Facilitating the Integration of Renewables in Latin America: The Role of Hydropower Generation and Other Energy Storage Technologies

Article *in* IEEE Power and Energy Magazine · September 2017

DOI: 10.1109/MPE.2017.2708862

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Facilitating the Integration of Renewables in Latin America

The Role of Hydropower Generation and Other Energy Storage Technologies

By Rodrigo Moreno, Rafael Ferreira, Luiz Barroso, Hugh Rudnick, and Eduardo Pereira

IT IS WELL KNOWN THAT STORAGE FACILITIES CAN provide value to various electricity sectors through several services, which we group into five main classes:

1) temporal energy arbitrage (the ability to shift megawatt-hours in time to increase energy market revenues)
2) capacity adequacy (the ability to economically and reliably meet system capacity requirements)
3) ancillary services, notably those related to system balancing (in various time scales), reserves, and frequency control (although voltage and reactive power control are also included)
4) network congestion relief and network investment deferral (including network security and thermal losses)
5) option value (the ability to provide a hedge against the uncertain future).

This categorization is useful for the purposes of this article, although the boundaries among the different classes of services often depend more on the regulatory and commercial frameworks of each jurisdiction than on absolute technical features. For instance, whether a facility is providing secondary frequency control by participating in automatic generation control or simply shifting power among different dispatch periods depends on the temporal resolution defined.

Furthermore, this categorization is based on the value delivered to the electricity system as a whole, regardless of

Digital Object Identifier 10.1109/MPE.2017.2708862
Date of publication: 17 August 2017

1540-7977/17©2017IEEE

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the business model under which it is developed. A storage facility sited behind the meter, for example, can lead to a lower electricity bill for a given retail consumer due to the possibility of managing net consumption patterns under dynamic tariffs or decreasing peak demand payments; however, while doing so, it also provides value to the electricity system via temporal energy arbitrage, contribution to capacity adequacy, and eventual deferral of transmission and distribution network capacity investments. The allocation of the value of storage among market participants, in contrast, does depend on the business model under which the storage facility is developed, as well as on the applicable regulatory framework. A similar rationale applies to storage facilities deployed as standalone resources or "behind the meter" of generation plants, which are of particular interest in this article.

The large reservoirs associated with hydropower plants have historically represented the storage technology in countries like Brazil and Chile, delivering temporal energy arbitrage, capacity adequacy, and ancillary services at low operational and opportunity costs. However, the low incremental costs of providing these services have also historically represented a barrier for the development of other, competing storage technologies. As we discuss later in this article, the situation is now starting to evolve in Brazil and Chile, due to factors ranging from changing patterns of hydro inflows to the increasing participation of renewable generation technologies, such as wind and solar power, with significant short-term variability. This results in opportunities for the development of other energy storage technologies that can not only capture the value of temporal energy arbitrage but also provide capacity adequacy, network congestion relief and investment deferral, and enhanced ancillary services to their value stack. The timing for the deployment of these other storage technologies is affected, however, not only by their intrinsic competitiveness—which, in turn, depends on the evolution of technology costs, as in the case of batteries—but also by the regulatory and commercial frameworks that currently result in both barriers and insufficient economic incentives for new investments.

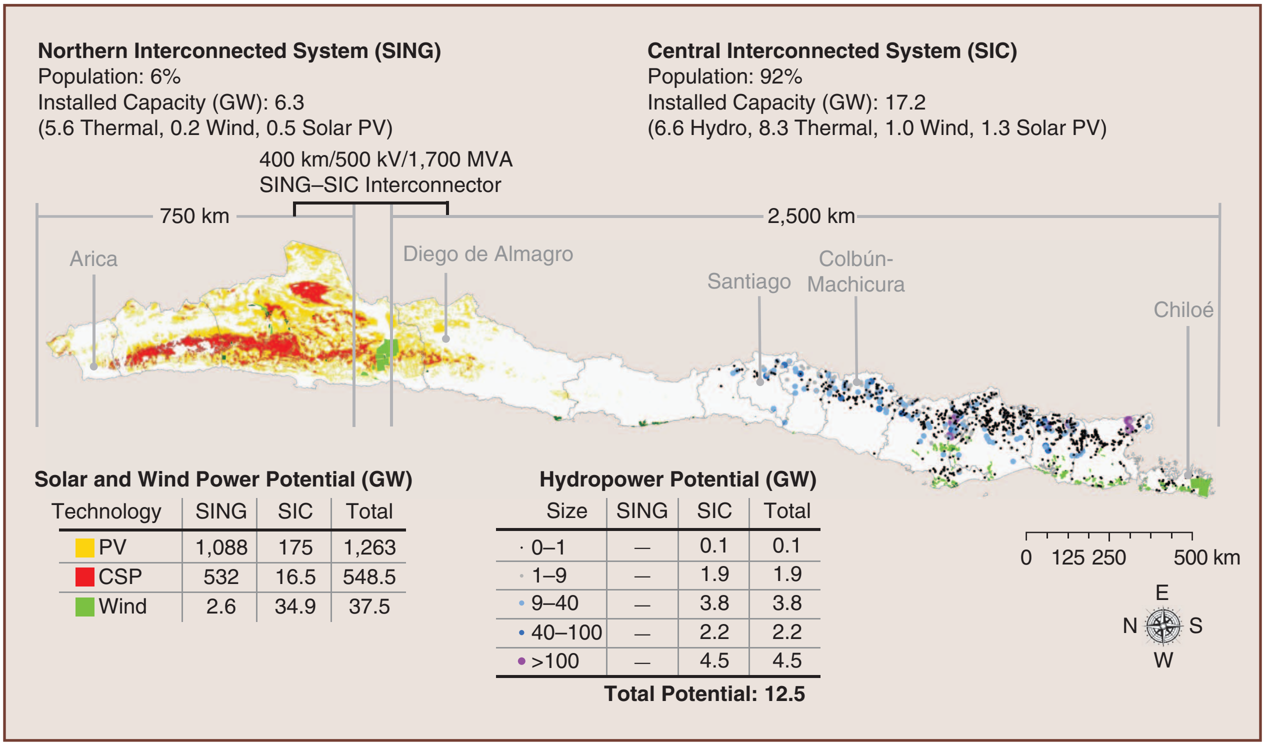
Here, by examining the experiences of Brazil and Chile, we show that hydropower will play a significant role in providing both traditional services (such as energy and capacity) and an array of ancillary and flexibility services needed in the new renewable context. We also demonstrate how further storage technologies and, in particular, battery energy storage plants can complement hydropower generation. Finally, we discuss the regulatory changes needed to foster a truly efficient portfolio of storage technologies in support of renewables integration.

The Case of Chile

Renewable resources in Chile are vast, and so renewable generation technologies present a significant opportunity to grow in the near future. In particular, solar and wind resources present a very large potential of about 1,800 GW and 38 GW, respectively, which can be balanced—in terms of the operational flexibility needed—by more controllable renewables such as hydro resources, which can (among other technologies) be further expanded by approximately 13 GW (see Figure 1). Interestingly, these potentials are much larger than the current 22 GW of total installed capacity in generation infrastructure.

Chile also presents very particular geographical conditions, with a transmission network characterized by long distances between the major load centers and large generating units. Furthermore, the system features a peak demand of 10 GW (which will increase to approximately 20 GW by 2050), with its major load center located in the middle of the country (Santiago) and a mixed portfolio of thermal and hydropower plants—the latter (mainly located in the southern part of the system) accounting for approximately 30% of the total generation installed capacity. Unlike other countries, the significant number of hydropower plants (including partially untapped hydropower potential) could offer important advantages in the future, providing several services for balancing the system in the presence of a high penetration of variable generation from solar and wind resources.

In terms of location, solar resources are sited mainly in the north, and wind resources are distributed mainly in the central south area, creating a challenge in managing intermittency through hydropower plants from the south. Importantly,



Solar and Wind Power Potential (GW)

Technology	SING	SIC	Total
🟨 PV	1,088	175	1,263
🟥 CSP	532	16.5	548.5
🟩 Wind	2.6	34.9	37.5

Hydropower Potential (GW)

Size	SING	SIC	Total
· 0–1	—	0.1	0.1
· 1–9	—	1.9	1.9
• 9–40	—	3.8	3.8
• 40–100	—	2.2	2.2
• >100	—	4.5	4.5

Total Potential: 12.5

figure 1. The Chilean power system and its renewable energy resources. PV: photovoltaics; CSP: concentrated solar power. [Data source: German Federal Enterprise for International Cooperation (GIZ), the Ministerio de Energía, and Centro de Energía, Universidad de Chile.]

There is a broad consensus that hydropower generation can play a key role in balancing the system and hence providing flexibility in the near future.

after the commissioning of the Sector Interconectado del Norte Grande (SING)–Sistema Interconectado Central (SIC) interconnector, the Chilean power system will be particularly long, covering more than 3,200 km geographically from Arica to Chiloé (shown in Figure 1), consequently increasing the risk of system instability. Of increasing importance, therefore, is the allocation of generation reserves across the network to ensure their deliverability (and not cause postcontingency, real-time congestion) and the stability of the system.

Flexibility, however, is a pressing need in managing not only the future power system but also that of the present. Currently, for instance, the amount of wind and solar power curtailment in the SIC is about 400 GWh/year, which represents 5% of the total energy produced by wind and solar power plants (equivalent to decommissioning a solar power plant with approximately 150 MW of installed capacity), which clearly demonstrates the present need for more flexibility in both operation and infrastructure.

There is a broad consensus that hydropower generation can play a key role in balancing the system and hence providing flexibility in the near future. However, there are a number of concerns at the technical level:

- ✔ The Chilean network will be (after the commissioning of the SIC–SING interconnector) particularly long and prone to congestion and stability problems.
- ✔ Existing and new hydropower resources are located in the south of the country; consequently, solar power generation (which is envisioned to be significantly developed in the near future) in the north will require balancing services (see Figure 1).
- ✔ The more limited ability of hydropower plants to deliver primary frequency control services which may be a problem under conditions where there is no contribution from thermal generation and decreased system inertia (i.e., conditions with combined high renewables outputs and low demand levels).

Further concerns include social opposition to hydropower projects; environmental impacts; lack of a clear land-use planning framework; excessively long design, construction, and delivery time scales; and potentially constrained operation due to, for example, irrigation (and other uses of water reservoirs) and hydro-peaking limits.

All these concerns create opportunities to cooptimize the development and use of hydropower plants with those from further storage technologies that, although more costly, can provide similar services (including flexibility) without posing some of these techno-environmental constraints. In this vein, battery storage systems are particularly interesting for several reasons:

- ✔ They can be located across the network in a distributed fashion (and across all voltage levels), minimizing renewables curtailment, facilitating congestion management, and providing an array of frequency control services (including very fast primary frequency response in contrast to hydropower plants).
- ✔ They do not present significant constraints in investment and operational decisions, as hydropower plants do.
- ✔ Investments can be rapidly deployed and delivered.

Thus, there is a significant opportunity to optimize the portfolio of storage technologies—in particular, between hydropower and battery storage plants—to deal cost-effectively and reliably with intermittent and uncertain renewable generation, network-related/stability problems and associated constraints on investment and operation related to societal and environmental concerns, and the multipurpose nature of hydropower reservoirs. Moreover, the long-term uncertainties inherent in investment decisions may be more efficiently managed through technologies that can be deployed rapidly and, therefore, provide more complete information about the actual realization of future conditions. Rapid deployment is an attractive feature of battery storage plants, with clear benefits for solving problems related to network congestion and renewables curtailments that must be addressed promptly.

Adapting the Present Hydropower Generation Infrastructure

In a country like Chile, increasing the installed capacity of hydropower generation will clearly contribute both to more low-carbon energy production and also to increased flexibility from hydropower resources, which facilitates the integration of intermittent renewable generation. As mentioned previously, however, hydropower plants present a number of techno-environmental constraints that impede their efficient development and operation.

One strategy to mitigate some of these constraints is to build run-of-the-river (rather than reservoir-based) power plants because they are more acceptable from an environmental point of view and can be built on a smaller scale. Interestingly, run-of-the-river power plants can be designed with a small reservoir capacity to still provide some intrahour and intraday balancing services needed for renewable generation such as wind and solar power. Although reservoir-based hydropower plants can provide significant

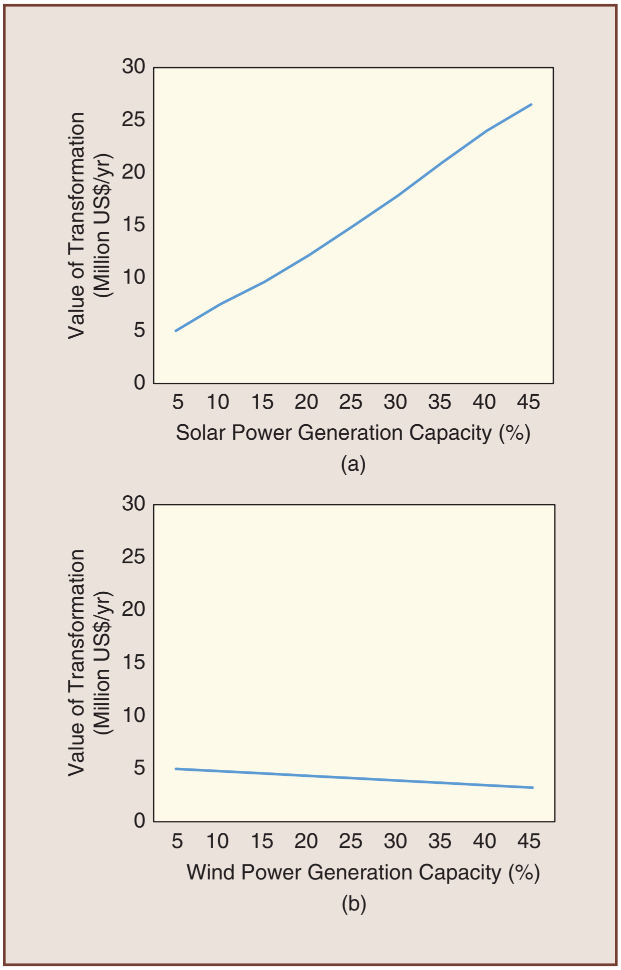


figure 2. The value (i.e., additional gross revenue per year) of a transformation from series hydropower generation to a pumped storage plant, as a function of the (a) solar and (b) wind generation capacity as a percentage of total generation installed capacity in the national power system.

flexibility to system operation in different time scales, run-of-the-river hydropower plants can still provide a valuable part of it. Furthermore, our analysis demonstrates that it is possible to capitalize on increasing the reservoir capacity of currently installed run-of-the-river power plants. In Chile, for example, doing so can reduce the nonnetwork curtailment of renewable generation (i.e., the curtailment caused by constraints other than network congestion) by 95%, if each run-of-the-river hydropower plant is equipped with a reservoir having an energy capacity equal to 3 h (i.e., the capacity to store enough energy to produce for 3 h at maximum power output without inflows).

Likewise, currently installed reservoir hydropower plants can be transformed into pumped storage plants that enhance both flexibility services to the electricity market (e.g., using pump-mode operation to withdraw energy from the market when an excess of renewable power outputs drives prices down) and coordination of multipurpose reservoir applications (e.g., more efficiently coordinating the electricity and agriculture sectors through decoupling water streams from generation and those associated with irrigation).

In this context, we studied the case of installing a 100-MW pump system between the Colbun and Machicura reservoirs (see the location in Figure 1), which are currently operated as conventional, reservoir hydropower plants in series (with Colbun located upstream of Machicura), and thus allow more flexibility in meeting irrigation requirements and maximizing revenues due to the provision of more efficient intraday balancing services (i.e., buying energy at low-price hours and selling energy at high-price hours in the spot market). Interestingly, we found that the higher the penetration of solar power generation, the higher the benefits of the transformation (which is not the case for increased wind power generation, as shown in Figure 2). This is so because an increase in solar power generation capacity leads to a drop in the energy price mainly when a storage plant charges/buys and not when it discharges/sells. In the case of an increase in wind power generation capacity in Chile, the consequent drop in energy prices is more distributed across the day. We also found that the irrigation requirements represent approximately 30% of the value of the transformation (i.e., without the irrigation requirements, the value of the transformation will be 30% lower).

Sectors Coordination to Facilitate Delivery of Flexibility from Hydropower Generation

In operational time scales, hydro reservoirs provide services to various sectors such as electricity, irrigation, recreation, and flood control: currently of concern is the cost-efficiency of the present coordination among these multiple applications. For instance, the regulatory framework that coordinates irrigation and electricity production has not changed since the 1960s and so does not reflect the real value of water in today's economy, especially in the light of renewables and the new services flexibility needed from hydropower plants. Similarly, new environmental constraints that protect local ecosystems from hydro-peaking consequences limit the system's ability to integrate renewable generation, an issue that could lead to an increase in renewable generation curtailment. Although environmental policies are necessary, interactions between such policies and those associated with renewables integration have to be carefully analyzed and finely tuned because, due to the coupling between hydro-peaking and flexibility for renewables, there is a clear conflict between mitigating local and global environmental impacts (see Figure 3).

In planning time scales, there is a growing need for a clearer regulatory framework related to land-use planning to enable projects that are both attractive for the economy (and, in particular, for the electricity sector) and also cause limited, acceptable impacts on the local environment. Here, a major concern arises from the new transmission lines needed to connect the new plants to the main transmission system because they could result in more severe impacts than the generation project itself.

Installing Battery Storage Technologies to Boost Delivery of Flexibility in Hydrothermal Power Systems

Battery storage plants can complement hydropower generation capacity because they are not subject to the same techno-environmental development and operational constraints (as hydropower generation) and can deliver further services that are also needed in today's power system. For instance, battery storage plants can be located (through a simpler environmental permit process) at basically any substation in the network that supports provision of local services associated with congestion management, voltage control, minimization of renewables curtailment, and so forth. Like hydropower plants, battery storage plants can provide system balancing services.

However, battery storage plants are capable of improved and faster frequency response, which can be critical in situations marked by lack of inertia (i.e., high renewables output) in the absence of thermal generating units (which can respond more rapidly to changes in system frequency). Figure 4 illustrates the benefits of installing battery storage plants in a hydrothermal system like the Chilean one in terms of frequency response, where cases A and B represent the same volume of scheduled reserves (i.e., 400 MW) but distributed among different technologies. In fact, in case B, part of the reserve held by hydropower plants in case A has been allocated to battery storage plants; as shown in Figure 4, this clearly improves the overall frequency response of the system.

The location of balancing services will be critical in the future power system. This is particularly problematic in a country like Chile, where hydropower resources (traditionally used to balance the system) are located in the south and the need for balancing will be mainly located in the north due to the development of solar power generation. Nevertheless, this will increase the value of a cooptimized portfolio of flexible storage technologies.

This locational issue can be combined with another fundamental difference between hydropower and battery storage

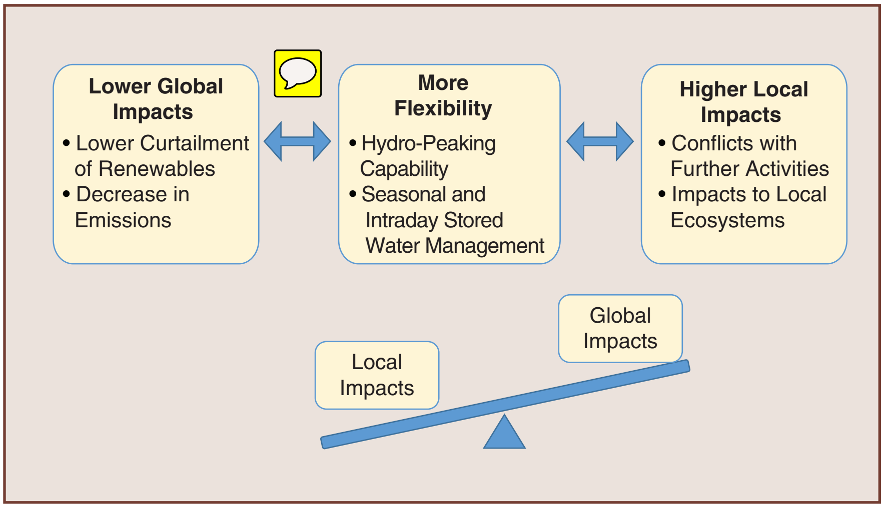
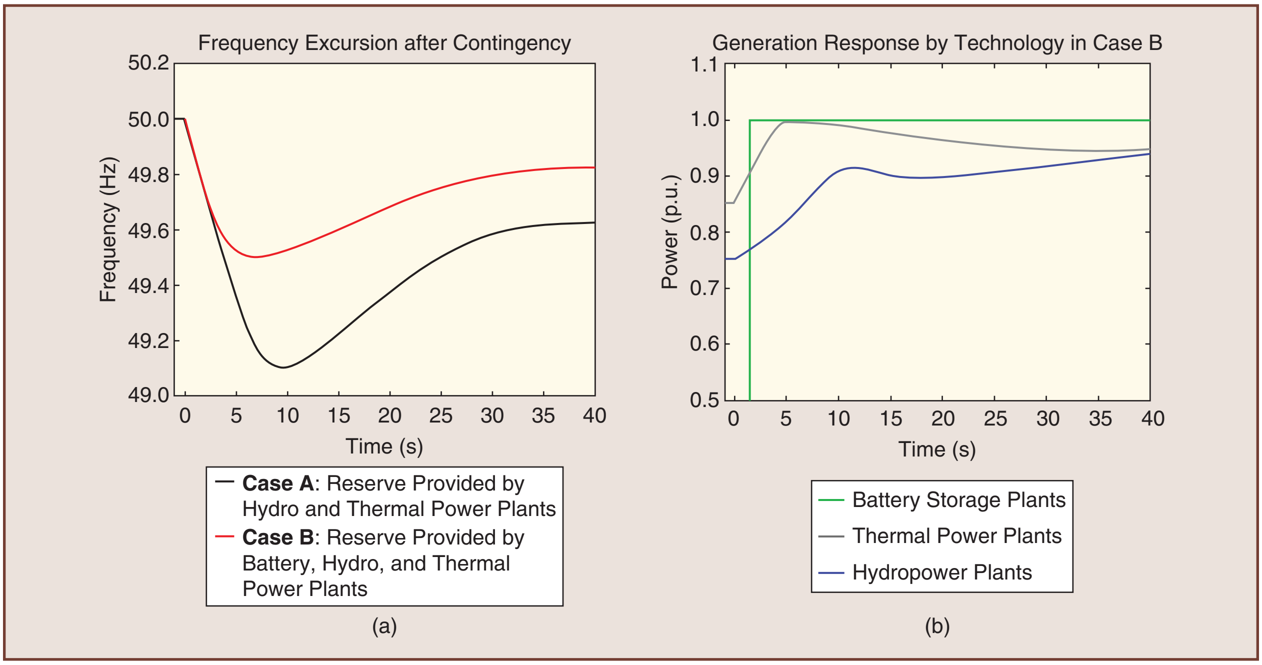


figure 3. The global and local environmental impacts dilemma associated with hydropower plant operation.



(a)

(b)

figure 4. The (a) frequency excursion and (b) generation response after a generation outage occurs in the Chilean power system.

plants: the lag between the investment decision and the commissioning time. Lag time provides opportunities for investment coordination, especially in the face of future uncertainty and transmission congestion. In this context, an optimal portfolio of storage plants will balance present and future investment decisions in such a way that strategic (or, using stochastic programming terminology, "here-and-now") investments in current traditional infrastructure (such as hydropower plants and transmission lines) are complemented later on through "wait-and-see" investments in battery storage plants that can be rapidly delivered, thus efficiently adapting the overall investment plan to the unfolding future.

Additionally, battery storage plants can be easily transported to a different location depending on system flexibility needs, increasing the cost-efficiency of the previously discussed adaptive approach. In Chile, for instance, there is currently a significant amount of renewables curtailment in the area of Diego de Almagro (see the location in Figure 1) due to delays in the delivery of the main network infrastructure; these can be mitigated by the installation of battery storage plants (which, after the main network infrastructure is finally delivered, may be moved to a different location to maximize their value). We have estimated that a 20-MW/80-MWh battery in that area will reduce curtailments by about 2%, increasing the yearly gross revenue of renewable generation by US$1 million (from US$13 to 14 million). Moreover, the battery can provide further energy and reserve services, with associated yearly gross revenues of US$1 million and US$0.5 million, respectively (the former refers to the revenue for buying energy during low-cost hours and selling when energy prices are higher; the latter refers to the revenue for allowing a conventional generator to increase its power outputs because it does not need to hold reserve capacity).

This situation is illustrated in Figure 5, where we have estimated that the overall value of this storage plant is equal to US$2.5 million. It is important to mention that under current practice in Chile—where battery plants are installed for the provision of reserve only (ignoring further applications of storage plants)—the expected value of the same storage asset would be approximately US$1.1 million per year (in contrast to the US$2.5 million calculated above), demonstrating that locating a battery to cooptimize its different services can significantly increase its revenue.

The Chilean power system currently includes 52 MW of installed capacity in battery storage plants, deployed entirely by market participants to provide reserve services (an idea pioneered by the AES Corporation)—even though the Chilean power sector does not feature a reserve market. The main idea is that new battery plants can replace the idle reserve capacity booked in conventional generators, which were forced to provide the service without appropriate remuneration. Thus, with a battery storage plant in place, a conventional generator can maximize its output while the reserve

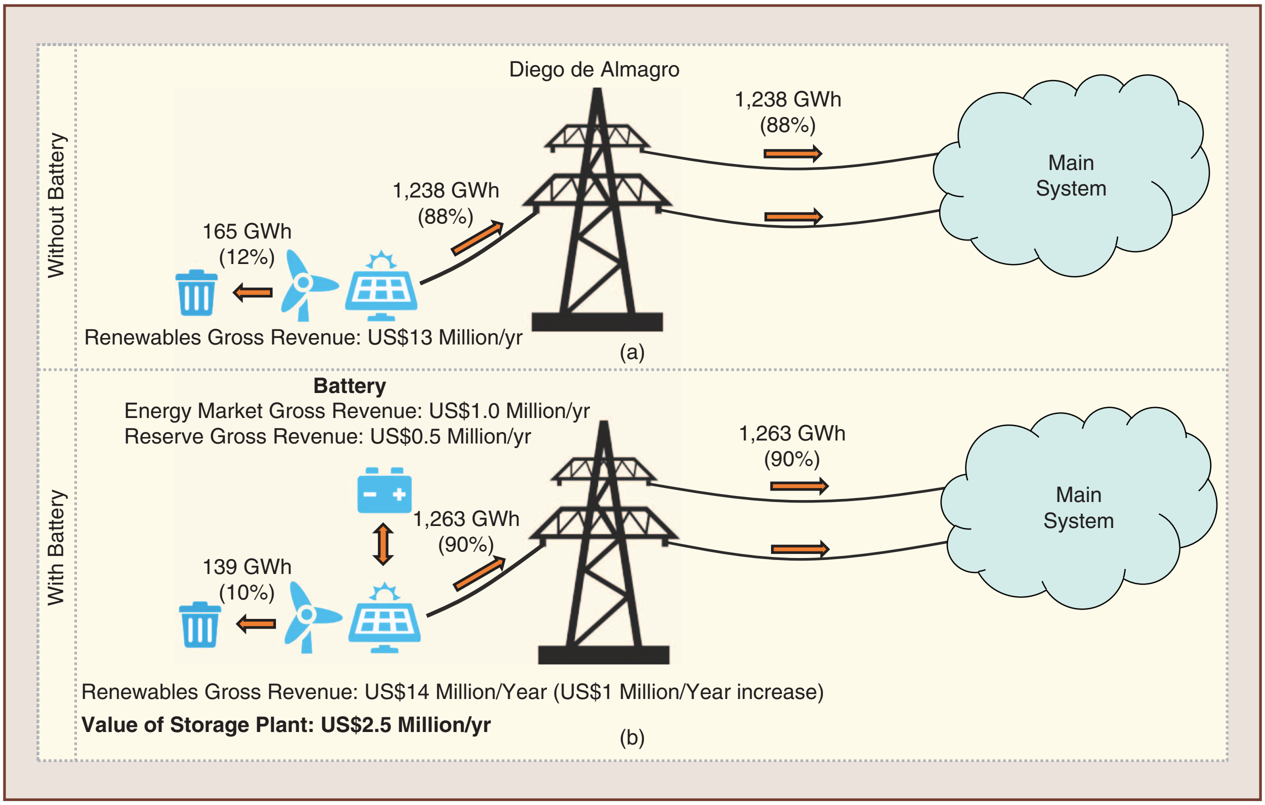


figure 5. The situation (a) without an energy storage plant and (b) with an energy storage plant that provides multiple services.

> In Chile, the absence of ancillary services markets has led to a situation in which competition is based only on energy prices.

provision is ensured by the idle capacity in its battery storage plant (the conventional generator and battery plant are located at the same substation and share the same owner).

Although this can clearly add value to market participants (and the overall system), it is important to point out that the absence of an appropriate reserve market significantly limits the deployment of battery plants (below the necessary levels) because, apart from the obvious lack of service remuneration, only the beneficiaries of storage services (rather than any market participant, including new entrants) will be willing to invest in battery plants. In fact, new battery plants allow generators to optimize their own asset portfolio without having the possibility of selling reserve services.

In Chile, the absence of ancillary services markets has led to a situation in which competition is based only on energy prices, in particular those bid in auctions to obtain regulated, long-term contracts meant to supply demand from distribution companies. This is particularly problematic for two main reasons: 1) the best bid prices to supply energy at low costs come from inflexible—and even uncontrollable—generation (e.g., solar power generation); 2) in the absence of appropriate remuneration for reserves and flexibility services, bid energy prices from hydropower plants (and, in particular, pumped storage hydropower) become higher so as to appropriately cover investment and operating costs (note that if the market were appropriately designed, costs should be recovered by an array of revenue streams, including those from reserves services). This situation clearly increases the need for flexibility, as per the first reason just outlined, and at the same time impedes the investments needed to provide the kind of flexibility that facilitates the optimal operation and development of the future power system, as per the second reason.

The Case of Brazil

Large Reservoirs of Hydropower Plants as the Historically Predominant Storage Technology

The significant participation of hydropower in the Brazilian generation mix is explained not only by the country's natural endowments (with several river basins providing complementary hydrological behavior) but also by macroeconomic factors. Oil price shocks in the 1970s strengthened both the country's eagerness to develop local hydro generation and the availability of capital, because oil-rich countries directed their funds to private banks, which perceived sovereign debt—including that of state-owned electricity utilities developing hydro projects—as high-quality investments. These investments resulted in the consolidation of business models and technical competence and allowed hydropower development to continue into the 1980s (albeit at a slower pace due to economic crises and after reforms of the electric power industry starting in the 1990s).

Several hydropower plants built in Brazil in those decades were granted large water reservoirs, not only to cope with the variability in water inflows but also to allow for other applications such as flood control and regular supply of water for irrigation and human consumption. Another implication of hydrological variability concerns the optimal engineering design of hydropower plants, the installed generation capacity of which is, in general, significantly higher than that required to turbine average inflows; this fact allowed the country to take advantage of particularly wet periods and provided the ability to easily modulate load supply. Figure 6 illustrates the variability of yearly water inflows in terms of the aggregated energy inflows to hydropower plants in the Brazilian grid's

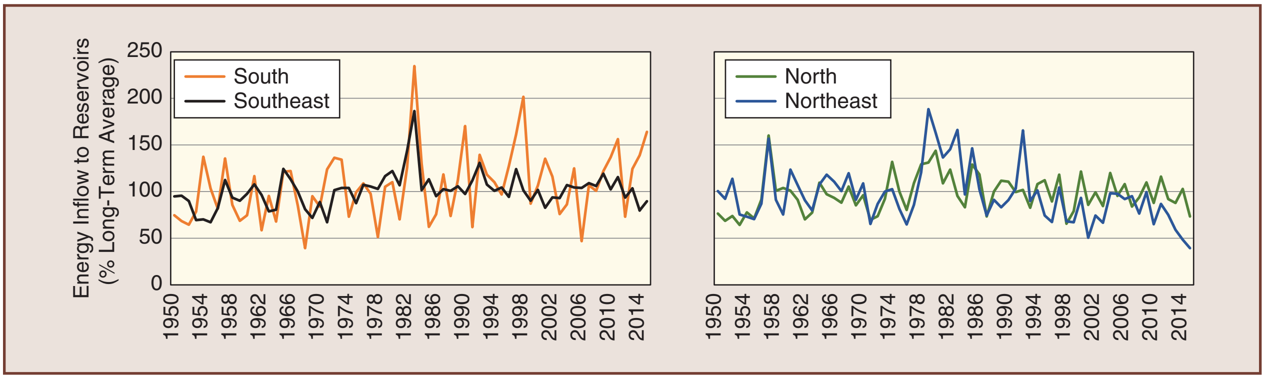


figure 6. The energy inflow to Brazilian reservoirs per subsystem: 1950–2015. [Data source: Operador Nacional do Sistema Elétrico (ONS).]

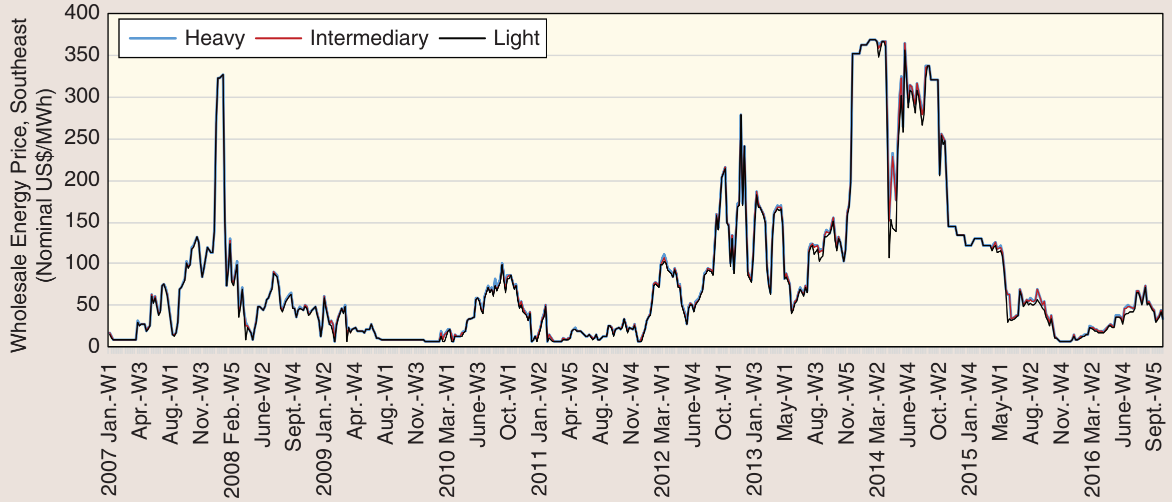


figure 7. The weekly wholesale energy prices for three load blocks: southeast, 2007–2016. [Data source: Câmara de Comercialização de Energia Elétrica (CCEE).]

four subsystems between 1950 and 2015; the figure clearly demonstrates the occurrence of significantly wet periods.

Such large water storage capacity and the surplus of generation capacity greatly influenced the operating conditions and regulation of the Brazilian power system. A unique wholesale energy pricing scheme (still in use today) was adopted, whereby prices are determined weekly and for three sets of noncontiguous hours (termed *load blocks*), representing periods of heavy, intermediary, and light loading in the power system. For instance, during any given week, the spot price calculated ex ante for the heavy loading block of hours applies for all hours between 6:00 and 9:00 p.m. on weekdays and Saturday, and the demand forecast for these hours is aggregated for purposes of the dispatch simulation employed in pricing. While this results in prices not reflecting variations among operating conditions within load blocks, the storage capability and surplus generation capacity available in Brazil at the time this pricing strategy was introduced were seen as reasonable justifications. In fact, prices did not even vary significantly across these three blocks of hours. This is illustrated in Figure 7, which shows the weekly spot prices applicable to the southeastern price zone (one of the four pricing zones in Brazil) for each of the previously mentioned load blocks.

The significant water storage capacity in Brazil also led to prices being less volatile in the short term. Price volatility manifested much more in the medium term than in the short term, due to seasonal and supraseasonal hydrologic variability, as indicated in Figure 7.

The fact that the Brazilian electricity system was much more subject to energy constraints due to hydrologic variability than to short-term capacity constraints also affected the basic mechanism for ensuring the country's resource adequacy. In fact, the reliability product acquired via long-term contracts in Brazil refers to "firm energy" rather than "firm capacity."

All of this demonstrates that hydropower plants with large reservoirs have been able to provide the services of temporal energy arbitrage and capacity at low costs, which deeply influenced the regulatory and commercial framework employed in Brazil. The rationale for relying on these assets for the provision of ancillary services—notably, primary and secondary reserves and frequency control—also merits discussion.

Hydropower plants are indeed flexible assets since their power outputs can be adjusted quickly and at very low incremental costs. Moreover, the water consumption required to keep the machinery spinning is relatively low. The opportunity costs associated with mobilizing generation capacity to provide reserves is also low for hydropower plants with large reservoirs because 1) reservoirs allow storing the water not used for energy production and 2) in a context where energy prices have low short-term variability, the energy not generated due to mobilizing capacity in a given instant can be produced at a later point in the near future, when the value of a megawatt-hour for the system is expected to be nearly equal. Moreover, surplus capacity due to the previously discussed optimal engineering design is often available, reducing the expectation of water spillage due to such operation. Several hydro plants with large reservoirs in all regions of the country enabled the coordinated provision of reserves and frequency control at low costs.

These features influenced the regulatory framework applicable to the selection and remuneration of assets providing secondary frequency control and associated reserves in Brazil. (Currently, primary frequency control is, for the most part, provided by generators as a mandatory grid connection requirement, except for wind and solar plants.) In short, the assets are selected by the system operator on an ad hoc basis under a command-and-control approach, with long-term contracts signed for the provision of these ancillary services. Also, remuneration consists solely of reimbursing the costs to install, operate, and maintain telecommunication and control systems to provide these services, without payments for incremental or opportunity costs. Due to the cost dynamics described earlier, all assets currently holding contracts for the provision of secondary frequency control and associated reserves are hydropower generators, most having large reservoirs. The monetary value of the associated reimbursements has been nearly negligible—for instance, in 2016 the Regulated Revenues for the Provision of Secondary Frequency Control were equal to BRL$44,200 (less than US$15,000 at that year's exchange rates) per year and per power plant, regardless of its installed power.

Changing the Technology Mix and Value of Energy Storage

Brazil is experiencing pressures toward changes in its electricity generation portfolio, which may result in development opportunities for storage technologies other than the water reservoirs associated with traditional hydropower plants. On the one hand, social/environmental constraints limit the addition of large hydropower plants capacity in the country and have fundamentally changed the profile of plants built in recent years. The decreasing share of hydropower plants in the expansion of the system is illustrated in Figure 8. Most of the economic potential of large hydro plants in the regions with the highest concentration of demand has been exhausted, limiting the exploration of new hydropower potential in the Amazon region or its vicinity. Recently built large hydropower plants have little reservoir capacity and significant seasonal inflow variability—as is the case with the Belo Monte hydropower plant, the total installed power of which will be approximately 11 GW. Although Belo Monte and other recently built hydropower plants have some reservoir capacity (allowing intradaily and, in some cases, intraweekly temporal arbitrage), the absence of large reservoirs affects their ability to provide all services mentioned earlier as efficiently as those power plants that have historically done so in Brazil.

On the other hand, and perhaps more importantly, the participation of renewable generation resources with significant variability in the short term has increased in recent years. Figure 9 shows the generation capacity contracted via long-term auctions in Brazil since 2007 and the average contracting prices for wind and solar photovoltaic power plants. This suggests that the participation of wind power in the Brazilian electricity matrix will continue to increase above the share shown in Figure 8, as many projects contracted via auctions held after 2013 have not yet begun operations.

As the most significant parcel of the already commissioned wind power plants is concentrated in the northeast of Brazil, the effects of the increasing participation of these renewable generation technologies on the value of the services discussed earlier—notably, temporal energy arbitrage and capacity adequacy—are already being experienced in this subsystem. The current situation in the northeastern subsystem is as follows.

The hydrological behavior of the São Francisco River basin has recently been the object of attention in Brazil. Most of the hydropower plants in the northeast are located in this river basin, which accounts for over 90% of the water storage capacity of the northeast. As indicated in Figure 6, water inflows in the northeast have been below the historical average in recent years, which has contributed to a significant depletion of reservoir levels in this region. In fact, according to reports issued by the Brazilian Independent System Operator, Operador Nacional do Sistema Elétrico, aggregated reservoir levels of the power plants in the São Francisco River basin reached levels close to 5% of the storable energy capacity at the beginning of 2016, and then increased to levels of approximately 17% by the end of that year.

Low reservoir levels impose hurdles for the exclusive reliance on the region's hydropower plants to provide the temporal arbitrage services necessary to cope with the variability of wind power output and cover the capacity needs of the system in periods of low wind power production. Figure 10 illustrates the variability of aggregated wind power production for the two states of the northeast with the largest installed capacity of this technology.

Considering the limits on the flexible operation of local hydropower plants imposed by the depleted reservoir levels, thermal plants in the region have been operating in a cycling regime, and imports from other regions have had a key role in the strategy to counteract the short-term variability of wind generation in the northeast. The operation of thermal power plants with frequent cycling has not been a common feature in Brazil until recently. In recognition of this fact, the Brazilian regulator recently held Public Consultation #014/2016 to gather contributions from various stakeholders for the elaboration of regulatory mechanisms to cope with the costs imposed by this operation modality. On the other hand, the use of transmission interconnections for imports has

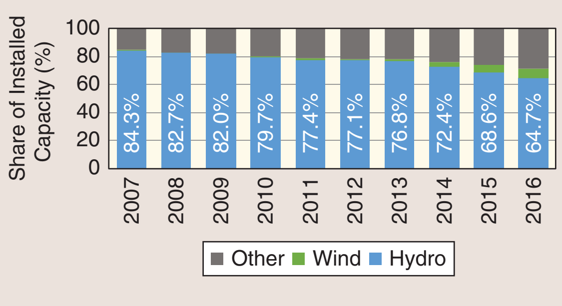


figure 8. The evolution of installed generation capacity in Brazil's National Interconnected System, 2007–2016. [Data source: ONS, Agência Nacional de Energia Elétrica (ANEEL).]

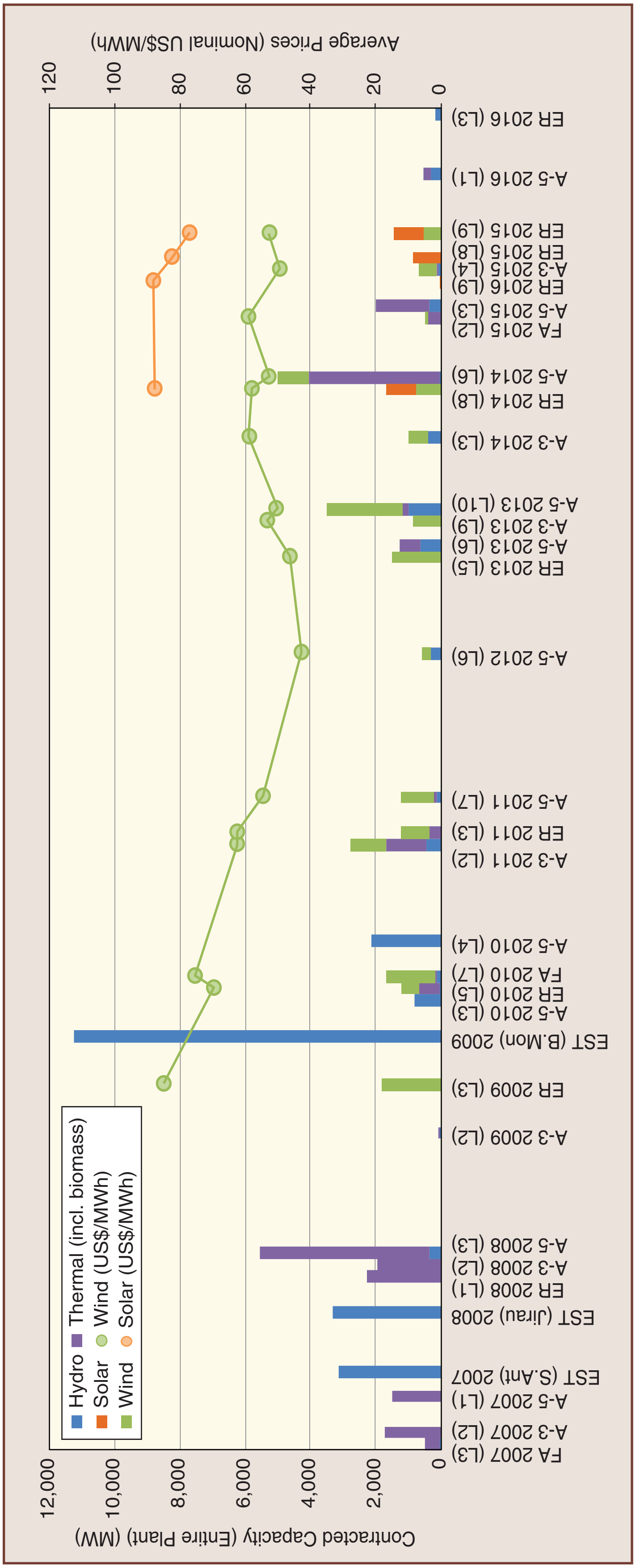


figure 9. The contracted generation capacity in long-term auctions held in Brazil since 2007. The approximately 11 GW of hydropower capacity additions in auction EST 2009 correspond to the Belo Monte hydropower plant. Data source: ANEEL.) FA: auctions for renewables; A-X: regular energy auctions, with contracting X years before delivery date; EST: large hydro auctions; ER: auctions of reserve energy (renewables).

contributed to congestion among pricing zones, also imposing costs on the systems.

These phenomena clearly illustrate the increasing demand for assets or solutions capable of providing temporal arbitrage and capacity adequacy services under high participation of renewable generation sources with significant short-term variability in Brazil. To date, clear evidence of this is limited to the northeastern region and, to a certain extent, associated with changes in the hydrological behavior of the main river basin in the region; but new wind and solar capacity additions in the country may lead to similar behavior being verified in other subsystems of the Brazilian grid in the future.

It is reasonable to assume an increasing demand for assets capable of providing temporal arbitrage and capacity adequacy services to be accompanied by increasing demand for secondary frequency control and associated reserves. Hydropower plants with large reservoirs can provide all these services at low incremental and opportunity costs, but they represent a decreasing share of the capacity mix at a time of rising participation of renewables with large short-term variability.

Opportunities for storage technologies other than the water reservoirs of traditional hydropower plants may increase in Brazil due to the increasing demand for assets able to provide temporal arbitrage, capacity adequacy, and, in particular, ancillary services. Obviously, other classes of assets, such as flexible thermal power plants and demand response, will compete with storage technologies for some of these market niches, with the optimal systemic solution depending on the competitiveness of the assets in providing these services—as well as congestion management and grid investment deferral (not discussed in this work, but equally important in Brazil)—as a bundle.

The Need for an Evolving Regulation

Relevant changes in the Brazilian regulatory and commercial framework are required if market mechanisms are expected to be the main drivers for the rollout of the optimal solutions mentioned in the preceding sections. We previously identified several features of the Brazilian wholesale market that prevent the values of (short-term)

Large water storage capacity and the surplus of generation capacity greatly influenced the operating conditions and regulation of the Brazilian power system.

temporal arbitrage, capacity adequacy, and ancillary services from being transparent to investors:

- ✔ weekly pricing intervals with the grouping of noncontiguous hours into blocks
- ✔ the absence of a reliability product based on the capacity contributions of assets to resource adequacy, although firm energy contributions are valued
- ✔ a command-and-control approach for the selection of assets providing secondary frequency control and associated reserves, along with remuneration mechanisms based solely on reimbursement of installation, operation, and maintenance costs for supervision and control equipment, taking historically low incremental costs for these services provided by hydropower plants with large reservoirs as benchmarks.

In fact, these features result in scarce public information to support the decision making of investors interested in evaluating opportunities for providing these services by other technologies. The modernization of these mechanisms, to reflect a future reality where hydropower plants with large reservoirs may not be the sole providers of these services, can reveal opportunities for other solutions, including storage technologies other than the accumulation water reservoirs associated with traditional hydropower plants.

A similar discussion applies to the retail segment, particularly tariffing mechanisms for consumers connected to low-voltage distribution systems. In practice, these consumers are currently subject to monomial tariff modalities, with all consumption being valued by a constant BRL$/kWh figure. There are regulatory commands to introduce an opt-in time-of-use tariff modality in 2018. This modality was original conceived in 2012, but its practical rollout has not yet materialized. Retail consumers connected to distribution networks at medium and high voltages already experience stronger incentives to modulate their consumption and decrease demand charges and even to jointly manage consumption and behind-the-meter generation patterns under the applicable net metering regulation.

Both in the wholesale and the retail segments, improvements in the current regulatory framework are needed to ensure that the systemic value of services delivered by storage facilities translates into economic incentives captured by market agents, leading to feasible business models and thus to investments. Considering the current technological profile of the Brazilian system, including the still large participation of hydropower plants with large reservoirs in the country, it is likely that these improvements would not immediately result in the feasibility of massive investments in other storage technologies in all regions of the country. Yet, even if investments are currently limited to a few regions and applications, paving the way for a future rollout of other storage technologies by adjusting regulatory instruments can be a sensible strategy considering the envisaged decrease in technology costs, especially for batteries.

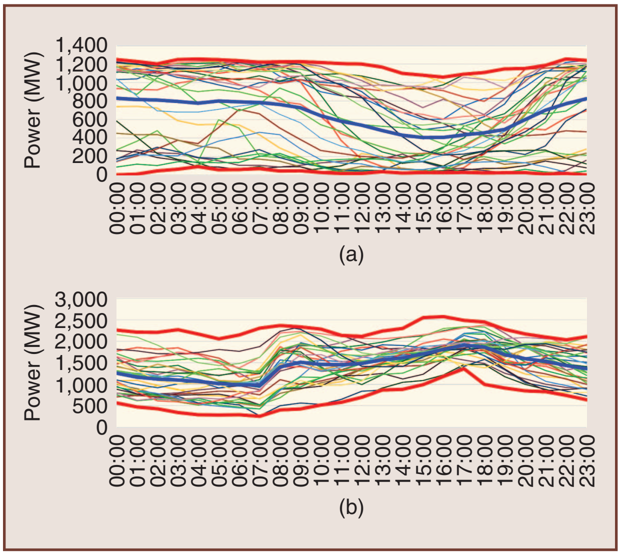


figure 10. The average aggregated hourly wind power output in states of (a) Bahia and (b) Rio Grande do Norte for all days in December 2016. The blue curve represents the average in the month, while the red curves represent the highest and lowest value within the month. Other colored curves represent output for each day. (Data source: ONS.)

The Way Forward: Energy Storage in Latin America

Hydropower generation has been the traditional source of flexibility in hydrothermal power systems and will be key for permitting efficient deployment of renewable generation in countries like Brazil and Chile. Also, there are interesting opportunities to cooptimize the development and use of hydropower plants with those from further storage technologies that, although currently more costly, can provide similar services (including flexibility) without presenting some of the techno-environmental constraints related to traditional hydropower generation. Furthermore, other storage technologies are indeed better placed to provide services such as very fast (frequency) response for stability purposes, congestion management, peak shaving at a local level, low-voltage network management, and so forth, which

> Large water storage capacity and the surplus of generation capacity greatly influenced the operating conditions and regulation of the Brazilian power system.

will be increasingly important with the higher penetration of renewables.

Unlocking the delivery of an optimal portfolio of storage technologies, however, will require significant changes in the future regulatory and incentive frameworks. Currently, hydropower plants and further storage technologies have been undervalued in the light of renewables and the need for advanced flexibility services. For example, in countries like Chile, the absence of an appropriate environmental and land-use planning framework, among other reasons, has impeded the development of new hydropower plants (although they can clearly play a crucial role in meeting the target for renewables and in the provision of flexibility). This is exacerbated by the absence of a proper electricity market design. In Brazil and Chile, for instance, there are no markets for providing generation reserves services. Moreover, energy prices in Brazil are averaged across several hours, which clearly reduces incentives to provide intraday balancing services. It is important to mention that policy makers and regulatory authorities (at least in Brazil and Chile) are aware of these problems and have already started fundamental reviews of various matters, including market design (in particular, remuneration for ancillary services), transmission expansion planning (including forward long-term planning and innovative smart grid technologies and control), and land-use planning for both hydropower and transmission infrastructure. Interestingly, the vast majority of the review processes in Chile have been undertaken in a participative manner, with a wide-ranging set of representatives from the electricity sectors (generation, networks, and consumers), authorities (policy makers and regulators), and further sectors relevant to energy (transport, environment, and so forth).

In this context, there may be room for both mandated and market-based decisions to capitalize opportunities in various storage technologies. On the one hand, energy and advanced capacity and ancillary services markets with both short-term price signals and long-term contracts could support efficient, market-based investment decisions from market participants. On the other hand, a planning authority (regulator or system operator) could proactively identify and mandate (or, at least, ease) new investments in storage technologies (similar to what happens with transmission plans) to unlock the deployment of storage technologies that cannot be encouraged through marginal price signals. This combined mandated and market-based approach can also eliminate the need to create a large set of ancillary services (which may present reduced participation and competition levels), limiting the escalation of transaction costs.

Acknowledgments

Dr. Moreno gratefully acknowledges discussions with Juan Carlos Araneda, Marcelo Olivares, and Jonathan Monsalve and the Ameba. Cloud team for facilitating the software used for the graphics in this article. The financial support of Conicyt-Chile is also acknowledged (through grants Fondecyt 1141082, Fondecyt/Iniciacion/11130612, Newton-Picarte/MR/N026721/1, Fondef/ID15I10592, SERC Fondap/15110019, and the Complex Engineering Systems Institute (CONICYT–PIA–FB0816, ICM P-05-004-F). The ideas and concepts set out in this article are those of the authors and do not necessarily reflect the official opinion of the Energy Research Company (EPE), Brazil.

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