assembly on November 4, 2016.

Figure 1. SAIDI for several European countries.



Source: Energy Transition 2015.

the primary resource may outstrip the growth of biomass, in the first case, or the replenishment of aquifers or sources of heat, in the second. Within the range of variable renewable energies, this paper will address solar and wind, so an unlimited supply over time is assumed—a supply unaffected by consumption rates.

Because VRE depends on climatic and atmospheric variables over the long term—absent the possibility of storing the original resource—we must refer to the interannual behaviors of hydro, solar, or wind. Although they store water, hydroelectric dams are not exempt because extreme weather events—including prolonged droughts, El Niño phenomena, and so forth—adversely affect the electricity they are supposed to supply.

All the analyses used to estimate the amount of electricity produced by plants based on VRE assume that the resources will display the same behaviors in the future as they have displayed up until now. The aim is to find the *average* amount of water, wind, or solar radiation available over each year the plants operate. Apart from uncertainties over past variability for renewable resources, any period analyzed may not be representative of the long term. Climate change adds additional uncertainties to the entire exercise, and several studies already address its likely effects on the future availability of resources like water or wind.

In fact, the Intergovernmental Panel on Climate Change (IPCC) has reported that future climate patterns will be less and less similar to past patterns. So governments seeking to shift their energy mix toward larger shares of VRE will want to be able to model the trends affecting these resources as a result of climate change. With scenarios provided by the IPCC, analysts have researched these changes over the past few decades. But different research approaches and analyses, not only of countries but also of entire regions, are already available. The analysis performed for developing countries in southern Africa (Fant 2016) is a good example. These studies project not only solar and wind resources but also seasonal and geographic variations and should be used in decision making on energy policies for the public sector.

Affordability and price

Returning to the definition of energy security ("affordable and reliable supply"), we may notice that the cost and stability of the resources play significant and even paramount roles. Fossil energies may offer a range of prices, a range that depends in turn on market and geopolitical variables. Although historically the first choice for electricity generation worldwide, fossil fuels have displayed price volatility in response to new technologies for their exploration and exploitation, international agreements, wars, or relevant political events.

So while the geopolitical climate affects the reliability of fossil energy sources, the atmospheric climate affects renewable sources. Renewable resources are abundant and affordable. They guarantee a constant price for humankind into eternity, or at least on a time scale of a mi-

llion years. For hydro, wind, or solar projects, planners always assume a zero cost for the fuel over the 20 or 30 years of operation of the power generation plants.

If the price stability for renewables is apparently assured, we must turn to the issue of variability. The geographic and temporal complementarity of renewables may help increase reliability and thus the energy security of the region's electricity systems.

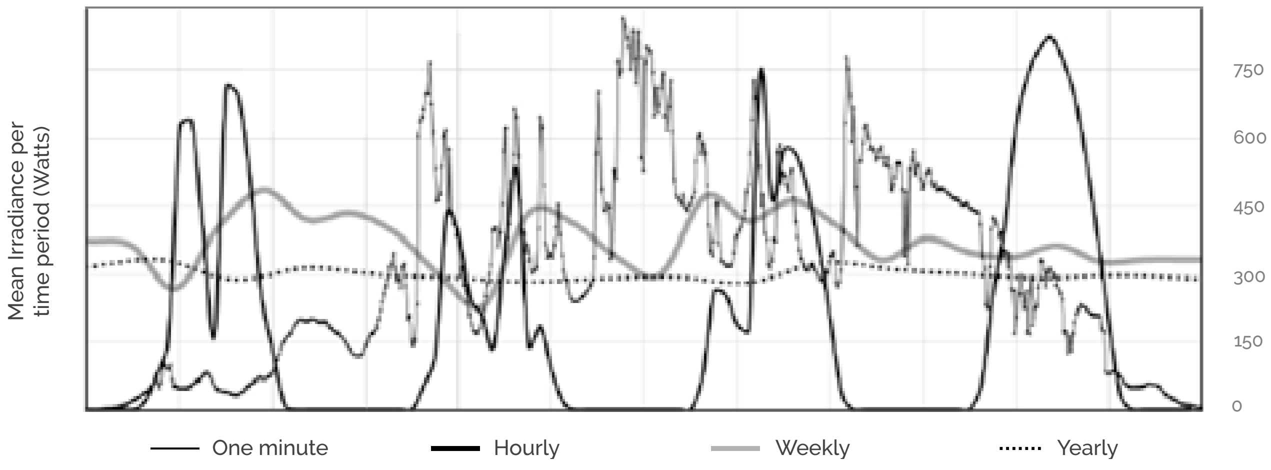
Complementarity: A review of the literature

The availability of natural renewable resources depends on variables of space and time, which is to say on a project's location, its height above sea level, temperature, humidity, topography, the presence of clouds, and so on. Onsite measurements can establish the average behavior of a resource in a specific region and, as already mentioned, extrapolate that behavior into the future. These appraisals of potential are essential when creating an inventory of possible energy exploitation for a country. In the same way that coal, gas, or oil may or may not be present in a country's subsoil, a country may or may not have water, wind, or sunshine distributed throughout its territory.

It should be noted that, although many countries have fossil fuels, these tend to be concentrated in certain regions—the Middle East, for example—and countries with vast territories like Russia or the United States. Yet every country possesses natural renewable resources. So national inventories to establish their amounts, quality, and complementarity are vital.

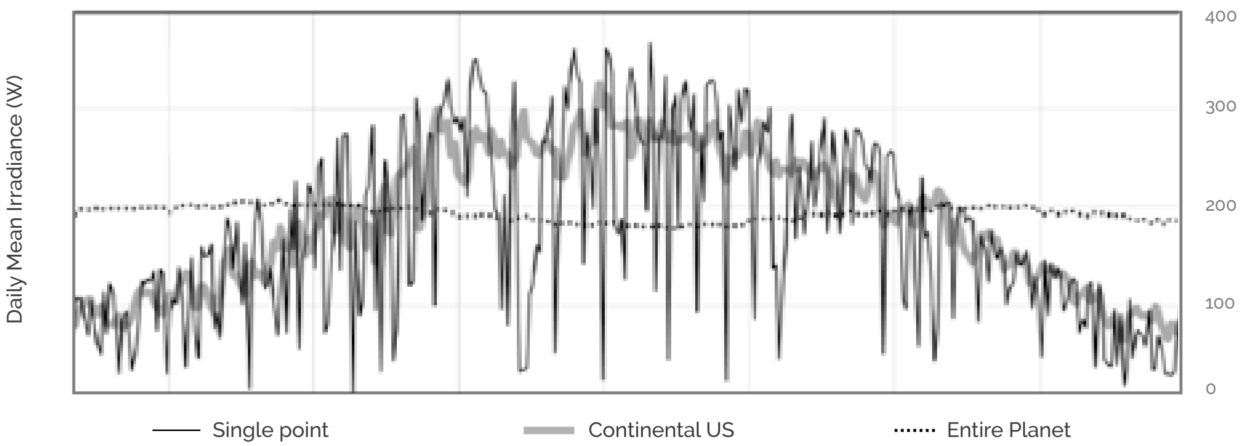
The larger the geographic distribution of the renewable plants, the greater the possibility that when a resource wanes in any one place, energy can be generated at another site. The so called "temporal and geographic complementarity"—how renewables correlate with each other—is becoming a very relevant aspect when planning future energy systems. A good case in point is solar variability. Sunshine is the most abundant renewable resource on the planet. According to Perez (2015), daily variability of solar radiation is high owing to changes in the geometry between the sun and the earth and the passing of clouds. But solar energy over several days at that same location will exhibit less variability. Variability becomes insignificant as the temporal integration increases to one year or more (figure 2). The same happens if a geographic integration of the solar resource is performed for locations scattered across a region or continent, which significantly reduces intermittency. In fact, when extending the spatial range to the whole planet, variability drops to almost zero.

Figure 2. Comparing the variability of global irradiance time series at a North American location, as a function of integration time. The figure includes 1 day's worth of one-minute data, 4 days' worth of hourly data, 26 weeks' worth of weekly data, and 16 years' worth of yearly-integrated data.



Source: Perez 2015.

Figure 3. Comparing the variability of daily global irradiance time series as a function of the considered footprint.



Source: Perez 2015.

Although complementarity in Latin America has not been researched in detail, what research exists will be summarized below. Much less research has been done on phenomena like climate change on the availability of hydro, solar, or wind resources, and on their interrelation. In fact, the Inter-American Development Bank (IDB) conducted one of the first regional studies on the vulnerability of hydropower generation to climate change (IDB 2015). "Vulnerability to Climate Change of Hydroelectric Production Systems in Central America and Their Adaptation Options" analyzed in detail the future availability of water in the most relevant watersheds of the six countries of Central America, using the IPCC global-warming scenarios

The first set of case studies discussed below addresses the complementarity between wind and solar resources on the one hand and hydropower on the other— in countries like Paraguay, Brazil, or Colombia these account for the largest percentage of electricity generation. The second set of studies analyzes the availability of wind over the long term, taking factors like climate change into account. Once complementarity has been ascertained, no advantage can be ensured if climatological models show resource declines. Not only complementarity but also availability are important. Taken together, complementarity and availability help to more accurately establish the implications of VRE for a region's energy security.

The literature review includes scientific journals available to the public online and through multilateral institutions. It is a representative, not exhaustive, sample of research to date, covering statistical diagnoses and forecasts regarding the future behavior of renewables.

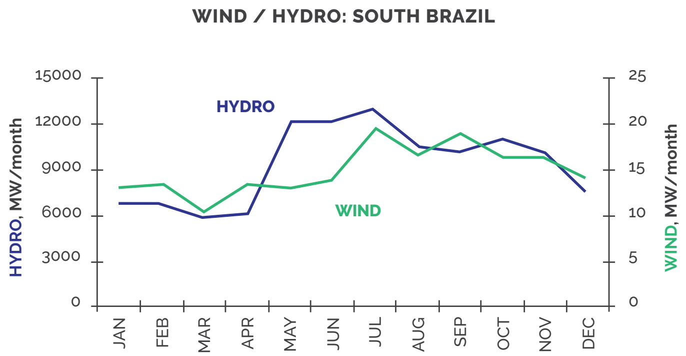
Brazil: Complementary seasonal regimes for wind and hydro

Brazil is largely dependent on hydropower for its energy needs. In 2014 65.4 percent of the electricity consumed in Brazil was generated from hydropower. But from 2011 on, the share of hydropower to the domestic supply has been dwindling—a 13 percent decrease for the 2011–14 timeframe. The 373,439 GWh output reached in 2014 is comparable to the output levels in 2007. Low hydrology and extreme droughts in parts of the country partly explain the decline.

Most of the largest hydropower plants are in southeastern Brazil, the country's most important production basin. So any extreme weather event affecting this region will adversely affect the balance of the country's electricity grid. Several independent studies have shown that southeastern and northeastern Brazil have similar regimes for hydrology and wind. Schultz (2005) describes this resource complementarity for both regions.

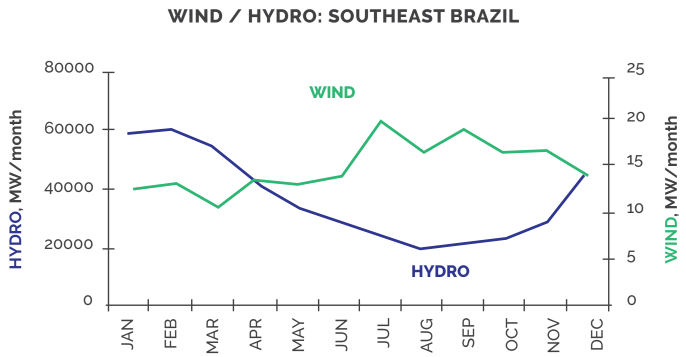
COPEL, the electric utility of the state of Paraná, performed simulations for the integration of wind power in the country's southern system. Time series conducted over 21 years were used to determining wind and water flows, using measurements and reference data from meteorological stations. They found the seasonality of wind power generation is similar to that of hydropower (that is to say, there is a lack of complementarity), with a positive correlation of 0.64, as shown in figure 4.

Figure 4. Comparison of wind and hydropower regimes in the electricity system of southern Brazil.



Source: Schultz 2005.

Figure 5. Comparison between the wind and hydropower regimes in the southeast electricity system of Brazil.

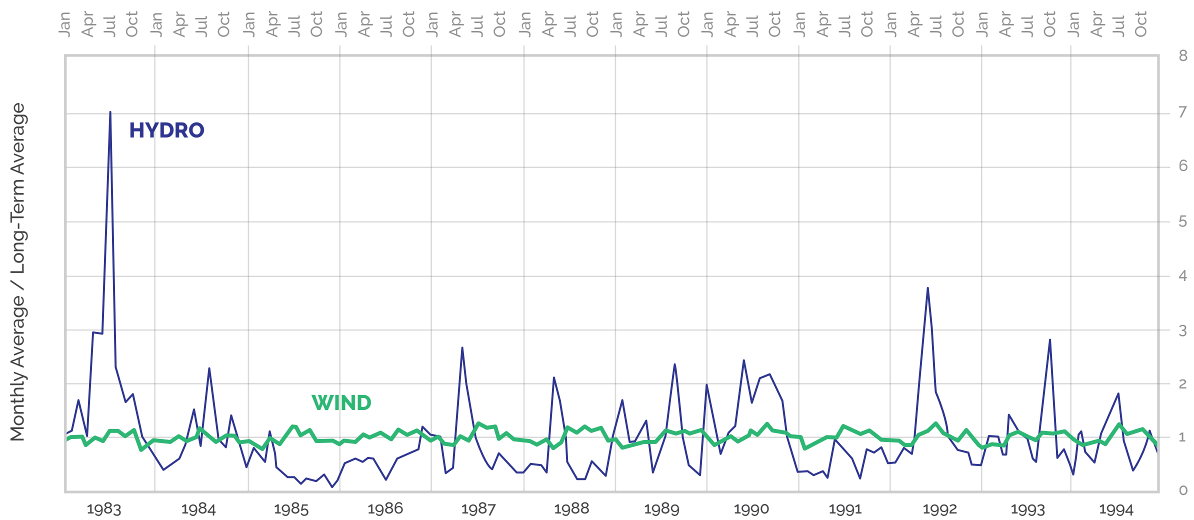


Source: Schultz 2005.

But when studies sought to integrate data on wind generation of the Paraná site with that for Brazil's southeastern subsystem—the greatest contributor to the country's energy mix—a strong negative correlation was found (-0.79) between wind generation and hydropower availability, demonstrating their complementarity (figure 5).

Taking more than 10 years' worth of data from the Iguazú river basin, analysts then compared interannual variability of wind vs. hydropower. They found that despite the hourly and daily variability in wind speeds, monthly and yearly scales show that wind power offers greater stability for electricity generation than hydropower (figure 6).

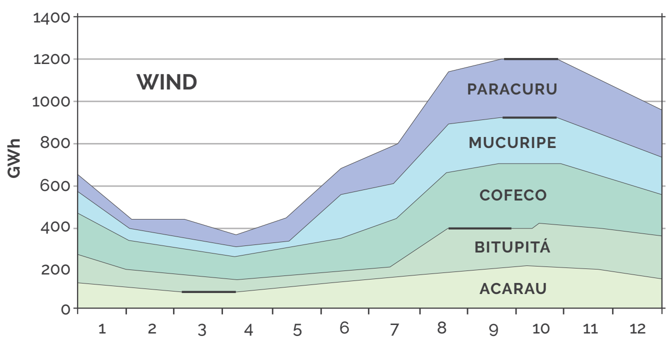
Figure 6. Monthly relative values for wind speeds at the Clevelandia station, and water flows at the Secredo hydropower plant in the Iguazú river basin.



Source: Schultz 2005.

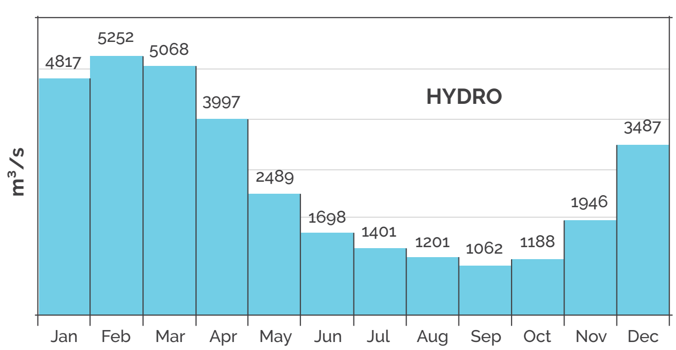
Using a similar approach, the electric utility CHESF performed simulations for northeast Brazil; there were two years' worth of wind data for five different areas along the coast of the Ceará and 60 years' worth of waterflow data for the San Francisco River. A clearly negative correlation was found between the power generation of these two resources (figures 7 and 8).

Figure 7. Simulated output for wind farms on the coast of Ceará.



Source: Schultz 2005.

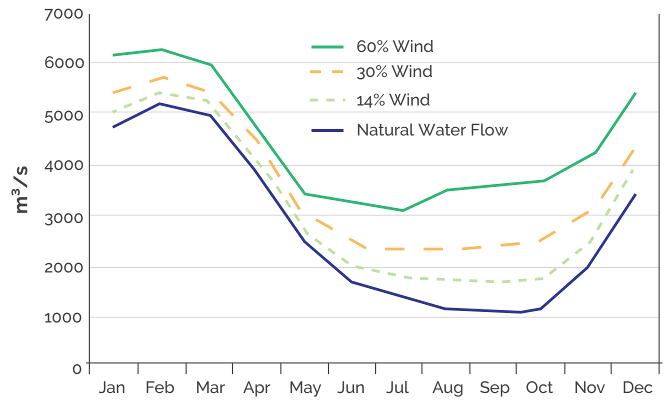
Figure 8. Water contributions of the San Francisco River to the hydropower plant in Sobradinho.



Source: Schultz 2005.

This comparative analysis for regions with starkly different climate patterns suggests that the integrated management of wind and hydro could introduce seasonal stability into Brazil's electricity system; the capacity the system might offer to meet demand increases with a complementary supply of energy—in this case, wind (figure 9). Apart from water savings, which are critical in water-constrained regions dominated by human consumption needs and farming, the integrated exploitation of complementary resources offers a scarcely tapped alternative for countries seeking to adapt in the face of climate change.

Figure 9. Equivalent waterflows in the Sobradinho hydropower plant associated with different levels of wind penetration.



Source: Schultz 2005.

Uruguay: Complementarity of wind, solar, and hydropower resources

Uruguay relies heavily on its hydropower resource to cover demand for electricity. But as shown in the study conducted by Fundación Julio Ricaldoni and Universidad de la República (Chaer et al. 2014), its system is vulnerable to variations in rainfall. The yearly contribution of hydropower may vary between 25 percent and 100 percent of the total amount of energy Uruguay requires. Moreover, the country's dams have low water-storage capacity over multiannual time periods.

To make matters worse, what little hydropower potential Uruguay possesses has been largely exploited. The authorities have been striving to diversify the generation mix. After achieving a political consensus, the government implemented regulatory and economic measures to encourage investments in clean energies and other fuels. These may provide the system with the stability it needs to overcome seasons of low rainfall.

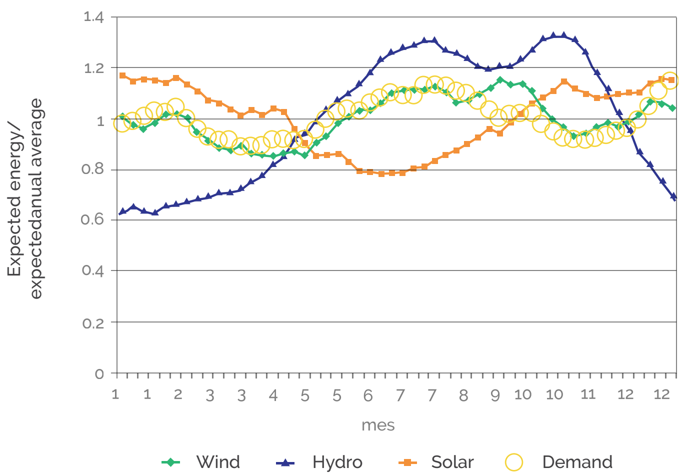
For wind as a resource, input data were drawn from a time series produced by the above-mentioned study over a two-year period from seven different geographic sites; for the solar resource, the simulation used irradiation records from eight different stations. Generation profiles were then created for different time scales; results were then compared with hydropower.

Figure 10 shows the results of the simulations. These results make it possible to compare the seasonal variations for solar, wind, and hydro (the three renewable resources) against demand. The results were all obtained from statistical assessments. Nevertheless, there is

great uncertainty resulting from the interannual variations discussed above. This is especially true with hydro. It is not the absolute values that are important here but rather the correlations among the resources arising from meteorological conditions.

Note the positive correlation between wind and demand, and the negative correlation for solar and hydro (figure 10). In the first case, resource competition will challenge the system, especially between hydro and wind, operating on hourly or daily scales. The second case could be construed as an economic benefit because a higher penetration of solar might lower costs during periods of low rainfall. Savings could be passed on to end-users. Solar power is, therefore, a good complement to hydro, but it does not contribute much to covering demand because it is actually scarce during the times of the year when demand is greater.

Figure 10. Annual variations of renewable resources and energy demand.

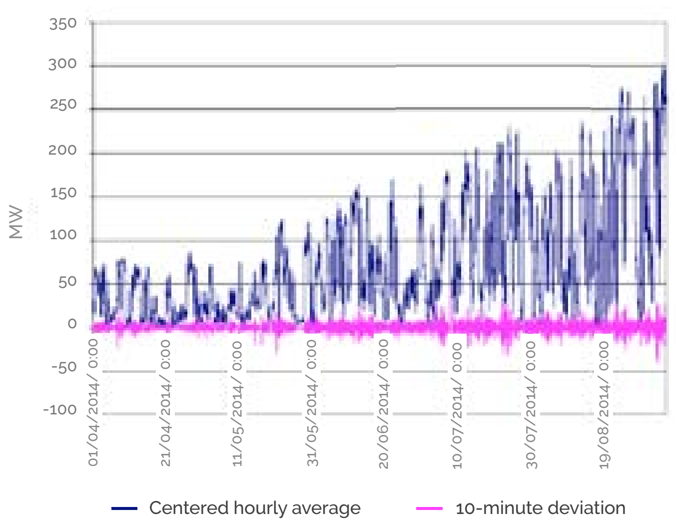


Source: Chaer et al. 2014.

The case of Uruguay is relevant here. The government has set ambitious goals, calling for VRE in its generation mix. By 2020 wind power is expected to contribute 40 percent of the energy Uruguay consumes each year, a capacity of 1,400 MW. This would vault Uruguay into the ranks of countries with the highest percentages of wind power in their energy systems—comparable only to Denmark, at 42.1 percent penetration in 2015.

With Uruguay reporting about 500 MW of wind-farm operating capacity at the end of 2015, the operation and long-term planning of the electricity system will be affected. The study also makes reference to the variability of the resource on a per-minute scale and to the fact that, although the wind output capacity increases in the period analyzed, the standard deviation of the capacity does not increase and remains at +/- 25MW (figure 11). These observations are consistent with those made at the outset of this section. They further confirm that a greater geographic distribution of wind generation tends to stabilize any variability in output. This stability facilitates operation and control in the short term and obviates the need for more backup systems to handle increases in wind-installed capacity.

Figure 11. Average hourly wind output and 10-minute deviation for the April–August 2014 timeframe.



Source: Chaer et al. 2014.

Future behavior of wind energy in Brazil

Studies on the historic behavior of wind and solar resources are helpful. But also relevant are research and modeling future VRE availability and variability. Few studies address these issues, partly owing to a lack of databases, the complexity of the exercise, and the capacity required for atmospheric-process analyses. Universities and research institutions have therefore undertaken these tasks of interpreting climate change data and adapting them to conditions in Latin America.

As mentioned above, in the case of Brazil, the complementarity of hydro and wind in some parts of the country is well known. The next step in the analysis is to establish the effects that climate change will have on electricity generation based on wind, which is the subject of a study by the Federal University of Rio de Janeiro and the Centro de Investigación de Energía Eléctrica (Pereira de Lucena et al. 2009). Wind-based energy gains even greater relevance because Brazil has seen the fastest evolution of installed wind-power capacity worldwide; with 8,350MW of wind farm installed capacity by 2016, or 6 per-

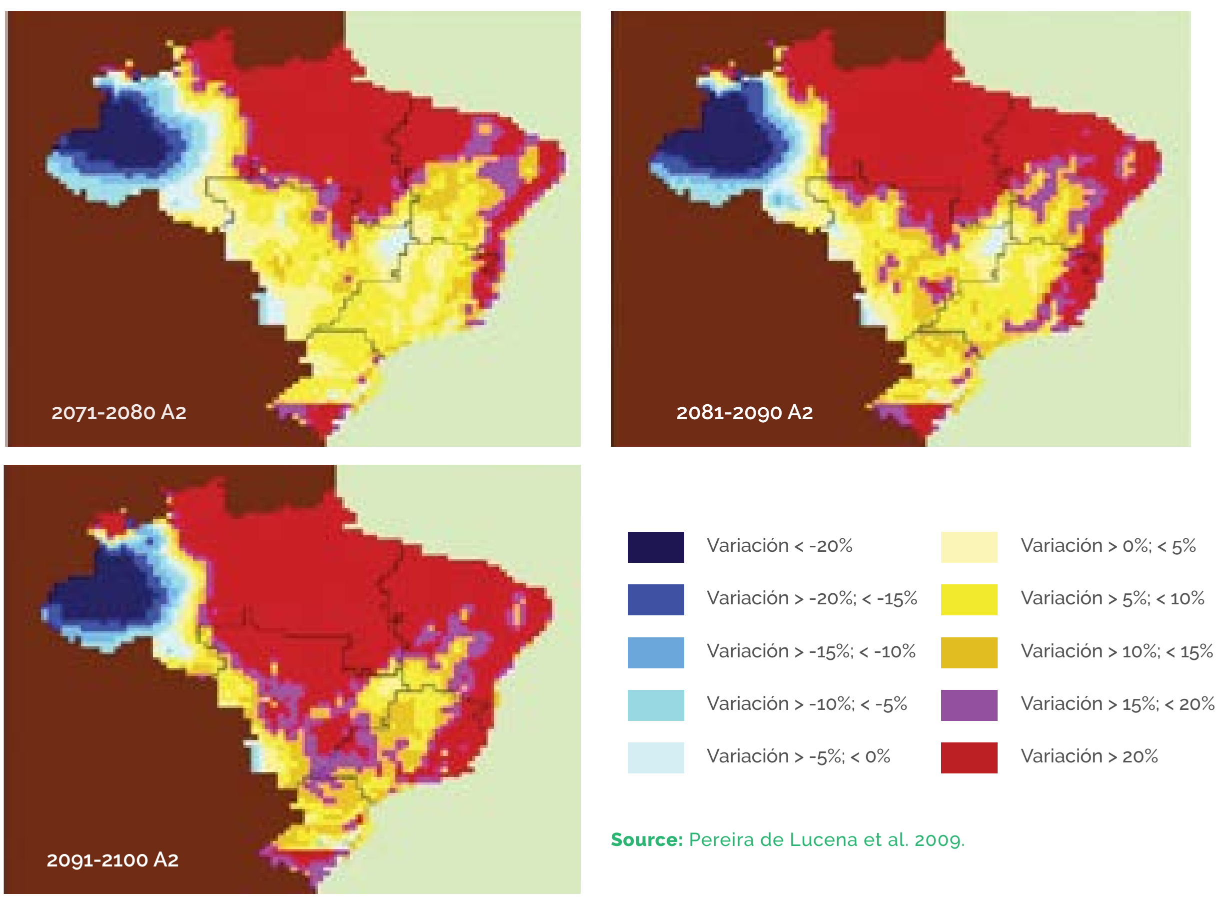
cent of the country's total power-generation capacity. In addition, the government plans to triple wind capacity over the next eight years to reach 24 GW capacity—constituting by 2024 an 11.6 percent share in the country's generation mix (MME/EPE 2015).

The impact of global climate change on the wind potential of the country is analyzed in a study using IPCC climate projections and the corresponding A2 and B2 emissions scenarios, described below. The first, scenario A2, presumes continued high emissions, scant cooperation among governments on policies to reduce greenhouse gases (GHGs), and uneven economic growth worldwide. The second, scenario B2, foresees low GHG emissions worldwide, great technological innovation, and, most notably, greater local and regional awareness and action to address the causes of climate change and to mitigate its effects.

This last point is worth noting because, owing to a host of uncertainties—arising from the model itself, economic activity projections (and therefore for GHG emissions), the representation of global climate processes, and therefore their extrapolation to regions, to name only a few—a long-term analysis can provide only a general trend, not an absolute value, for potential variations. In spite of these uncertainties, this type of analysis is the only one that can shed some light on the future.

As for the methodology, the study compares wind speeds (and wind output) found on the wind map of Brazil using two different timeframes (1961–90, the baseline, and 2071–2100), after including the climate conditions suggested by scenarios A2 and B2.[4] The climate projections show that average wind speeds will greatly increase along the coast, precisely where nowadays we find the highest speeds and therefore the greatest potential for electricity generation. In Brazil the coastal areas consume the most energy. Moreover, the study shows that the centers with the greatest consumption of electricity in Brazil are also located in coastal areas, making it unnecessary to expand the transmission structure as much as in other regions and therefore reducing the level of electricity losses associated with transmission.

Figure 12. Scenario A2: Variations in average wind speeds against the baseline (1961–90) .



Source: Pereira de Lucena et al. 2009.

Simulations for scenario A2 show wind-speed variations increasing fourfold in average wind potential (figure 12). The simulation for scenario B2 shows an almost threefold increase in average potential. The uncertainties and assumptions of this model require us to regard the results not as absolute facts. But we can use them to discard arguments that climate change will be adversely affecting wind as a future resource for Brazil.

Quite the contrary: climate change promises to boost wind as a resource for Brazil, making it a likely and valuable alternative to hydropower during low-rainfall seasons. The electricity-generation costs of wind projects are already competitive, especially in northeastern Brazil, where it might even replace fossil fuel technologies like natural gas. If in addition we consider that a greater abundance of wind and the progress of technology together ensure lower prices in the future, we may reasonably expect wind power to become a sustainable option for Brazil's long-term energy security.

Impact of climate change on coastal winds in western South America

The second regional study of the effects of climate change, carried out by researchers from the University of Chile, is focused on winds along the subtropical coast of South America; this is north-central Chile, between 25th and 35th parallels south (Garreaud & Falvey 2009). Model-based predictions show that the climatic situation in this highly arid region is not likely to change, although surface winds along the Pacific coast are expected to increase. This analysis is also based on the IPCC scenarios A2 and B2, explained above.

Results from 15 different global circulation models were the first data to be analyzed, along with the estimated changes in surface winds off the coast. This helped researchers to establish a first gross estimation; the resolution of these models does not exceed 200 km so details about ocean and coastal wind streams are easy to miss. Even so, this exercise confirms the consistency of these models, which couple the behaviors of atmosphere and oceans. They show the large-scale behaviors of wind streams running south to north along the Chilean coast and westerly winds at the 35th parallel south; the movement at the borderline for these two regions is also shown, with wind directions changing according to the prevailing season (figure 13a).

When comparing the average wind conditions in the two 30-year periods (1961–1990 and then 2071–2100 for scenario A2), winds in the southeastern Pacific Ocean are observed to increase—a positive anomaly (figure 13b). The highest increase in wind speed on the central Chilean coast is 1 m/s as compared with baseline conditions. Fall and winter see similar behavior, although maximum speeds along the coast occur more in the north. As regards scenario B2, with lower concentrations of CO_2 in the atmosphere (600 parts per million, ppm, instead of the 820 ppm of scenario A2), the value of the change is 25 percent lower than for A2.

Researchers used PRECIS, a regional climate model, at a 25 km resolution to verify the baseline period for wind variability and seasonality along the Chilean coast. After including the effect of climate change through scenarios A2 and B2 with PRECIS, models show coastal wind speeds increasing for 2071–2100. Owing to the greater detail and resolution of the model (the PRECIS used for Brazil was at a 200 km resolution), researchers could see that the periods marked by strong winds were less dependent on the seasons. As a result, the so-called coastal jets, or southerly winds, were more sustained.

In spite of the complex atmospheric behaviors, global circulation and regional climate models capture the historic conditions and characteristics of winds along Chile's subtropical coast.

As for estimates of the impact of climate change on wind potential, both models predict greater wind potential along the Chilean coast. In fact, the greater frequency and duration of strong wind events may lead to localized cooling of the upper layers of coastal waters. The fisheries are already benefiting from the cooler, nutrient-rich waters being brought up from the southern reaches of the Pacific.

[4] The global circulation model, HadCM3, was downscaled for Brazil using PRECIS (Providing Regional Climates for Impact Studies).

Figure 13. (a) (top panel). Average between the different models for climatic simulation of surface winds for spring and summer (arrows), meridional wind speed (colored areas) and sea-level atmospheric pressure isobars (lines) for 1961–90.

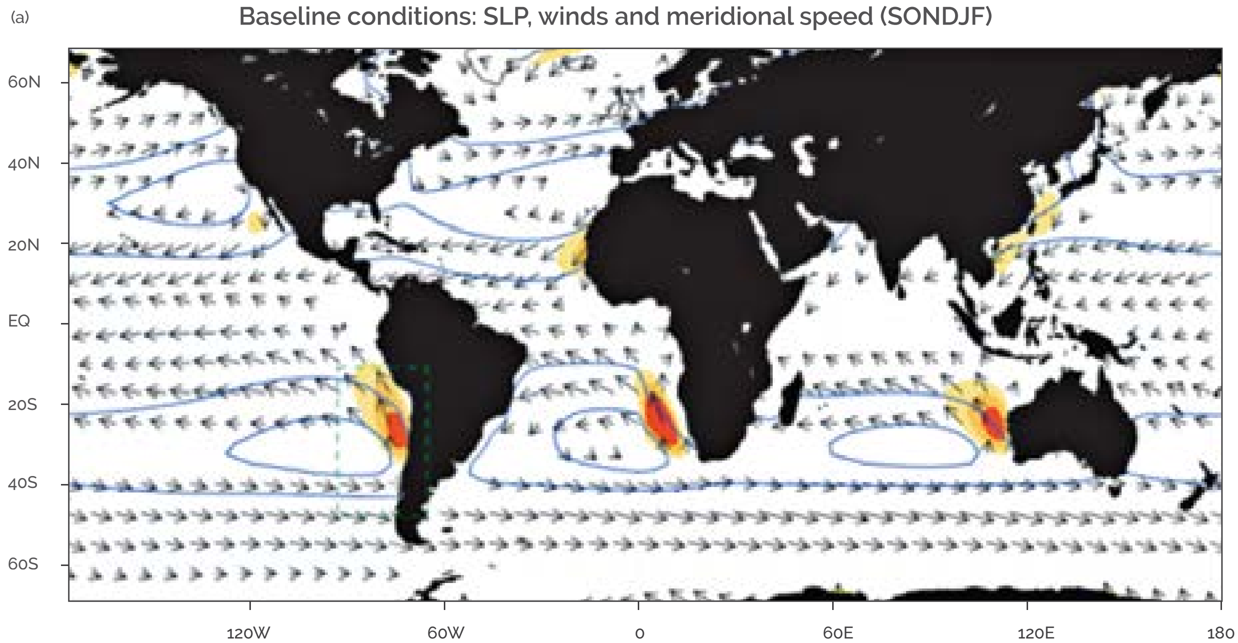
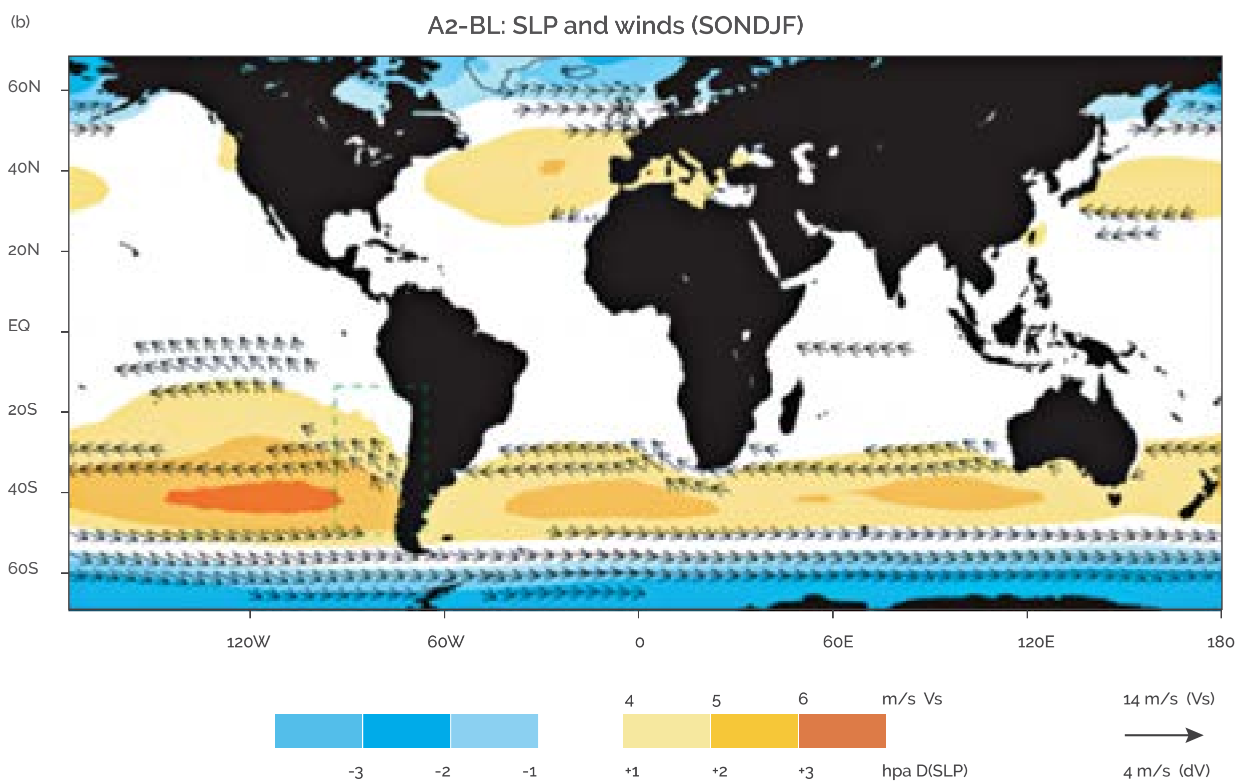


Figure 13. (b) (bottom panel). Difference of average surface winds for spring and summer (arrows) and above-sea-level atmospheric pressure (colored areas) from the period between 1961–90 and 2071–2100.



Source: Garreaud and Falvey 2009.

Case Study

Complementarity between renewable resources for power generation in Colombia

We have observed earlier that energy is key to any country's development and that threats to energy supply have led countries to establish national policies that incentivize VRE projects. Colombia's energy mix is about 70 percent hydropower (UPME 2015c). In view of its reliance on hydro, the following issues could play crucial roles in encouraging the development of VRE:

- **Vulnerability to the El Niño Southern Oscillation (ENSO).** Fluctuations in El Niño have reduced precipitation in Colombia and caused droughts over the past two decades (GRID-Arendal 2015). These low-flow hydrological periods affect energy generation, and in 1992 and 1993 brought blackouts and electricity rationing. More recently, these periods caused energy spot prices to spike (UPME 2015b). In 2015 the severity of El Niño left reservoirs at 65 percent capacity (Colombia Reports 2015), forcing thermal power plants to be online in order to back up the system. Given the current prices within the regulatory framework, some thermal power plants are not financially viable. To provide financial support to these plants, the government authorized drastic measures, including temporary and controversial hikes in energy prices paid by end-users (Market Watch 2015).

- **Natural gas shortages.** Because thermal power plants run mostly on natural gas, the electricity sector is concerned about natural gas deficits forecast for 2018–20 (UPME 2015a). In 2017 a regasification terminal on Colombia's Caribbean coast for the import of liquefied natural gas (LNG) (UPME 2015b) will begin operation; future plants on the Pacific coast are being analyzed (Argus Media 2015).

- **Vulnerability to climate change.** Modeled consequences of climate change show decreased precipitation throughout Colombia. Lower inflows would adversely affect hydropower-based electricity generation (CorpoEma and UPME 2010; IDEAM and Ruiz-Murcia 2010; Unión Temporal ACON-OPTIM and UPME 2013).

Permitting issues and social and environmental opposition also challenge the development of conventional power plants in Colombia. The interactions between VRE based on wind and solar affect different areas of the country in different ways. By providing backup energy during low-flow hydrological periods, VRE could complement hydropower and increase Colombia's energy security over the long run.

Research on the complementarity of wind, solar, and hydro resources

Research on the complementarity of renewables in Colombia (COWI 2015; Ealo-Otero 2011; Vergara et al. 2010) focused on the wind resources along the coast of northern Guajira. Because VRE could be backup energy sources during low-flow hydrological periods, more research is needed on the complementarity of wind, solar, or hydro throughout Colombia.

The VRE technologies best suited to Colombia's climate can be determined with more research about VRE behaviors and characteristics over monthly, seasonal, and yearly timeframes. With more research, planners could improve the day-to-day operation of Colombia's electricity system. In addition, more information, and better analysis, about interannual behaviors of these renewable forms of energy available in Colombia would improve policy decisions over the long term. We therefore want to know how the seasonal (and by seasonal, we refer to *intra-annual* behavior in a given year) and interannual temporal and geographical distribution of wind and solar resources compliment the hydro resources available at current hydropower plants?

General objective

All VRE (hydro, wind, and solar) have patterns that fluctuate over time in response to various conditions. The objective of this section is, first, to examine the seasonal and interannual patterns for wind and solar patterns in Colombia (and their interrelationship). Second, the case study will examine the correlation of wind and solar patterns with hydro resources used for power generation. Seasonal and interannual energy patterns produce a qualitative relationship well. This connection arises from the estimates of energy production (see below) and is based on meteorological reanalysis (or data assimilation) and data regarding local inflows.

This study uses grid points across Colombia as the unit of analysis and presents data to sector stakeholders (transmission systems operators, electricity market participants, government authorities, and policymakers) regarding the future development of VRE in the national electricity generation fleet. The first reanalysis-based annual resource indexes for VRE offer us tools for analyzing how best to finance future projects based on the interannual variability (IAV) of renewable energy.

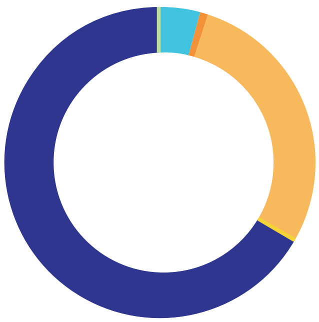
This study addresses neither technical characteristics of Colombia's transmission grid nor any VRE economy aspects. Similarly, the market-related operational strategies of the hydropower plants in the country are not considered.

National energy mix

Colombia's power system operator and market administrator, XM, provided the data about the country's energy mix (XM 2015). Colombia has more than 15 GW of installed capacity (figure 14), supplied mostly by large hydropower plants (approximately 67 percent of the total); large thermal power plants, fueled mostly by natural gas, supply the rest (28 percent). A 'large power plant' in Colombia refers to power plants, centrally dispatched by XM, with an installed capacity greater than 20 MW (CREG 2015). Power plants below 20 MW are independently operated. This study focuses on large hydropower plants, powered either by dams or run-of-the-river, because both are used to power Colombia's generation park.

Figure 14. Installed capacity in Colombia in 2015.

		Rated capacity [MW]	Share percentages
Centrally dispatched (≥ 20MW)	Hydraulic	10,335	66.6
	Thermal	4,410	28.4
Not centrally dispatched (< 20MW)	CHP	82	0.5
	Wind	18	0.1
	Hydraulic	585	3.8
	Thermal	91	0.6
Total installed capacity (MW)		15,522	100



Source: Ramírez 2015.
Note: CHP = combined heat and power, also known as cogeneration.

Regulatory framework for renewables

Colombia has been promoting VRE since 2001 while also setting policy goals and providing tax exemptions[5]. There are entry barriers, however, to the large-scale development of VRE. These barriers include high investment costs, market concentration, and a hydropower-based market structure (COWI 2015).

Severe dry seasons have challenged Colombia's dependence on hydropower. The country's vulnerability to a strong El Niño effect became evident in 1992, which brought severe electricity shortages. In 1998 (high energy spot prices) and 2003 (rationing programs) highlighted the country's vulnerability. More recently, in 2015–16, El Niño struck again, and more severely than ever before. Electricity prices shot up. Thermal power plants were turned on to provide relief for hydropower plants. But when hydrology is normal, thermal plants operate at low capacity and are not financially viable.

Responding to these challenges in 2006, the Energy and Gas Regulatory Commission (CREG) modified the regulatory mechanism governing capacity expansion, changing its capacity charge to a reliability charge;[6] it provided a market mechanism for auctioning determined amounts of energy to generation companies. The company with the winning bid offers a specific amount of 'firm energy' in exchange of a reliability charge, or an ENFICC. (*Firm energy* refers to the actual energy guaranteed to be available). The ENFICC is the maximum energy a generation asset can continuously deliver during a yearlong period of low-flow hydrology. The commitment is backed with physical assets that ensure firm energy when the energy spot price rises.

When the spot price reaches the scarcity price, which is predetermined, the company commits to deliver the quantity of energy determined at auction. As compensation, the generation company receives a stable payment (the reliability charge) during a specific time period of up to 20 years.[7] The end-users pay for this compensation via fees charged by commercialization companies in the National Interconnected System (SIN) (CREG 2015).

Although any generation technology has been permitted, the CREG waited until 2011 to address the rules for firm energy and wind power. Current regulations stipulate that the ENFICC for a wind farm is based on a capacity factor of 6 percent for project sites with fewer than 10 years of data on wind speeds.[8] Similarly, the CREG developed a new regulation on firm energy payments and solar farms (Fonroche énergies renouvelables and CREG 2015).[9]

[5] 2001 Law 697, 2002 Law 788, and 2003 Decree 3683.

[6] CREG resolution No. 071.

[7] The main difference between the former Cargo por Capacidad and the new mechanism developed in 2006 was that the generators were not committed to deliver firm energy in cases of low-flow hydrological periods, limiting its effectiveness as an incentive to promote generation expansion.

[8] CREG resolution N. 061 of 2015 (May 8, 2015).

[9] CREG regulatory decree 227, 2015.

Considering average ENFICCs of 55 percent for hydro with dam, 30 percent for hydro (without dam), 97 percent for coal, 93 percent for natural gas, and 88 percent for fuel oil (COWI 2015), the reliability charge promotes the development of thermal power plants. The low calculated-capacity factors do not encourage investment in generation assets based on VRE.

The reliability charge does not reward other advantages the VRE could confer on the generation mix. This includes generation diversity and the seasonal and interannual complementarities seen throughout Colombia and across technologies. Colombia's recent energy crisis due to the strength of El Niño is testing the country's regulatory framework and creating opportunities around greater energy security (Market Watch 2015).

In 2015 the government issued a decree according to the 2014 Renewable Energy Law 1715. Decree 2143 was implemented to achieve a more balanced generation mix and includes four tax incentives for VRE projects: (1) a 50 percent tax break on investment over five years, (2) accelerated depreciation, (3) zero sales tax, and (4) exemption from import duties.

Methodology

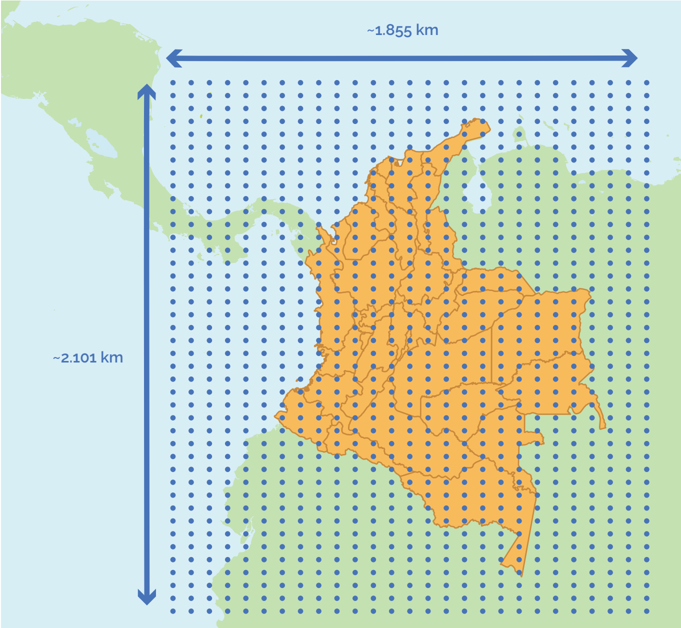
Global reanalysis. Reanalysis uses a data assimilation scheme and a numerical model of the atmosphere to make global observations based on measurements made every 6 to 12 hours of the weather, including surface measurements, radiosondes, and those collected by aircraft and satellites. These provide constant estimates of the climate that can be used to create a three-dimensional global dataset. The study selected MERRA (Modern-Era Retrospective analysis for Research and Applications dataset), which is part of NASA's Global Modeling and Assimilation Office (GMAO) (NASA 2015; Rienecker et al. 2011). Evaluated widely, this reanalysis dataset has the best spatial resolution (two-thirds of a degree longitude and half a degree latitude)[10] and the best temporal resolution (hourly) for the desired variables in this study. The timespan extends from 1979 to the present for near-real-time climate analyses.

MERRA data processing. The study analyzed hourly wind speeds at 50m height and solar surface irradiances and processed that information for 1,014 grid points (26 longitudes and 39 latitudes) (figure 15) representing an area of approximately 1,855km times 2,101 km. The data covers years 2001 to 2014 (Stream 3 of MERRA).

Site selection for wind and solar. Site selections were based on (a) the highest mean wind speeds and solar irradiation values within the analyzed timeframe, (b) the location of protected natural parks, (c) the location of the transmission grid, and (d) the existence of roads. We selected 26 sites with development potential—13 for wind power and 14 for photovoltaic, or PV (figures 17 and 18 show the mean values of the resource).

Figure 15. MERRA grid points (blue)

	Number of grid points used	Coordinates		Distance between first and last point
		First point	Last point	
Longitude	26	- 82.66°	- 66°	~1,855 km
Latitude	39	- 5.5°	+ 13.5°	~2,101 km

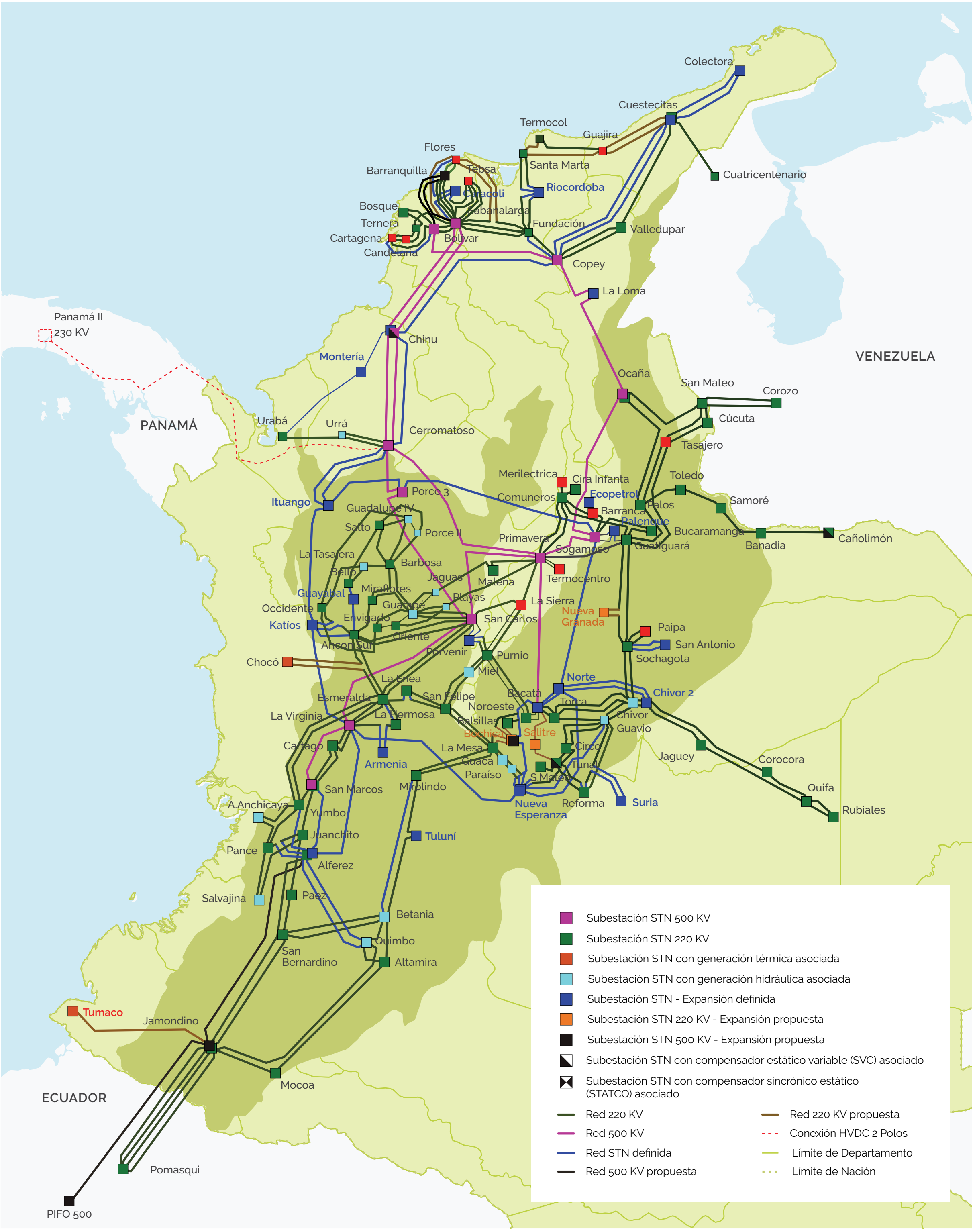


Source: Ramirez 2015.

[10] Two-thirds of a degree on the longitude corresponds approximately to 74 km on the Equator; half a degree on the latitude to approximately 55 km.

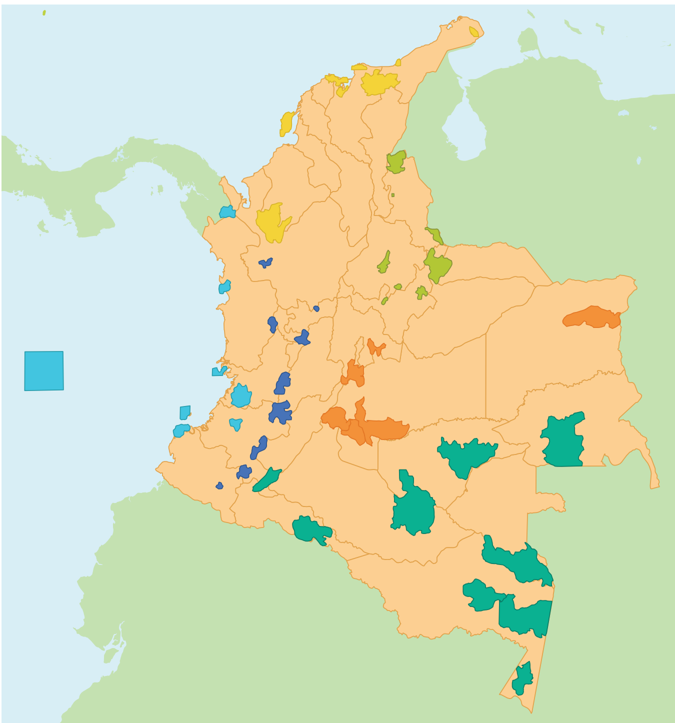
Case Study

Figure 16 (a). Transmission Grid – Vision 2028.



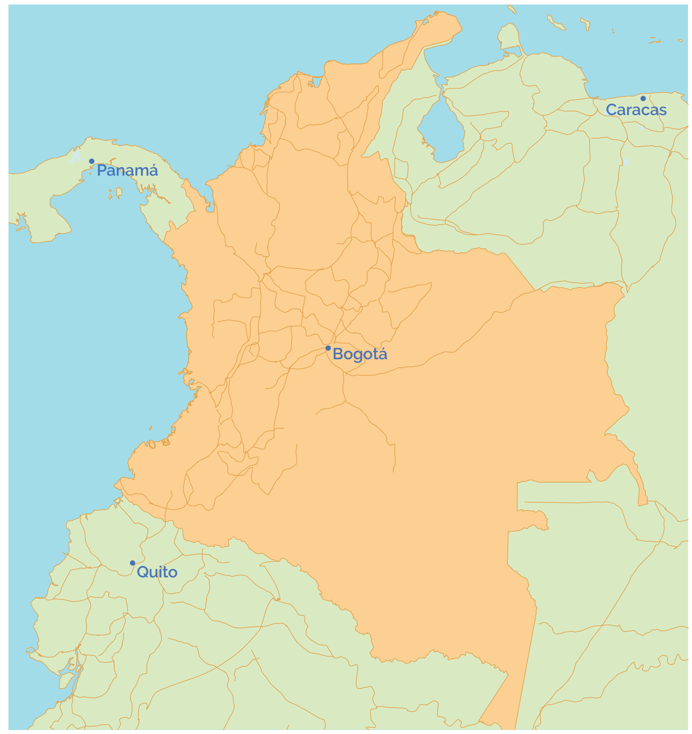
Source: UPME 2015c.

Figure 16 (b). Natural Parks



Source: Parques Nacionales Naturales de Colombia 2015.

Figure 16 (c). Road Networks in Colombia



Source: Ramirez C. 2015.

Location of hydropower plants and retrieval of river inflows. Along with the rated power and the conversion factors of 19 large hydropower plants (>20 MW), the inflows of the 24 rivers feeding into them on a monthly basis from 2001 to 2014 were obtained from XM (XM 2015). UPME conducted a study to review generation chains and hydrography (UPME, Macias, and Andrade 2014) and created an online hydrography platform (IDEAM and SiGaia 2013), using both sources to establish the river-generation basins. To properly select power plants in a particular basin, planners need to determine the amount of water flowing into each power plant. For modeling purposes, an aggregated national group of rivers was also created.

Energy production assessment. Based on UPME scenarios for the development of renewables in the country by 2028 (up to 1.370 MW of wind power and up to 240 MWp of solar power), a 99 MW wind farm and a 50 MWp PV solar farm were proposed for each of the wind/solar sites (UPME 2015c).[11] Then the first estimates of monthly energy production (MEP) and annual energy production (AEP) were calculated. The following MERRA data for the wind farms was used: extrapolated hourly wind speeds at 100m hub height, roughness lengths, and monthly air densities. The study used a typical 3.3 MW wind-turbine power curve and estimated losses. For solar farms, MERRA data on hourly surface solar insolation and hourly temperature at 2m heights was applied. The expected performance ratio and thermal factors of a typical solar module was taken from another research document (Mulcué-Nieto and Mora-López 2014). For hydropower plants, XM data were used for monthly inflows and also XM's conversion factor and rated power. The data were collected and processed on every month over 168 months from 2001 to 2014, or 14 years.

Seasonal complementarity analyses[12]. The Pearson's correlation coefficient[13] R was computed according to meteorological resources observed over a 12-month period—using monthly wind speeds of 50m at each wind site and, for hydropower plants, river inflows. Also assessed over the same period: the correlation coefficients between the mean monthly solar surface insolations and the monthly river inflows.[14] As a result, for

wind-hydro and solar-hydro, 14 seasonal *R* coefficients were identified for the selected timeframe. The average of these 14 coefficients was calculated to determine the complementarity of the two sites. This study includes the averaged seasonal *R*. For all the analyses in this study, the more negative the *R*, the more complementary the pairs. In addition, in energy terms, the same calculation was used for the MEP for every year for both wind-hydro and solar-hydro. The average *R* from the 14 coefficients for each pair was then found.

Interannual complementarity analyses. Meteorological resources were used to assess the interannual *R* between the 14 mean annual wind speeds of 50m (for wind sites) and the 14 mean annual river inflows (for hydropower sites). A unique interannual *R* was found for each wind-hydro pair. The same process was executed for the annual solar-hydro pair values. In energy terms, the AEP was used, and there is also a unique interannual *R* for each pair. These unique energy interannual *R* are not presented here but are included in the original thesis work (Ramírez C. 2015).

Annual wind, solar, and hydro indexes with their IAV. We assessed the MERRA-based wind and solar resource indexes for each year based on 50m mean annual wind speeds and on the mean annual solar surface insolation of each wind and solar site. The 100 percent values correspond to the mean value in the given time frame. The XM-based hydro resource indexes represent the same but are applied to the mean annual river inflows. In terms of energy, the same method to the AEP was applied. The Interannual Variability (IAV) was defined as the standard deviation of the annual values divided by the overall mean, both in meteorological resource terms and in energy terms.

Results and analysis

Wind and solar resources.

The wind and solar sites are named after the regions used in the MERRA grid points. The grid points are located in the center of a box that represents approximately 74km in longitude and 55km in the latitude and represent the average values of the area located inside the box. The grid points are located in regions with MERRA altitudes from sea level to approximately 2,600m.

The mean magnitude and direction of wind speed between 2001 and 2014 are plotted in figure 17. The mean wind speed found at 50m varies from 3.3 to 7.7 m/s. The normalized mean seasonal patterns of the monthly wind speed at 50m are exhibited at six sites in different regions.[15] Figure 18 shows the mean annual solar surface insolations for the same timeframe. The mean annual insolation values range from 1,645 to 2,175 kWh/m²/year. These values correspond to mean daily insolations of 5.74 to 5.96 kWh/m²/day. Normalized mean seasonal patterns of monthly solar surface insolations are presented in six sites in different regions.

The accuracy of MERRA wind and solar resources, and reanalysis data, is heavily site-dependent; the complexity of the terrain is also a factor. Several international case studies have proved highly accurate when relying on MERRA data for fairly flat areas over large distances. But for complex terrain (shorelines, hills, and mountain ranges), these data values might have strong negative or positive biases, which in turn skew any estimates about the resource. The reanalysis model uses surface smoothing for rough terrain, which prevents the model from properly reproducing the flow dynamics when complex topography and airsheds are involved.[16] These phenomena also influence cloud formation and the transport of gas and aerosols, which at some sites affect solar irradiation calculations.
As a result, a significant bias is expected in the magnitude of mean wind and solar resources, principally along the three *cordilleras* of the Colombian Andes[17] and their valleys. For example, considering only global meteorological dynamics, the bias is likely negative (underestimation) on the windward of the eastern Andes (eastern because the trade winds come from the northeast and southeast). Wind farms could be located at sites in this region if sufficient wind resources are identified. Nevertheless, local thermal circulation and topography might produce stronger or weaker winds on both sides of each *cordillera*. Although this requires further investigation, considering onsite measurement in the country, important instances of MERRA over- and underestimation were first identified by comparing resource maps from the *Global Atlas* (IRENA 2015) to the *Wind and Solar Atlas of Colombia* (IDEAM and UPME 2005, 2006).[18]

[11] The UPME is considering 3,131 MW of wind power and 574 MW of combined power from geothermal, biomass, and solar (UPME 2015d).

[12] 'Seasonal' refers to intra-annual distributions in a given year.

[13] The Pearson's correlation coefficient R measures the strength and direction of linear relationships between two variables. It is independent of the scale of their magnitudes. It ranges from -1 to +1. A value of 0 indicates no association, meaning that the behaviors of the variables are independent. A positive value indicates a direct association: as the values of one variable increases, so does the other. A negative value indicates an inverse or complementary association: as the values of one variable increases, the other decreases.

[14] Sum of all the hourly solar-surface irradiances in each month.

The following points explain the differences in estimations:

• For wind resources: In general, both atlases present fairly similar distributions of wind. When MERRA is compared to the IRENA dataset, an underestimation is evident everywhere except for the Guajira area. MERRA greatly underestimates wind in areas over the eastern and central Andes. Compared with the UPME-IDEAM wind atlas, MERRA shows higher wind speeds in the Guajira and the eastern Andes. MERRA also fails to document high wind speeds in Catatumbo between the northern coast and the eastern Andes, the middle of the central Andes, and north of the western Andes.

• For solar resources: MERRA and IRENA datasets show a similar distribution of solar resources. But MERRA does display increased resources in the eastern *cordillera*. The IRENA dataset shows more resources in the three *cordilleras*. The distribution of resources in MERRA was much different from those in the IDEAM solar atlas. IDEAM displays the highest level of solar resources in the northern coastal area, the Oriental Plains, and some areas of the eastern Andes. MERRA presents similar or underestimated values outside the Andes.

Note that for the analyses in this study, the correlation coefficient R depends not on the magnitude of the values themselves but on their behavior during a given period. Several studies note that MERRA captures time variations, but certainly not in every area. Therefore, we conducted qualitative comparisons of the seasonal patterns of monthly wind and solar resources with the appendixes (IDEAM 2005a) of the IDEAM *Climatologic Atlas* (IDEAM 2005b). Most of the wind sites have similar patterns. The patterns at the solar sites show greater differences, however, especially in the Andes—probably because the resource modeling is so heavily site-dependent. Onsite measurements from airports or meteorological stations cannot be directly compared with reanalysis data, which represent vast areas, without a detailed evaluation of the quality of the stations and their surroundings. This requires further investigation and validation studies. For the purposes of this study, MERRA seasonal patterns of wind and solar sites are taken as representative on a regional scale.

See Figure 17 (p. 33-34) and Figure 18 (p. 35-36).

Hydro resources.

The analysis selected 24 rivers that feed 19 large hydropower plants; table 1 lists the rivers and the power plants from south (top) to north (bottom). Mean inflows ranged from approximately 4.5 to 414.6m³/s at power plants generating more than 1.200 MW. A national artificial hydrographic group of 21 rivers was created. Figure 19 (p. 37-38) shows the location and rated capacities of the hydropower plants. Figure 20 (p. 40-41) shows the location of river inflow measurements. The normalized mean seasonal patterns of the monthly river inflows are presented for six of the sites in different regions.

As listed in table 1 and exhibited in figure 19, 4.100 MW of hydropower is generated in the Antioquia region (from the eight power plants in the yellow circle in figure 19). This represents approximately 45 percent, of all current large hydropower capacity in the country. Two new hydropower plants, Porvenir II with 352 MW and Ituango with 2,400 MW will soon start operations in the region and two more are planned. After the implementation of the two future projects shaded in table 1, the Antioquia region will represent 52 percent, of the total installed hydropower capacity of large hydro plants.

Table 1. Characteristics of 19 large hydropower plants and their 24 rivers. The two shaded plants correspond to two future projects.

Source: Ramirez C. 2015.

[15] Mean of the 14 normalized curves related to the average of each year.

[16] Such as land–sea and mountain–valley breezes and Foehn effect.

[17] Several peaks have altitudes over 5,000 meters. "Surface smoothing" means that MERRA "sees" altitudes in Colombia only up to 3,000m and so reproduces the western and central cordilleras as a single mountain range.

[18] International Renewable Energy Agency, 3TIER map.

[19] This aggregates data from 16 hydropower plants, including 21 rivers (collected from 2002 to 2014). The 21 rivers are: Magdalena Betania, Cauca Salvajina, Digua, Alto Anchicayá, Calima, Prado, Bogotá N.R., Chuza, Guavio, Batá, San Carlos, Guatapé, Nare, A. San Lorenzo, Grande, Guadalupe, Concepción, Tenche, Desv. EEPPM (Nec, Paj, Dol), Porce II, and Sinú Urrá. Not included: Amoyá, Miel I, and Porce III due to lack of data for some years.

				Rivers feeding plant				
Hydropower plant	Rated capacity (MW)	Type	Conversion factor (MW/m³/s)	Name	Mean inflow (m³/s)	Years with data from/to (years)		
Quimbo	400	Dam	-	-	-	Started in 2015		-
Betania	540	Dam	0.6236	Magdalena Betania	414.58	2001	2014	14
Salvajina	285	Dam	0.9928	Cauca Salvajina	127.40	2001	2014	14
Alban	429	Dam	3.9055	Alto Achincayá	46.10	2001	2014	14
				Digua	28.86	2001	2014	14
Calima	132	Dam	1.8712	Calima	11.71	2001	2014	14
Amoyá	80	Run-of-the-river	4.8664	Amoyá	15.32	2014	2014	1
Prado	51	Dam	0.4916	Prado	57.13	2001	2014	14
Pagua	600	Run-of-the-river	16.573	Bogotá N.R.	30.94	2001	2014	14
				Chuza	10.23	2001	2014	14
Guavio	1.213	Dam	9.7433	Guavio	68.57	2001	2014	14
Chivor	1.000	Dam	7.0123	Batá	78.10	2001	2014	14
Miel I	396	Dam	2.0092	Miel I	94.51	2003	2013	11
Porvenir II	352	Dam	-	-	-	Starts in 2018		-
San Carlos	1.240	Dam	5.4694	San Carlos	27.48	2001	2014	14
				Guatapé	36.31	2001	2014	14
				Nare	51.08	2001	2014	14
				A. San Lorenzo	40.65	2001	2014	14
Playas	207	Dam	1,5605	Guatapé	36,31	2001	2014	14
				Nare	51,08	2001	2014	14
				A. San Lorenzo	40,65	2001	2014	14
Tasajera	306	Dam	7.7642	Grande	32.70	2001	2014	14
Guatron	512	Dam	8.315	Guadalupe	22.13	2001	2014	14
				Concepción	6.76	2001	2014	14
				Tenche	4.52	2001	2014	14
				Desv. EEPPM (Nec, Paj, Dol)	8.02	2001	2014	14
Porce II	405	Dam	2.23	Grande	32.70	2001	2014	14
				Porce II	98.32	2002	2014	13
Porce III	700	Dam	3.1723	Guadalupe	22.13	2001	2014	14
				Concepción	6.76	2001	2014	14
				Tenche	4.52	2001	2014	14
				Desv. EEPPM (Nec, Paj, Dol)	8.02	2001	2014	14
				Porce III	23.39	2011	2014	4
Ituango	2.400	Dam	-	-	-	Starts in 2018-22		-
Sogamoso	820	Dam	-	-	-	Started in 2014		-
Urrá	338	Dam	0.4471	Sinú Urrá	334.67	2002	2014	13
National[19]	13.136	-	-	21 of 24 rivers	1550.80	2002	2014	13

Figure 17. Mean wind speed (m/s) and direction @ 50m from MERRA (2001–14) and normalized mean seasonal (monthly) wind patterns of six sites. **Source:** Ramirez C. 2015.

Note: •**1**-Nariño, •**2**-Pacifico Sur, •**3**-Buenaventura Sur, •**4**-Tolima, •**5**-Cundinamarca, •**6**-Casanare, •**7**-Boyacá, •**8**-Arauca, •**9**-Norte de Santander, •**10**-Córdoba, •**11**-Atlántico, •**12**-Guajira, •**13**-San Andrés

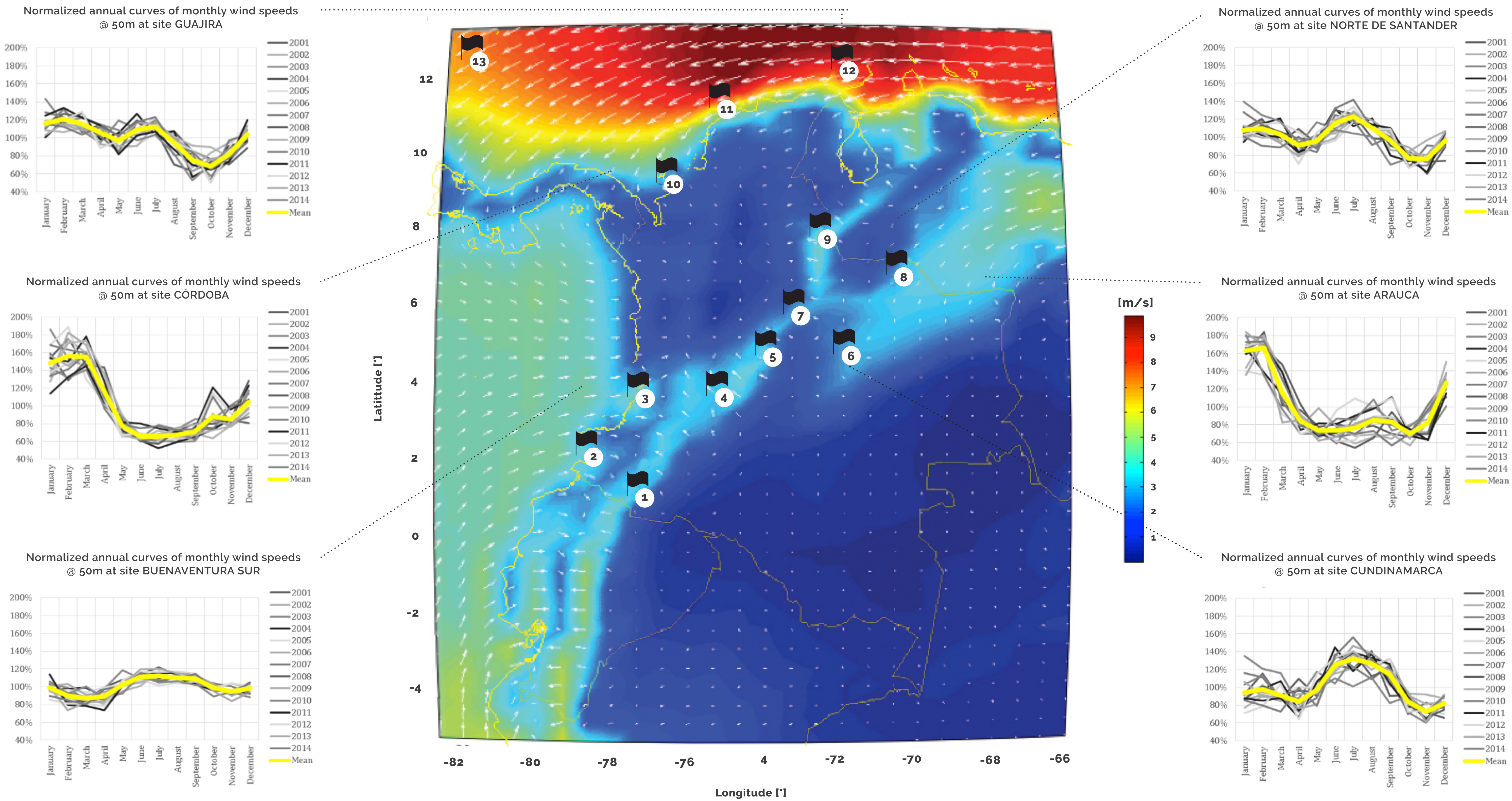


Figure 18. Mean annual solar surface insolation (kWh/m²/year) from MERRA (2001–2014) and normalized mean seasonal (monthly) solar patterns of six sites. **Source:** Ramirez C. 2015.

Note: •**1**-Nariño Sur, •**2**-Cauca •**3**-Huila, •**4**-Cundinamarca Occidente, •**5**-Casanare, •**6**-Boyacá, •**7**-Antioquia, •**8**-Arauca, •**9**-Norte de Santander, •**10**-Bolivar, •**11**-Cesar, •**12**-Atlántico, •**13**-Guajira, •**14**-San Andrés (Ramirez C. 2015)

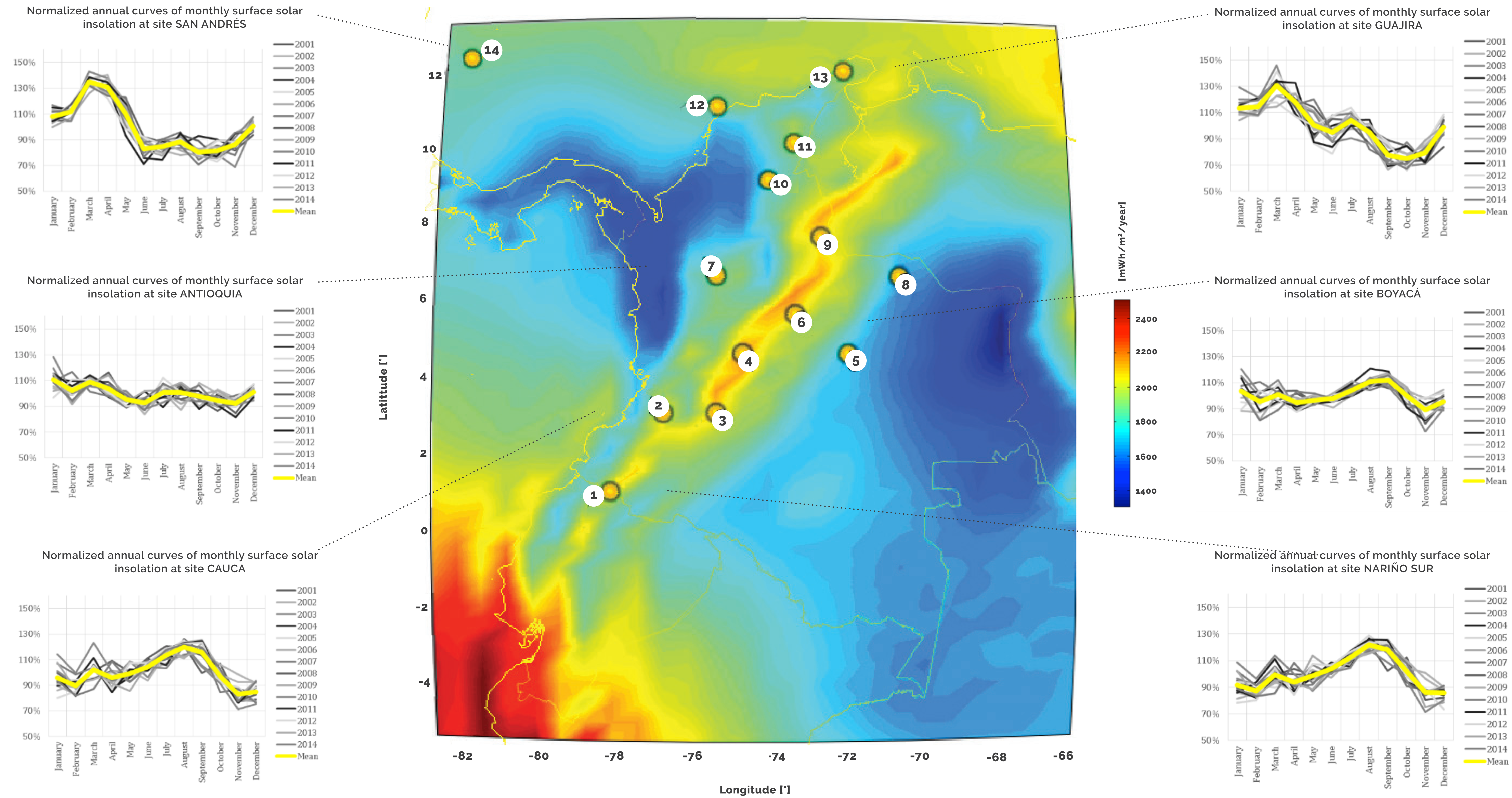
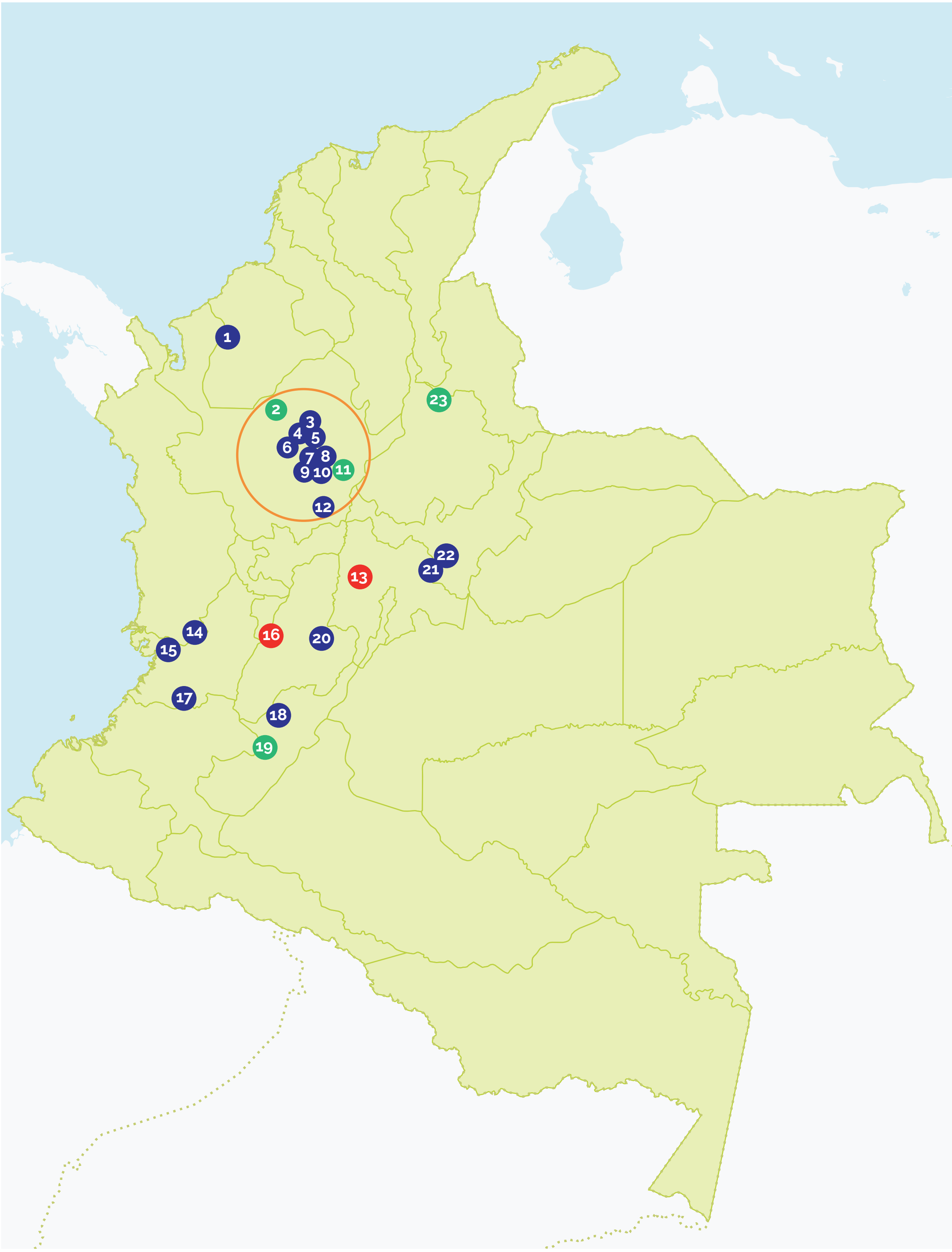


Figure 19. Location and rated capacity (in MW) (proportional to the area of the square) of the large (>20 MW) hydropower plants considered in the study. **Source:** Ramirez C. 2015.



Case Study

Blue: current dam-power plants. **Red:** current run-of-the-river plants. **Green:** future/recent dam-power plants.
The yellow circle surrounding the eight current and two future hydro generation assets in Antioquia.

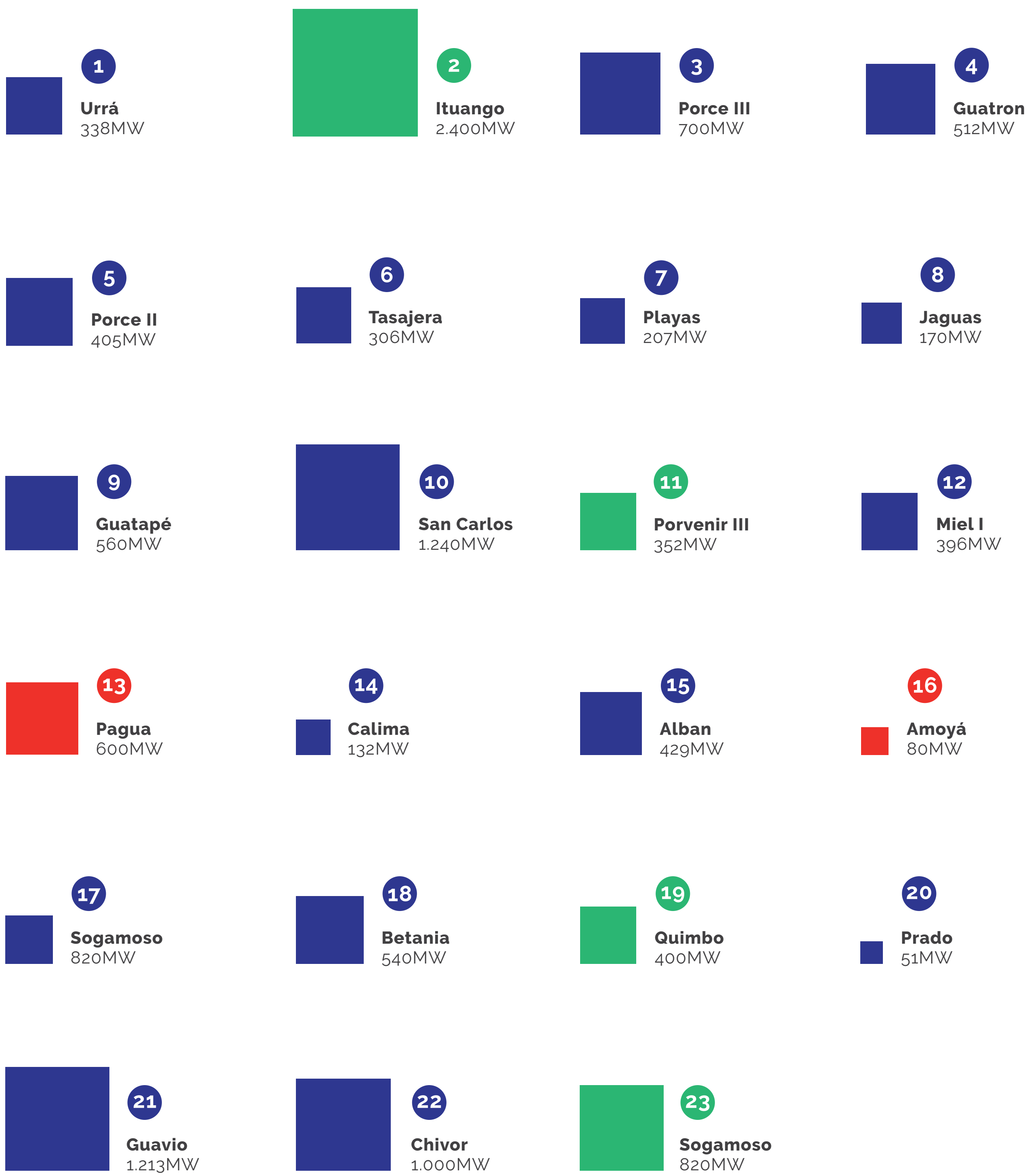
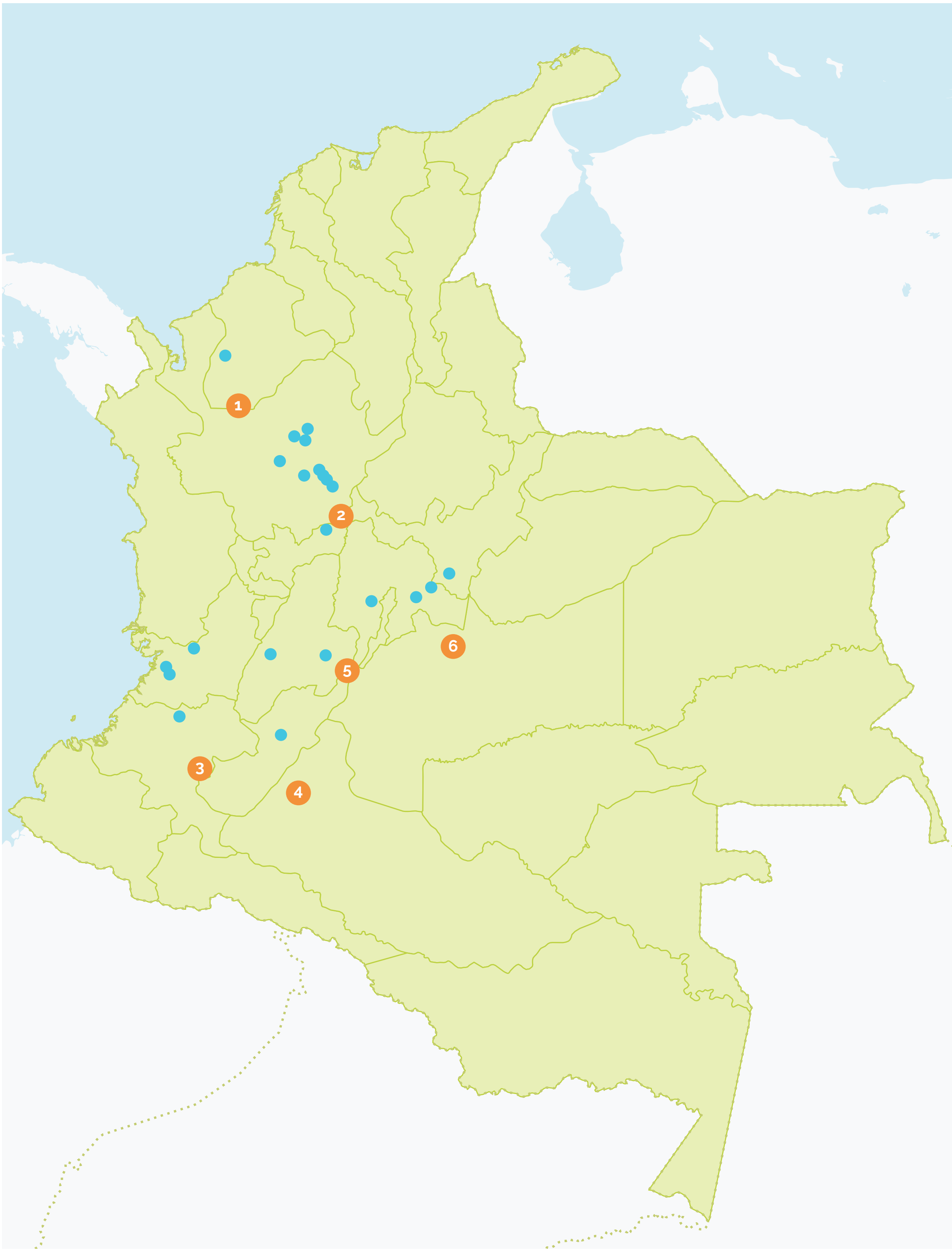
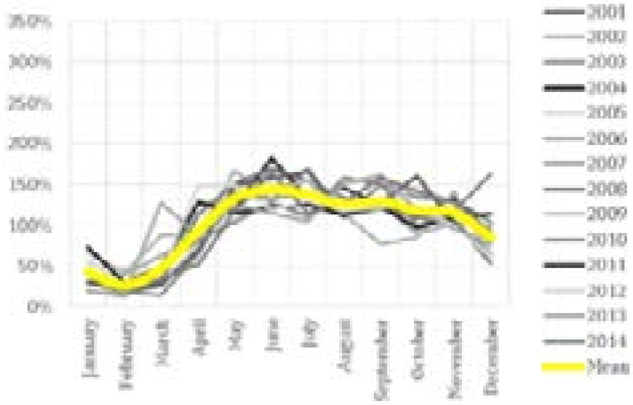


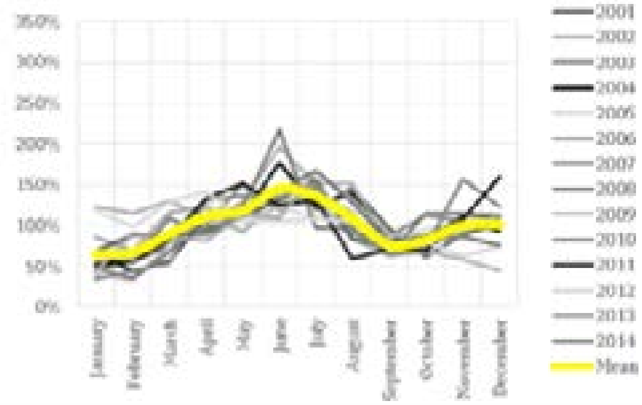
Figure 20. Location of the selected rivers (blue points) and normalized mean seasonal (monthly) river inflows of six rivers.
Source: Ramirez C. 2015.



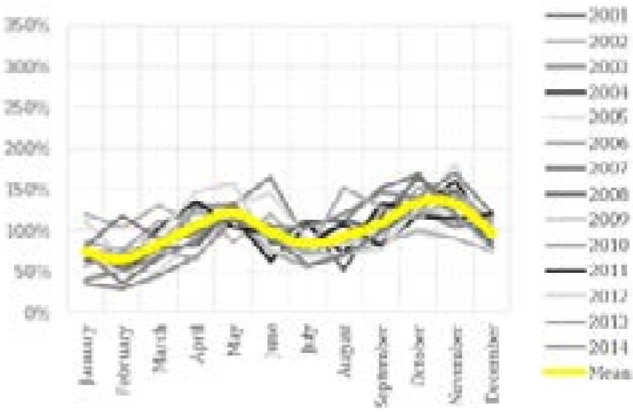
1 Normalized annual curves of monthly in-flows of river SINÚ URRÁ



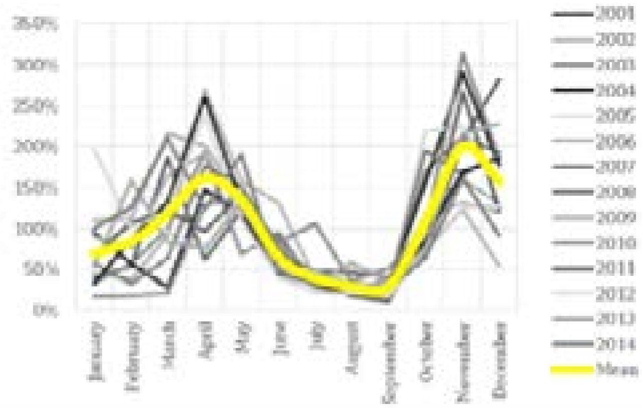
4 Normalized annual curves of monthly in-flows of river MAGDALENA BETANIA



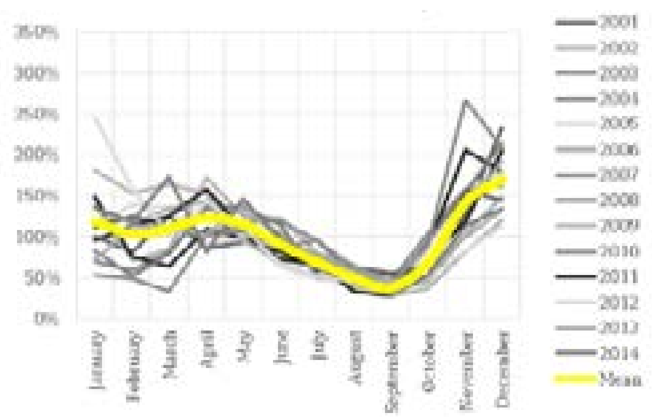
2 Normalized annual curves of monthly in-flows of river GUATAPÉ



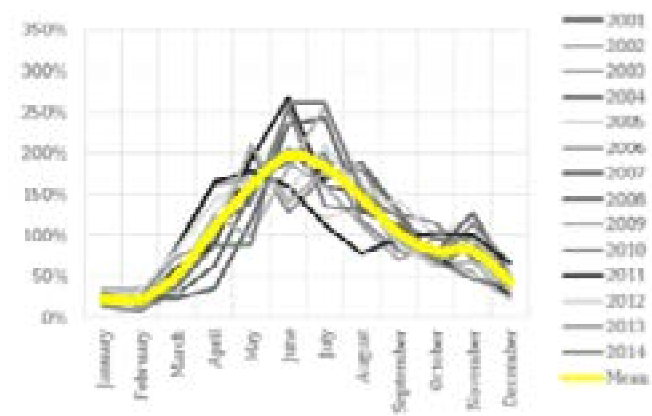
5 Normalized annual curves of monthly in-flows of river PRADO



3 Normalized annual curves of monthly in-flows of river CAUCA SALVAJINA



6 Normalized annual curves of monthly in-flows of river GUAVIO



Energy results.

This study examines wind and solar resources based on their relationship to hydrology. Energy calculations were made to provide the initial estimates for AEP values. The methodologies for calculating wind and solar farm energy production were confirmed with online engineering tools (Meteonorm 2015; The Swiss Wind Power Data Website 2015). The assessment used wind and solar resources from the MERRA database. As previously mentioned, the likely under- and overestimation of the magnitude of wind speed and solar irradiation in MERRA directly affects assessments of the AEP, especially along the Andes cordillera and to a lesser extent coastal areas. This affects AEP for wind farms more than for solar farms because wind has a higher resource-to-energy sensitivity.[20] As a result, the energy calculations in the 2015 study by Ramírez C. are preliminary and should not be used for commercial purposes without further analysis. Although these values are not presented in this document, the energy seasonal and interannual patterns of these VRE will be addressed in the following subsection.

In the case of hydroelectric energy, the methodology used to assess the AEP produced similar results compared with annual real XM generation data. Different seasonal patterns were observed, however, when plotting the monthly generation curves of hydropower plants. Differing seasonal patterns are likely traceable to the influence of large water reservoirs and operational procedures based on market strategies. Other studies—for example, "Impact Analysis for Integration of Wind Power Generation in Colombia"—documents this monthly non-correlation (COWI 2015). These energy assessments represent the current condition of hydrology in the country, including hydropower plants using dams and those using run-of-river.

Seasonal complementarities.

The seasonal complementarities of meteorological resources are presented in two matrixes (wind-hydro in table 2 and solar-hydro in table 3) organized from south to north, depending on the geographic location of the sites. Hydropower plant names are used instead of the river names listed in table 1. On the one hand, the name *Betania* represents the Betania power plant and the Magdalena River. On the other hand, the name *San Carlos* represents the power plant San Carlos and the San Carlos, Guatapé, Nare, and A. San Lorenzo rivers.

The seasonal analysis includes 14 correlation coefficients *R* between each wind site and each of the rivers that feeds into a hydropower plant based on the 12 monthly values of each year. (Seasonal here refers to *intra-annual* distributions, meaning the behavior within a year.) This also applies to names for the solar sites and the rivers. The tables below show the average of these 14 values. The redder values represent the more negative correlation coefficients, which show high inverse behavior within a pair. As a consequence, these are the pairs with the highest seasonal complementarity and therefore the ones of interest in this study. The greener values represent the more positive correlation coefficients, which are the most highly dependent pairs. The closer the values are to zero, the more independent the behavior of the pairs. Furthermore, the white columns represent hydropower plants with little data (low representativeness) or future hydropower plants for which there is no data (NaN = Not-a-Number).

As can be seen from the tables below, the meteorological dynamics in Colombia and the associated hydrology present complex behaviors that cannot be expressed as a homogeneous correlation. There are large positive, negative, and noncorrelated seasonal correlations depending on the location of the wind-solar sites and the hydropower plants. Four plots are presented in order to provide a better understanding of the values in the tables. In figure 21 the wind-hydro resource analysis shows why the Arauca wind site has a mean seasonal negative *R* of -0.69 in relation to the national group of rivers. The monthly wind speed at Arauca is highly inverse to the national inflows during the year. This is the site with the highest seasonal complementary pattern for national rivers. The largest negative mean seasonal *R* is between the river for the hydropower plant Urrá and the wind site at Córdoba; it has a mean seasonal *R* of -0.81, indicating the high complementarity between the sites. Figure 22 shows that the national group of rivers and the solar site Arauca have a negative mean seasonal *R* of -0.73, which means that the solar site has the highest mean seasonal complementarity for the national group. The rivers that power the Salvajina hydropower plant and the Huila solar site represent the largest negative mean seasonal *R* of -0.82.

[20] Wind power is proportional to wind speed to the power of 3.

Table 2. Mean seasonal correlation coefficients *R* between wind speeds at 50m and river inflows on the hydropower plants within 2001 and 2014. **Source:** Ramírez C. 2015.

Wind speeds @50m (North <-South)	River(s) in-flows of hydro power plants (South -> North)											
	Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II
Nariño	NaN	0,36	-0,62	-0,53	-0,58	0,86	-0,67	0,28	0,64	0,72	-0,74	NaN
Pacífico Sur	NaN	0,20	-0,39	-0,09	-0,23	0,75	-0,37	0,36	0,46	0,61	-0,33	NaN
Buenaventura Sur	NaN	0,24	-0,53	-0,37	-0,43	0,84	-0,62	0,28	0,54	0,62	-0,58	NaN
Tolima	NaN	0,34	-0,64	-0,48	-0,53	0,83	-0,63	0,31	0,65	0,72	-0,70	NaN
Cundinamarca	NaN	0,25	-0,64	-0,66	-0,66	0,80	-0,77	0,12	0,50	0,57	-0,76	NaN
Casanare	NaN	-0,41	0,21	-0,10	-0,03	-0,72	-0,12	-0,55	-0,59	-0,53	0,08	NaN
Boyacá	NaN	0,28	-0,65	-0,66	-0,67	0,86	-0,75	0,17	0,55	0,62	-0,78	NaN
Arauca	NaN	-0,47	0,26	-0,10	0,00	-0,83	-0,04	-0,64	-0,70	-0,66	0,16	NaN
Norte de Santander	NaN	0,18	-0,29	-0,65	-0,51	-0,59	-0,63	-0,08	0,22	0,23	-0,52	NaN
Córdoba	NaN	-0,44	0,33	0,02	0,12	-0,85	0,21	-0,55	-0,70	-0,77	0,35	NaN
Atlántico	NaN	-0,27	0,45	-0,05	0,13	-0,64	0,19	-0,46	-0,59	-0,68	0,33	NaN
Guajira	NaN	0,13	0,23	-0,34	-0,11	-0,04	-0,15	-0,17	-0,09	-0,19	-0,04	NaN
San Andrés	NaN	-0,02	0,48	-0,02	0,15	-0,17	0,15	-0,18	-0,33	-0,37	0,34	NaN

Wind speeds @50m (North <-South)	River(s) in-flows of hydro power plants (South -> North)											
	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Nariño	-0,10	-0,07	-0,14	0,14	-0,08	0,35	0,01	0,20	NaN	NaN	0,51	0,28
Pacífico Sur	0,25	0,24	0,20	0,35	0,25	0,50	0,33	0,36	NaN	NaN	0,61	0,37
Buenaventura Sur	0,02	0,04	0,01	0,22	0,03	0,39	0,10	0,30	NaN	NaN	0,53	0,26
Tolima	0,01	0,04	-0,04	0,24	-0,01	0,41	0,08	0,24	NaN	NaN	0,57	0,31
Cundinamarca	-0,32	-0,28	-0,33	-0,07	-0,29	0,12	-0,20	0,08	NaN	NaN	0,29	0,08
Casanare	-0,55	-0,55	-0,50	-0,59	-0,47	-0,59	-0,53	-0,56	NaN	NaN	-0,61	-0,59
Boyacá	-0,26	-0,23	-0,28	-0,02	-0,24	0,17	-0,16	0,15	NaN	NaN	0,35	0,13
Arauca	-0,58	-0,59	-0,54	-0,65	-0,52	-0,69	-0,61	-0,61	NaN	NaN	-0,76	-0,69
Norte de Santander	-0,60	-0,56	-0,54	-0,41	-0,50	-0,27	-0,48	-0,20	NaN	NaN	-0,10	-0,15
Córdoba	-0,45	-0,47	-0,42	-0,58	-0,45	-0,72	-0,53	-0,53	NaN	NaN	-0,81	-0,63
Atlántico	-0,58	-0,59	-0,51	-0,69	-0,51	-0,79	-0,62	-0,69	NaN	NaN	-0,80	-0,56
Guajira	-0,63	-0,60	-0,54	-0,58	-0,51	-0,57	-0,56	-0,50	NaN	NaN	-0,48	-0,27
San Andrés	-0,50	-0,50	-0,40	-0,60	-0,36	-0,61	-0,45	-0,58	NaN	NaN	-0,52	-0,27

Table 3. Mean seasonal correlation coefficients *R* between solar surface insolations and river inflows for hydropower plants between 2001 and 2014. **Source:** Ramírez C. 2015.

		River(s) in-flows of hydro power plants (South -> North)											
		Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II
Solar insolations (North <- South)	Nariño Sur	NaN	0,06	-0,82	-0,56	-0,67	0,71	-0,72	0,07	0,43	0,53	-0,77	NaN
	Cauca	NaN	0,08	-0,78	-0,65	-0,69	0,69	-0,75	0,01	0,40	0,47	-0,78	NaN
	Huila	NaN	-0,03	-0,82	-0,56	-0,64	0,67	-0,71	0,00	0,36	0,44	-0,75	NaN
	Cundinamarca Occ.	NaN	0,02	-0,77	-0,70	-0,73	0,76	-0,82	-0,06	0,35	0,43	-0,81	NaN
	Casanare	NaN	-0,41	-0,26	-0,41	-0,39	-0,36	-0,44	-0,49	-0,37	-0,25	-0,34	NaN
	Boyacá	NaN	-0,35	-0,73	-0,64	-0,68	0,57	-0,76	-0,36	-0,03	0,10	-0,71	NaN
	Antioquia	NaN	-0,34	0,00	-0,36	-0,23	-0,39	-0,18	-0,49	-0,44	-0,45	-0,14	NaN
	Arauca	NaN	-0,47	0,00	-0,33	-0,24	-0,78	-0,24	-0,64	-0,59	-0,52	-0,09	NaN
	Norte de Santander	NaN	0,00	-0,69	-0,66	-0,70	0,61	-0,72	-0,09	0,28	0,38	-0,77	NaN
	Bolívar	NaN	-0,19	0,25	-0,28	-0,12	-0,44	-0,09	-0,42	-0,44	-0,45	0,05	NaN
	Cesar	NaN	-0,14	0,15	-0,39	-0,22	-0,31	-0,19	-0,42	-0,36	-0,37	-0,08	NaN
	Atlántico	NaN	-0,15	0,39	-0,12	0,09	-0,54	0,17	-0,36	-0,43	-0,56	0,20	NaN
	Guajira	NaN	-0,05	0,25	-0,26	-0,04	-0,42	0,03	-0,29	-0,25	-0,40	0,03	NaN
	San Andrés	NaN	-0,17	0,37	-0,02	0,20	-0,72	0,32	-0,29	-0,39	-0,58	0,25	NaN

		River(s) in-flows of hydro power plants (South -> North)											
		San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Solar insolations (North <- South)	Nariño Sur	-0,08	-0,06	-0,16	0,15	-0,18	0,26	-0,06	0,25	NaN	NaN	0,40	0,05
	Cauca	-0,20	-0,18	-0,27	0,03	-0,30	0,13	-0,19	0,09	NaN	NaN	0,29	-0,01
	Huila	-0,08	-0,05	-0,15	0,15	-0,19	0,23	-0,08	0,20	NaN	NaN	0,37	-0,01
	Cundinamarca Occ.	-0,32	-0,28	-0,36	-0,06	-0,39	0,05	-0,28	0,02	NaN	NaN	0,22	-0,09
	Casanare	-0,62	-0,61	-0,62	-0,55	-0,60	-0,51	-0,60	-0,54	NaN	NaN	-0,43	-0,60
	Boyacá	-0,39	-0,38	-0,45	-0,20	-0,48	-0,14	-0,39	-0,04	NaN	NaN	0,01	-0,39
	Antioquia	-0,69	-0,70	-0,64	-0,72	-0,63	-0,72	-0,70	-0,62	NaN	NaN	-0,62	-0,62
	Arauca	-0,66	-0,65	-0,64	-0,65	-0,64	-0,68	-0,69	-0,63	NaN	NaN	-0,71	-0,73
	Norte de Santander	-0,30	-0,28	-0,34	-0,09	-0,37	0,02	-0,29	-0,02	NaN	NaN	0,19	-0,11
	Bolívar	-0,69	-0,68	-0,61	-0,71	-0,56	-0,72	-0,64	-0,64	NaN	NaN	-0,72	-0,53
	Cesar	-0,72	-0,71	-0,65	-0,71	-0,61	-0,70	-0,69	-0,62	NaN	NaN	-0,67	-0,52
	Atlántico	-0,55	-0,55	-0,48	-0,63	-0,46	-0,71	-0,56	-0,53	NaN	NaN	-0,73	-0,46
	Guajira	-0,55	-0,53	-0,48	-0,55	-0,46	-0,61	-0,55	-0,42	NaN	NaN	-0,60	-0,38
	San Andrés	-0,29	-0,29	-0,25	-0,38	-0,29	-0,54	-0,38	-0,36	NaN	NaN	-0,62	-0,38

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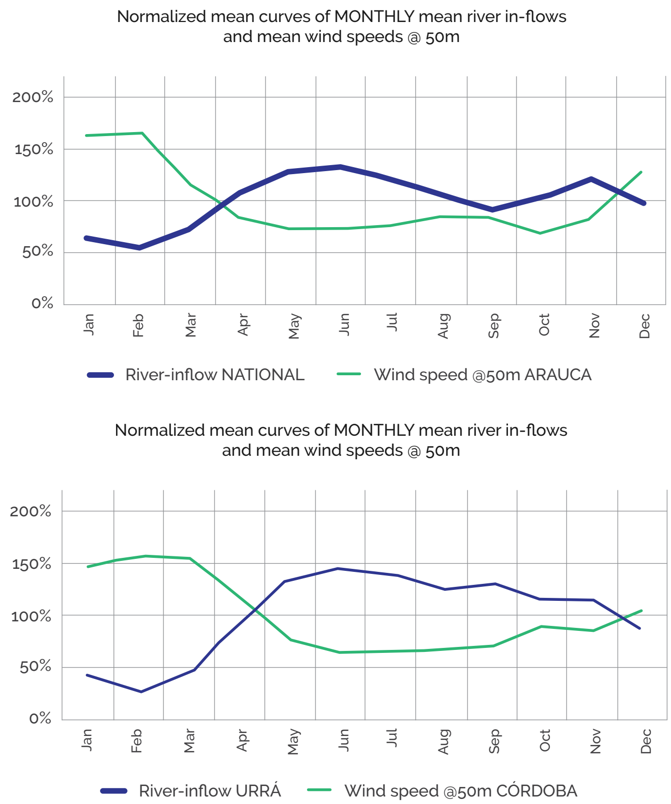
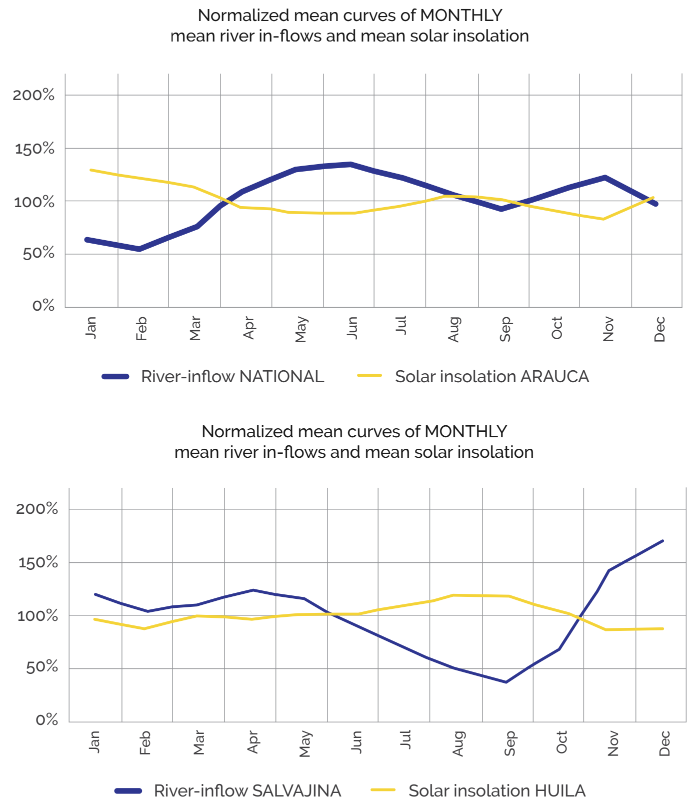
Figure 21. Normalized mean curves of monthly river inflows and wind speeds at 50m between the national group of rivers and the wind site with the most negative seasonal *R* (Top) and the river through a hydropower plant and the wind site with the highest negative seasonal *R* (bottom).



Source: Ramírez C. 2015.

Figure 22. Normalized mean curves of monthly river inflows and solar surface insolation between the national group of rivers and the solar site with the most negative seasonal *R* (Top) and the river through a hydropower plant and the wind site with the highest negative seasonal *R* (bottom).



Source: Ramirez C. 2015.

On a national level, the highest negative mean seasonal coefficient R between the wind-hydro pairs was found at the wind sites on the Oriental Plains (Arauca -0.69 and Casanare -0.59) and on the Caribbean coast (Córdoba -0.63 and Atlántico -0.56). In relation to the solar-hydro pairs, the highest negative seasonal coefficient R was also found at solar sites on the Oriental Plains (Arauca -0.73 and Casanare -0.60) and in the Antioquia region, with -0.63.

Although seasonal R coefficients vary widely, generally speaking, large[21] negative seasonal correlation coefficients are found between hydropower plants in the north and wind and solar sites in the north and hydropower plants in the south and wind and solar sites in the south. These are listed in p. 46.

As a consequence, future wind and solar farms built near the wind/solar sites selected for the present study might be able to back up hydropower plants in nearby regions experiencing periods of critical low-flow hydrology. This would certainly benefit energy transport in the national transmission system.[22]

Qualitative comparisons were carried out for the matrices of, on the one hand, the seasonal complementarities of the meteorological resource and, on the other, the seasonal complementarities of energy production (Ramírez C. 2015). Although mean seasonal R values are not identical, the negative correlation coefficients for wind-hydro and solar-hydro have a similar distribution in terms of energy production. So tables 4 and 5, which show regions having large negative seasonal R between sites, are also valid for energy production between hydropower and VRE powered by wind and solar resources.

[21] $R < -0,5$ indicates strong seasonal complementarity.

[22] This refers to a physical distance of several hundred km between the hydropower plants and the wind/solar sites selected in this study.

Table 4. Some of the regions with hydropower plants and wind sites with strong seasonal complementarity (large negative seasonal correlation coefficients).

River inflows of hydropower plants	Wind speeds @ 50m
North (Antioquia region and farther north) Rivers flowing to San Carlos, Playas, Guatapé, Jaguas, Tasajera, Guatron, Porce II, Porce II, and Urrá	**North (Caribbean coast)** Wind sites Atlántico, Cordoba, and Guajira **Northeast (Catatumbo region)** Wind site Norte de Santander **East (Oriental Plains)** Wind sites Casanare and Arauca
South (West Andes) Rivers flowing to Salvajina, Alban, Calima **Center (East and Central Andes)** River flowing to Prado and Miel I	**South and Center (East Andes)** Wind sites Nariño, Tolima, Cundinamarca, Boyacá

Table 5. Some regions with hydropower plants and solar sites with strong seasonal complementarity (large negative seasonal correlation coefficients).

River inflows of hydropower plants	Surface solar insolations
North (Antioquia region and its north) Rivers flowing to San Carlos, Playas, Guatapé, Jaguas, Tasajera, Guatron, Porce II, Porce II, and Urrá	**North (Caribbean coast and Magdalena plains)** Solar sites Guajira, Atlántico, Bolivar, and Cesar **North (Antioquia region)** Solar site Antioquia **East (Oriental Plains)** Solar sites Casanare and Arauca
South (western Andes) Rivers flowing to Salvajina, Alban, Calima **Center (eastern and central Andes)** River flowing to Prado, and Miel I	**South and Center (eastern and western Andes)** Solar sites Nariño Sur, Huila, Cundinamarca Occidente, and Cauca

Seasonal meteorological patterns in Colombia.

Apart from regional systems and local atmospheric circulations owing to its location in the tropics,[23] the seasonal wind and solar resource patterns in Colombia that appear in this study are mainly governed by the Inter-Tropical Convergence Zone (ITCZ) (IDEAM 2005b).[24] The ITCZ is a narrow low-pressure belt around the globe and it developed thanks to the global atmospheric circulation of Hadley cells between the tropics and the Equator, as shown in figure 23. Trade winds converge above this belt and air masses rise. The ITCZ produces clouds, rain, and becalmed winds; also called "the doldrums."[25]

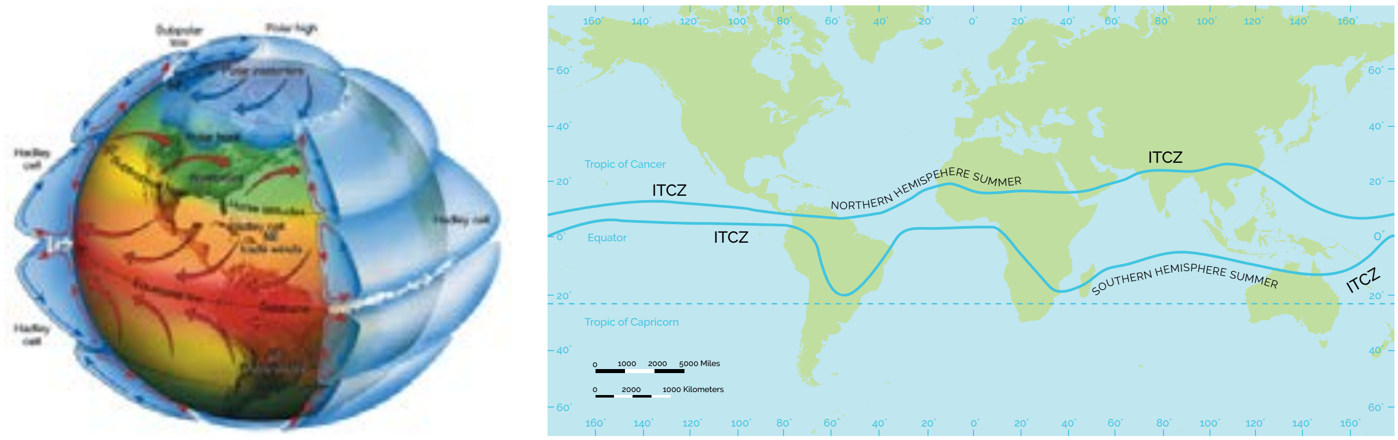
As exhibited in figure 23 on the right, the zone moves throughout the year. From December through February it travels to the farthest southern reaches, and from June through August it is at the northernmost regions. When the ITCZ is in the far south, it is obviously farther away from northern Colombia, a region that generates stronger winds. More clouds and precipitation are expected in the south. By way of contrast, when the ITCZ is in the far north, it is farther away from southern Colombia, where there are stronger winds in the south and more clouds

[23] These include the easterly waves (or Atlantic hurricanes) observed mainly between June and November.

[24] These are the mountain–valley and sea–land breezes, in addition to the Foehn effect.

[25] Air masses flowing from the tropics toward the Equator and deflected to the west in both hemispheres by the Coriolis force.hacia el oeste en ambos hemisferios por la fuerza de Coriolis.

Figure 23. Global circulation of the atmosphere (IDEAM 2005b) (left); ITCZ lines (blue) (right). In the Northern Hemisphere summer, the ITCZ is in the extreme north (June–August). In the Southern Hemisphere summer, the ITCZ is in the extreme south (December–February). **Source:** "Intertropical Convergent Zone (ITCZ)" 2013.



and precipitation in the north. The regions in between experience the ITCZ twice a year. Although the presence of this zone might explain precipitation patterns in Colombia, it cannot so easily explain the seasonality of river inflows owing to their time-delayed formation. The seasonality of river inflows recorded by XM come from onsite observations of actual hydropower plants. Further studies should be undertaken to understand (1) the impact of having both ITCZ extremes in the country and (2) the development of the hydrology over the Andes.

Interannual complementarities.

The interannual complementarities of meteorological resources are shown in the wind-hydro matrix (table 6) and the solar-hydro matrix in table 7 and are organized from south to north. There is only one unique interannual correlation coefficient R between each pair of wind-hydro and solar-hydro resources, as there are only 14 annual values for each site. As for the seasonal analysis, the reddest values represent the most negative correlation coefficients and the highest possible complementarity. These pairs are of interest in this study. The greenest values show the most dependent pairs. The closer the values are to zero, the more independent the behavior of the pairs. Furthermore, the white columns represent hydropower plants with little data or future hydropower plants for which there is no data.

The following tables show that the interannual global climatological patterns affecting Colombia represent a wide variety of unique positive, negative, and noncorrelated interannual R depending on the location of the wind/solar sites and the hydropower plants. To better understand the values exhibited, figure 24 presents two plots. The wind site Tolima has a negative interannual R of -0.74 owing to the highly inverse behavior of its annual mean wind speeds compared with the mean annual inflows of the national group from 2002 to 2014. Further large negative interannual R was also found at wind sites in the eastern Andes (Cundinamarca -0.67; Boyacá -0.64 and Norte de Santander -0.60). For the solar sites, Nariño Sur presents the largest negative interannual R, with a value of -0.74. The eastern and western Andes had other areas with large negative values (Nariño Sur -0.74; Huila -0.69; Boyacá/Cauca with -0.61).

The tables show various negative and positive values. Tables 6 (p.48) and 7 (p.49) show several large negative interannual correlation coefficients between sites.

Table 6. Unique interannual correlation coefficient *R* between wind speeds @50m and river inflows at hydropower plants between 2001 and 2014. **Source:** Ramirez C. 2015.

Wind speeds @50m (North <- South)	River(s) in-flows of hydro power plant (South -> North)											
	Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II
Nariño	NaN	-0,36	-0,54	-0,21	-0,41	NaN	-0,67	-0,49	0,63	0,27	-0,47	NaN
Pacífico Sur	NaN	-0,48	-0,40	0,30	-0,27	NaN	-0,40	-0,62	-0,31	-0,71	-0,16	NaN
Buenaventura Sur	NaN	-0,38	-0,39	-0,03	-0,33	NaN	-0,55	-0,84	-0,14	-0,71	-0,02	NaN
Tolima	NaN	-0,51	-0,70	-0,32	-0,52	NaN	-0,79	-0,62	0,43	0,05	-0,54	NaN
Cundinamarca	NaN	-0,37	-0,64	-0,36	-0,62	NaN	-0,74	-0,70	0,53	-0,04	-0,41	NaN
Casanare	NaN	-0,09	-0,20	0,11	-0,13	NaN	-0,43	-0,28	0,59	0,43	-0,26	NaN
Boyacá	NaN	-0,33	-0,59	-0,38	-0,57	NaN	-0,73	-0,71	0,52	-0,04	-0,31	NaN
Arauca	NaN	0,16	-0,04	0,12	-0,04	NaN	-0,30	-0,39	0,58	0,25	-0,15	NaN
Norte de Santander	NaN	-0,33	-0,61	-0,38	-0,63	NaN	-0,66	-0,67	0,45	-0,15	-0,38	NaN
Córdoba	NaN	-0,41	-0,05	-0,29	0,11	NaN	-0,20	-0,29	-0,06	-0,14	0,33	NaN
Atlántico	NaN	-0,13	-0,36	-0,39	-0,40	NaN	-0,48	-0,58	0,49	-0,04	-0,14	NaN
Guajira	NaN	-0,29	-0,59	-0,33	-0,66	NaN	-0,52	-0,57	0,45	-0,18	-0,54	NaN
San Andrés	NaN	-0,27	-0,53	-0,66	-0,63	NaN	-0,50	-0,47	0,53	-0,05	-0,30	NaN

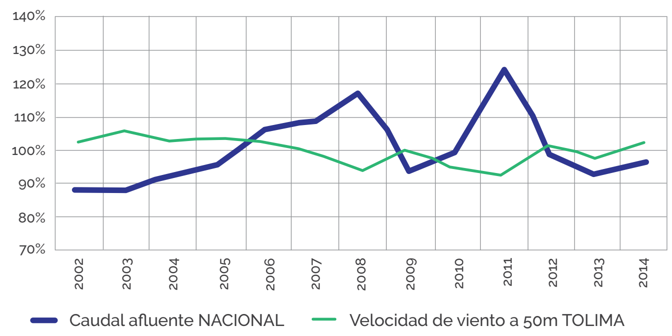
Wind speeds @50m (North <- South)	River(s) in-flows of hydro power plant (South -> North)											
	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Nariño	-0,79	-0,80	-0,73	-0,80	-0,76	-0,44	-0,67	-0,76	NaN	NaN	-0,45	-0,55
Pacífico Sur	-0,44	-0,50	-0,50	-0,44	-0,44	-0,06	-0,41	-0,69	NaN	NaN	0,22	-0,46
Buenaventura Sur	-0,50	-0,55	-0,58	-0,42	-0,52	-0,17	-0,44	-0,91	NaN	NaN	-0,03	-0,50
Tolima	-0,84	-0,86	-0,84	-0,78	-0,84	-0,46	-0,76	-0,80	NaN	NaN	-0,41	-0,74
Cundinamarca	-0,87	-0,88	-0,85	-0,80	-0,84	-0,57	-0,82	-0,89	NaN	NaN	-0,47	-0,67
Casanare	-0,42	-0,43	-0,27	-0,68	-0,46	-0,34	-0,35	0,60	NaN	NaN	-0,18	-0,24
Boyacá	-0,84	-0,86	-0,82	-0,79	-0,82	-0,57	-0,78	-0,88	NaN	NaN	-0,46	-0,64
Arauca	-0,28	-0,33	-0,23	-0,45	-0,44	-0,42	-0,35	-1,00	NaN	NaN	-0,29	-0,15
Norte de Santander	-0,77	-0,77	-0,77	-0,64	-0,72	-0,54	-0,73	-0,98	NaN	NaN	-0,39	-0,60
Córdoba	-0,20	-0,08	-0,01	-0,08	0,01	0,02	0,17	0,70	NaN	NaN	0,10	-0,17
Atlántico	-0,52	-0,50	-0,49	-0,39	-0,50	-0,46	-0,44	-0,98	NaN	NaN	-0,39	-0,37
Guajira	-0,67	-0,68	-0,73	-0,48	-0,68	-0,53	-0,72	-0,95	NaN	NaN	-0,48	-0,56
San Andrés	-0,60	-0,57	-0,62	-0,35	-0,55	-0,50	-0,56	-0,77	NaN	NaN	-0,63	-0,51

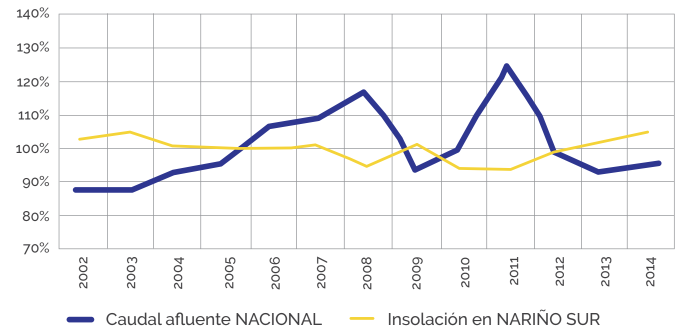
Table 7. Unique interannual correlation coefficient *R* between solar surface insolations and river inflows at hydropower plants between 2001 and 2014. **Source:** Ramirez C. 2015.

	River(s) in-flows of hydro power plants (South -> North)											
Solar insolations (North <- South)	Quimbo	Betania	Salvajina	Alban	Calima	Amoyá	Prado	Pagua	Guavio	Chivor	Miel I	Porvenir II
Nariño Sur	NaN	-0,50	-0,74	-0,13	-0,66	NaN	-0,72	-0,72	0,33	-0,26	-0,68	NaN
Cauca	NaN	-0,42	-0,59	-0,14	-0,52	NaN	-0,74	-0,72	0,39	-0,08	-0,39	NaN
Huila	NaN	-0,52	-0,65	-0,11	-0,47	NaN	-0,79	-0,82	0,16	-0,30	-0,34	NaN
Cundinamarca Occ.	NaN	-0,42	-0,49	-0,19	-0,38	NaN	-0,72	-0,68	0,39	0,03	-0,21	NaN
Casanare	NaN	-0,23	-0,42	0,14	-0,41	NaN	-0,53	-0,47	0,42	0,04	-0,46	NaN
Boyacá	NaN	-0,50	-0,61	-0,27	-0,57	NaN	-0,80	-0,78	0,20	-0,22	-0,22	NaN
Antioquia	NaN	-0,22	-0,29	-0,08	-0,19	NaN	-0,55	-0,50	0,52	0,24	-0,11	NaN
Arauca	NaN	0,35	0,16	0,31	0,04	NaN	0,06	-0,03	0,34	0,11	-0,26	NaN
Norte de Santander	NaN	-0,25	-0,40	-0,27	-0,52	NaN	-0,56	-0,61	0,13	-0,27	-0,05	NaN
Bolivar	NaN	0,30	0,05	-0,11	-0,13	NaN	-0,15	-0,19	0,67	0,36	0,19	NaN
Cesar	NaN	0,25	-0,06	-0,13	-0,28	NaN	-0,19	-0,33	0,58	0,08	0,06	NaN
Atlántico	NaN	0,33	0,07	-0,22	-0,23	NaN	0,08	-0,16	0,37	-0,10	0,28	NaN
Guajira	NaN	0,17	-0,16	-0,15	-0,36	NaN	-0,14	-0,36	0,43	-0,12	-0,14	NaN
San Andrés	NaN	0,45	0,18	-0,17	-0,09	NaN	0,35	-0,38	0,40	0,33	-0,08	NaN

	River(s) in-flows of hydro power plants (South -> North)											
Solar insolations (North <- South)	San Carlos	Playas	Guatapé	Jaguas	La Tasajera	Guatron	Porce II	Porce III	Ituango	Sogamoso	Urrá	NATIONAL
Nariño Sur	-0,82	-0,87	-0,90	-0,74	-0,87	-0,48	-0,87	-0,96	NaN	NaN	-0,37	-0,74
Cauca	-0,84	-0,85	-0,81	-0,79	-0,76	-0,37	-0,73	-0,90	NaN	NaN	-0,25	-0,61
Huila	-0,85	-0,87	-0,86	-0,78	-0,78	-0,33	-0,72	-0,95	NaN	NaN	-0,11	-0,69
Cundinamarca Occ.	-0,80	-0,76	-0,69	-0,75	-0,66	-0,34	-0,56	-0,82	NaN	NaN	-0,16	-0,53
Casanare	-0,63	-0,67	-0,64	-0,65	-0,64	-0,39	-0,63	-0,82	NaN	NaN	-0,20	-0,44
Boyacá	-0,81	-0,77	-0,73	-0,68	-0,63	-0,31	-0,60	-0,90	NaN	NaN	-0,01	-0,61
Antioquia	-0,62	-0,60	-0,48	-0,68	-0,51	-0,28	-0,38	-0,82	NaN	NaN	-0,16	-0,30
Arauca	0,13	0,03	0,01	0,02	-0,15	-0,28	-0,22	-0,88	NaN	NaN	-0,32	0,00
Norte de Santander	-0,55	-0,52	-0,54	-0,35	-0,40	-0,22	-0,42	-0,82	NaN	NaN	-0,01	-0,32
Bolivar	-0,30	-0,32	-0,24	-0,39	-0,31	-0,42	-0,31	-0,26	NaN	NaN	-0,40	-0,02
Cesar	-0,34	-0,39	-0,36	-0,37	-0,46	-0,56	-0,47	-0,75	NaN	NaN	-0,48	-0,15
Atlántico	-0,11	-0,14	-0,17	-0,02	-0,21	-0,45	-0,28	-0,71	NaN	NaN	-0,45	0,01
Guajira	-0,31	-0,37	-0,41	-0,25	-0,50	-0,57	-0,53	-0,88	NaN	NaN	-0,51	-0,21
San Andrés	0,30	0,27	0,21	0,32	0,18	-0,06	0,10	0,92	NaN	NaN	-0,46	0,36

Figure 24. Normalized mean curves of the annual national river group inflows and wind data from the site with the most negative interannual *R* (left) and solar data from the site with the most negative interannual *R* (right).





Source: Ramirez C. 2015.

Table 8. Some of the regions with hydropower plants and wind sites with strong interannual complementarity (large negative interannual correlation coefficients).

River inflows of hydropower plants	Wind speeds @ 50m
North (Antioquia region) Rivers flowing to San Carlos, Playas, Guatapé, Jaguas, Tasajera, Guatron, and Porce II	**South, Center, North (eastern Andes)** Wind site Nariño, Tolima, Cundinamarca, Boyacá, Norte de Santander **North (Caribbean Coast)** Wind site Guajira

Table 9. Some of the regions with hydro power plants and solar sites with strong interannual complementarity (large negative interannual correlation coefficients).

<table>
<tr><th>River inflows of hydropower plants</th><th>Surface solar insolations</th></tr>
<tr><td>North (Antioquia region)
Rivers flowing to San Carlos, Playas, Guatapé, Jaguas, Tasajera and Porce II</td><td rowspan="2">South and Center (eastern Andes)
Solar sites Nariño Sur, Cauca, Huila, Cundinamarca Occidente and Boyacá</td></tr>
<tr><td>Center (eastern/western Andes)
Rivers flowing to Prado and Pagua</td></tr>
</table>

Similarly, as we saw in the section on seasonal complementarities above, the matrices of interannual resource were qualitatively compared to interannual energy production as shown in (Ramírez C. 2015). Although the resource and the energy interannual *R*s are not identical, the distribution of negative correlation coefficients for wind-hydro and solar-hydro are similar. This means that tables 8 and 9, which point out the regions with large negative interannual *R* between sites, are also valid in terms of energy production between hydropower and VRE like wind and solar resources.

Annual resource indexes and IAV.

Tables 11 and 12 represent the annual MERRA-based wind and solar resource indexes. Table 13 presents XM-based hydro resource indexes. The 100 percent value corresponds to the 50m average of all wind speeds, of all the annual solar surface insolations, and of all river inflows respectively during the study period. The bluest values refer to the highest indexes, which are the years with larger resource availability. The red values correspond to years with low resources. Two main observations can be made when comparing MERRA- and XM-based resource indexes:

- The climatological phenomena governing wind, solar, and hydro resources produce similar upward or downward behaviors for the same resource in several areas of the country. For example, in 2011 all the wind and solar sites had lower than average values.

- Interannual complementarity behaviors are observed for several of the wind/solar sites as compared to the hydropower plants. A good example is the year 2002, when most of the hydropower plants suffered from low inflows as compared to the higher than average values for the wind and solar resources seen at most sites. In contrast, the values at wind/solar sites were below average in 2011, while hydropower plants had higher than average values.

We recommend further investigation of ENSO phenomena in relation to interannual complementarities (ENSO stands for El Niño Southern Oscillation, or El Niño and La Niña phenomena). Table 10 shows important El Niño values (or a more than 1-degree centigrade anomaly), which in 2002 produced scant precipitation in Colombia (GRID-Arendal 2015) and the low river inflows seen in table 13.

Table 10: Oceanic Niño Index (ONI) from the U.S. National Oceanic and Atmospheric Administration (NOAA). SST (sea surface temperature) anomaly in the tropical pacific, with a threshold of +/- 0,5°C identifying El Niño (warm, red) and La Niña (cold, blue)

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2001	-0.7	-0.6	-0.5	-0.3	-0.2	-0.1	0	-0.1	-0.1	-0.2	-0.3	-0.3
2002	-0.2	-0.1	0.1	0.2	0.4	0.7	0.8	0.9	1.0	1.2	1.3	1.1
2003	0.9	0.6	0.4	0	-0.2	-0.1	0.1	0.2	0.3	0.4	0.4	0.4
2004	0.3	0.2	0.1	0.1	0.2	0.3	0.5	0.7	0.7	0.7	0.7	0.7
2005	0.6	0.6	0.5	0.5	0.4	0.2	0.1	0	0	-0.1	-0.4	-0.7
2006	-0.7	-0.6	-0.4	-0.2	0.0	0.1	0.2	0.3	0.5	0.8	0.9	1.0
2007	0.7	0.3	0	-0.1	-0.2	-0.2	-0.3	-0.6	-0.8	-1.1	-1.2	-1.3
2008	-1.4	-1.3	-1.1	-0.9	-0.7	-0.5	-0.3	-0.2	-0.2	-0.3	-0.5	-0.7
2009	-0.8	-0.7	-0.4	-0.1	0.2	0.4	0.5	0.6	0.7	1.0	1.2	1.3
2010	1.3	1.1	0.8	0.5	0	-0.4	-0.8	-1.1	-1.3	-1.4	-1.3	-1.4
2011	-1.3	-1.1	-0.8	-0.6	-0.3	-0.2	-0.3	-0.5	-0.7	-0.9	-0.9	-0.8
2012	-0.7	-0.6	-0.5	-0.4	-0.3	-0.1	0.1	0.3	0.4	0.4	0.2	-0.2
2013	-0.4	-0.5	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3
2014	-0.5	-0.6	-0.4	-0.2	0	0	0	0	0.2	0.4	0.6	0.6
2015	0.5	0.4	0.5	0.7	0.9	1.0	1.2	1.5	-	-	-	-

Source: Climate Prediction Center NOAA 2015.

Table 11. MERRA-based wind resource indexes with IAVs for the 13 selected wind sites. **Source:** Ramirez C. 2015.

	Mean wind speed @50m (m/s)	MERRA-based wind resource index														IAV
	100 Percent	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
Nariño	3.73	107	109	110	107	106	109	98	92	93	85	87	101	93	104	8.4
Pacífico Sur	3.90	102	100	103	99	102	97	104	97	100	101	96	95	103	104	2.9
Buenaventura Sur	4.53	103	99	100	100	102	97	104	99	103	99	94	97	101	104	2.9
Tolima	3.58	102	103	106	103	104	103	99	93	100	95	92	102	97	102	4.0
Cundinamarca	3.83	107	110	103	103	102	103	100	93	103	87	88	99	97	106	6.6
Casanare	3.34	100	106	102	108	106	100	105	98	95	90	98	98	97	97	4.7
Boyacá	3.29	106	110	102	103	103	103	100	94	103	87	88	99	96	105	6.3
Arauca	3.43	99	104	100	106	103	101	104	105	98	86	94	99	100	101	4.9
Norte de Santander	4.41	109	114	100	102	95	102	100	96	105	87	87	98	101	105	7.2
Córdoba	3.31	103	103	99	108	104	98	98	103	103	106	96	92	94	93	4.8
Atlántico	6.18	105	111	96	108	93	101	101	103	108	87	89	97	99	101	6.7
Guajira	7.66	110	112	103	102	88	101	97	96	107	84	88	98	104	111	8.5
San Andrés	7.38	106	109	97	106	92	100	95	98	107	94	92	101	97	106	5.7

Table 12. MERRA-based solar resource indexes with IAVs for the 14 selected solar sites. **Source:** Ramírez C. 2015.

	Mean annual solar surface insolation (kWh/m²/year)	MERRA-based solar resource index														IAV
	100	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
Nariño Sur	2.082	104	102	105	101	100	100	100	95	101	94	93	99	102	105	3.6
Cauca	2.057	107	106	105	101	102	102	102	96	99	91	92	97	98	103	4.8
Huila	2.105	104	103	105	100	102	102	103	95	101	95	91	97	99	103	3.8
Cundinamarca Occ.	2.175	108	109	107	103	105	103	102	98	98	90	89	96	93	99	6.2
Casanare	1.695	102	104	107	99	101	100	102	99	96	93	95	100	99	104	3.7
Boyacá	2.092	106	107	103	100	101	98	103	98	102	95	93	99	97	99	3.8
Antioquia	1.875	107	109	103	105	104	105	102	101	96	89	92	96	94	97	5.7
Arauca	1.645	96	100	101	100	99	98	102	104	97	95	98	103	102	106	3.1
Norte de Santander	2.096	104	103	100	98	99	99	101	101	101	97	97	101	100	100	2.0
Bolívar	1.733	100	107	98	102	100	103	101	104	99	91	98	99	95	104	3.9
Cesar	1.939	100	105	97	100	100	101	100	103	101	92	97	100	99	105	3.2
Atlántico	1.833	101	105	94	98	97	100	98	106	103	93	98	99	101	108	4.3
Guajira	1.908	101	102	98	100	98	101	98	102	103	91	97	99	103	107	3.6
San Andrés	1.845	102	99	96	101	95	101	98	101	101	97	103	103	102	102	2.5

Table 13. XM-based hydro resource indexes with the IAVs for the 24 rivers and the national group. **Source:** Ramírez C. 2015.

	Mean inflow (m^3/s)	XM-based hydro resource index														IAV
	100	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
Magdalena Betania	414.6	83	92	79	90	98	112	112	119	99	85	127	105	92	108	13.8
Cauca Salvajina	127.4	78	74	76	89	105	111	116	147	91	102	140	89	82	101	21.8
Alto Achincayá	46.1	97	86	107	94	102	102	111	107	88	107	110	89	105	95	8.2
Digua	28.9	92	104	105	95	96	99	120	101	91	80	106	95	108	110	9.4
Calima	11.7	73	61	88	102	104	132	126	140	84	117	117	83	88	87	22.7
Amoyá	15.3														100	0.0
Prado	57.1	64	71	76	80	92	109	87	146	93	112	178	80	100	112	29.7
Bogotá N.R	30.9	45	86	70	91	82	118	69	117	54	131	231	120	89	97	43.7
Chuza	10.2	100	113	102	95	91	106	102	91	87	97	94	115	101	104	7.8
Guavio	68.6	101	116	93	125	97	104	90	96	84	79	100	109	94	112	12,1
Batá	78.1	90	107	95	122	97	118	95	98	75	82	127	121	80	93	16,0
Miel I	94.5			76	83	112	105	109	122	108	111	109	85	80		15,0
San Carlos	27.5	65	65	72	91	96	108	133	108	82	95	131	107	125	124	22,6
Guatapé	36.3	82	77	90	94	91	102	111	117	101	108	132	105	100	92	13,7
Nare	51.1	71	70	75	97	95	100	115	144	90	117	157	99	93	77	25,1
A. San Lorenzo	40.6	88	70	95	90	81	94	94	135	115	118	125	106	95	94	17.2
Grande	32.7	88	72	81	84	81	106	119	136	96	130	146	99	82	80	22.8
Guadalupe	22.1	103	75	100	91	88	104	126	107	94	119	112	97	92	92	12,7
Cencepción	6.8	91	72	86	98	93	115	120	115	92	110	131	95	90	91	15.5
Tenche	4.5	106	71	95	86	87	110	120	112	87	117	127	106	88	89	15,6
Desv. EEPPM (Nec.Paj.Dol)	8.0	137	102	113	104	100	104	94	85	108	101	75	98	89	89	14.2
Porce II	98.3		74	89	101	93	105	115	129	95	119	118	97	85	79	16,0
Porce III	23.4											167	94	73	67	39.9
Sinú Urrá	334.7		97	106	85	100	100	116	104	101	108	104	93	102	85	8,3
NATIONAL	1,550.8		88	88	92	96	106	109	117	94	99	124	99	93	96	10.5

MERRA- and XM-based indexes underwent a qualitative comparison of the meteorological resource and the ones calculated in energy terms though the AEP (Ramírez C. 2015). Although the values of the energy indexes do not exactly match the resource indexes, the distributions of below and above average annual energy production based on wind, solar, and hydropower are quite similar. Tables 11–13 represent energy production from VRE based on wind, solar, and hydropower.

Interannual Variability (IAV) measures the solar or wind resource or energy production variation from one year to the next; it is presented the far right columns of tables 11–13. Table 14 summarizes the extreme IAV values of meteorological resources and energy production:

Table 14. Maximum and minimum values found for meteorological resources and energy indexes and the IAV for wind/solar sites and hydropower plants between 2001 and 2014

	Meteorological resource		Energy	
	Index	IAV	Index	IAV
Wind sites (based on MERRA)	84 – 112	2.9 – 8.5	59 – 140	7.7 – 22.7
Solar sites (based on MERRA)	89 – 109	2.0 – 6.2	90 – 108	1.9 – 5.3
Hydropower plants (based on XM)	45 – 231	8.2 – 43.7	61 – 148	6.0 – 23

Source: Ramirez C. 2015.

The IAV for meteorological resources found in the study resembled those found in the literature reviewed. In the ITCZ area affecting Colombia, higher IAV were expected in subtropical areas (Brower et al. 2013). Annual wind speeds were measured at IAVs between 2.9 and 8.5 percent from 2001 to 2014.

Annual solar insolation IAVs were measured at 2 to 6.2 percent. This shows the higher variability of wind as compared with solar. In the case of hydro, and likely due to the ENSO, strong interannual variability of up to 43.7 percent was observed, which shows the vulnerability of Colombia's hydropower-dependent generation matrix. When translated into energy, extreme interannual variability values for wind power obviously increase relative to the volatility seen for the wind resource.[26] This is not so extreme for solar, where the energy and resource IAVs remain similar. For hydropower, energy IAV is reduced compared with the IAV for hydro. This is partly explained by the limits on power production: Colombia's hydropower plants have a maximum rated capacity regardless of the volume of river inflows.

Conclusions and future work

Colombia's hydropower-dependent energy mix threatens the country's energy security. This has been made abundantly clear over the past few decades given the impact of El Niño. Colombia's energy security faces additional risks in expected natural gas shortages and changes in rainfall patterns owing to climate change.

The accuracy of reanalysis datasets (including MERRA) is site-dependent. The more complex the terrain, the larger the potential for under- and overestimation. As a result, considerable negative and positive biases are seen in the magnitude of wind and solar resources, especially over the Andes. Surface smoothing and the MERRA observational system, which may have few measurements in or close to the Colombian territory, may contribute to these biases. For validation purposes, we recommend further investigation of MERRA data with onsite meteorological measurements (for example, from the IDEAM) near the selected wind and solar sites.

Colombia has more than 15 GW of installed capacity. About 67 percent corresponds to large hydropower plants (>20 MW) and 28 percent to thermal power plants that mainly rely on natural gas. After the implementation of two hydro projects by 2022, the region of Antioquia will represent approximately 52 percent of the total installed capacity and will be the most important (concentrated) generation node in the country.

Due to uncertainties in the magnitude of wind and solar resources, the energy assessments mentioned in this paper must be addressed carefully and should not be used without further analyses and validation (Ramírez C. 2015). Some of the calculated seasonal patterns for

[26] The relation of wind power to wind speed to the power of 3 is highlighted.

hydroelectric energy production are different from real-generation curves. This issue is evident in other studies and is likely caused by the influence of large reservoirs and market-driven operational strategies (COWI 2015). The patterns in this study, however, represent the real condition of seasonal hydrology in different areas of the country, which impacts hydropower plants with dams and those powered by run-of-the-river.

The locations we analyzed in this case study represent a variety of seasonal resource patterns for wind, solar, and hydro. We concluded that the ITCZ is the main influence on wind and solar seasonal patterns owing to the zone's movement from south to north throughout the year within the country. The ITCZ creates more precipitation and clouds in some areas and higher wind speeds in others. Further research is therefore recommended both to explain seasonal wind and solar resource patterns and to better understand the complex relationship between precipitation and river inflows in the Andes. We also recommend further studies on ITCZ's seasonal movements in Colombia, which could present an advantage for the energy mix.

Nationally, the highest negative mean seasonal *R* coefficients were found at wind and solar sites on the Oriental Plains and at solar sites in the Antioquia region. Regionally, wind sites in the north and east show seasonal complementarity with northern rivers. Wind sites in the south and center show seasonal complementarity with the rivers there. Similarly, north and east solar sites show seasonal complementarity with northern rivers; solar sites in the north-central and the south-central rivers show seasonal complementarity.

The range of interannual *R* coefficient at wind-hydro and solar-hydro sites is diverse. On a national level, the highest complementarities were found at the wind sites over Tolima and the eastern Andes and at solar sites in the southeastern and western Andes. On a regional level, wind sites over the eastern Andes and in the north showed interannual complementarities with the northern rivers. Solar sites in the eastern Andes and rivers in the north/center exhibited interannual complementarity.

Future wind and solar farms located at the selected sites might be able to back up hydropower plants during seasonal and interannual periods of low-flow hydrological periods.

The weather dynamics governing wind, solar, and hydro resources produce upward or downward trends for the same resource in several areas of the country. Interannual complementarity (inverse behaviors compared to the hydropower plants) is observed in the tables with the MERRA based indexes for several of the wind and solar sites. A good example is the year 2002, when wind/solar farms could have served as backup energy plants during low-flow hydrological periods.

The research shows 2.9 to 8.5 percent IAV for the selected wind resources during the timeframe defined in this study. For solar resources, the values were between 2 and 6.2 percent. For hydro resources, much higher IAV were found in some rivers, likely because of El Niño. This shows the vulnerability of an energy mix that is highly dependent on hydropower.

The current regulatory framework for the *reliability charge* does not encourage investment in generation assets based on VRE. This is because of the low firm energy payments assigned to them according to the current framework. As a result, the Colombian energy market has not yet valued the advantages of the complementarity and the diversity of renewable resources. Diversity or complementarity charges should be considered in future regulatory discussions in order to improve the capacity of hydropower plants with reservoirs, while balancing the system in case of high fluctuations. The ongoing energy crisis caused by El Niño might provide a suitable opportunity for these discussions.

Further research is recommended so Colombia is able to promote regulatory market schemes that reward seasonal and interannual complementarity. Multistakeholder research is highly recommended, including government bodies such as the Ministries of Energy and Environment, CREG, IDEAM, and XM, as well as generators, transmission systems operators, financial institutions, and universities.

At the international level, countries with high shares of hydropower in their electricity mix have developed regulatory measures that take into account the complementarity between variable renewable energies. This is the case in Brazil, where solar or wind technologies that participate in the frequent capacity or energy auctions are rewarded if they can demonstrate by statistical methods that their seasonal generation profile complements the generation profile of hydropower.

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