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Analysis of the impact of increased Non-Conventional Renewable Energy generation on Latin American Electric Power Systems

Tools and Methodologies for assessing future Operation, Planning and Expansion

Carlos Batlle

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Discussion paper

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January 2014

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0 EXECUTIVE SUMMARY

The new renewable sources, such as sun or wind, show a specific set of characteristics such as geographical and temporal variability that challenge their integration into traditional energy systems to supply electricity. These aspects have a great impact in the operation of electricity systems that go from the need for generation reserve in the system in order to guarantee operational reliability to possible changes in network and electricity infrastructure planning.

In electrical power systems with a large component of hydro electrical output, such as many Latin American systems, issues associated with the integration of intermittent resources are minor, especially if the hydro plants have a significant storage capacity. As a result of this, the integration of the new renewable sources has not had a major impact in terms of operation up to date. Additionally, as presented in this paper some renewable sources and the hydro resource (wind-hydro, biomass-hydro) complement to each other seasonally, in some regions significantly. Complementarity reduces the impact of the intermittence of resources, increasing power supply reliability, optimizing the utilization of hydropower resources.

However, increasing difficulties associated with the construction of new hydro plants and, especially, the construction of new hydro plants with reduced (or null) storage capacity associated with thermal generation penetration and the considerable growth of the new renewable sources, will increase the operation complexity in the region. This will call for changes in planning and operation of the electric system.

Certain technical resources may help operators successfully deal with intermittent generation. An example of these resources are pumped hydro storage systems, improved plant flexibility, improvements in wind and solar resource forecasts, and, in a relatively near future, energy storage by batteries and electric vehicles. Most of these aspects are part today of a broader concept called *smart grids,* which constitute the first link in the optimization chain of the electric system.

On the other hand, the need for additional flexible resources in power systems with great penetration of intermittent generation can be reduced through an accurate combination of: (i) adequate transmission capacity; (ii) larger balancing areas; and (iii) more frequent scheduling (within and between areas). Consequently, the need for ancillary services would be less, and the costs of running the power system would be lower with the added social, economic and environmental benefits of non-conventional renewable energies.

1 BACKGROUND AND OBJECTIVES

As widely known, the new renewable energy sources (wind, biomass, and solar, among others), also known as non-conventional renewable energy sources (NCREs), are playing an increasingly prominent role in several countries which mainly seek to diminish greenhouse gas emissions, while increasing supply reliability by diversifying the energy mix and reducing their reliance on third parties for satisfying their energy needs.

Although the experience in Latin America has its own distinct features which differentiate it from other experiences like that of the European Union or some (few) states of the United States, the integration process for this type of resources has already started, though at a different pace in each country. However, considering the great potential of some of these alternative sources in some countries in the region, together with the expected soar in electricity consumption, these energy sources can be reasonably expected to play an even more critical role in the future.

Power Systems New Management Needs

Given their specific nature, especially their variable output (seasonal, non controllable and non dispatchable), these sources have originated a change of paradigm as regards the way of operating and planning electric power systems worldwide.

- To begin with, the analysis of the proceedings applied to define the short-term planning of generation units is a priority worldwide. Research on this area focuses on two main aspects:
  - In those systems/markets where every day dispatch is obtained by solving the "unit commitment" problem through a mixed integer optimization program based on either audited costs (the standard practice in Latin America) or complex offers freely issued by market participants (US ISOs), the main challenge is to find the best way to represent the uncertainty associated with the variability of these new generation sources on the one hand, while coordinating daily and secondary or balancing markets (deviation markets, reserve markets, etc.) on the other hand.
  - In those other markets where dispatch simply results from market dynamics around bilateral arrangements between market participants and simple matching between supply and demand resulting from spot, intraday and deviation markets (power exchanges and balancing markets in Europe), the current challenge is to study which is the optimum design for the energy and transaction markets sequence in order to maximize the flexibility of generation facilities.
- In addition, great efforts are being placed in the development of new methodologies for analyzing and foreseeing the future expansion of the generation capacity, which should be capable of properly considering the role being played by these new generation sources.
  - For systems where decision-making on these aspects is fairly centralized, these analyses are mainly focused on further developing the traditional planning and expansion optimization tools, so as to reflect in an accurate manner (and in sufficient detail) how variability (volatility and inability to dispatch) will contribute to

the sufficiency of the systems in the long term, and thereby establish system investment needs as accurately as possible.

- In markets where investment in “conventional” generation is somewhat expected to originate from the free initiative of the market participants, the need to develop new tools and market mechanisms is even greater: besides of the mentioned issues in the last paragraph there is a need to review the price formation mechanism and the associated uncertainties in a competitive market environment. Additionally in the case of regulation bodies, the current challenge is to analyze if the short-term market mechanisms need some kind of regulatory aid (capacity mechanism) to target investment towards facilitating a massive penetration of these new clean energies without endangering security and reliability.

But the penetration of new renewable sources creates challenges not only for the future development of generation. Given its scattered and distributed nature, these technologies pose great challenges to the proper development of the networks, of both high and low voltage. The integrated planning of transportation systems taking into account multiple generation and demand scenarios is the subject matter of thorough research. At the same time, the proliferation of small-scale generation in distribution networks, makes it necessary to revise not only the operating procedures for these networks, but also the criteria for their expansion and, most critical, the regulations which govern them (see Pérez-Arriaga et al. (2013))..

Finally, resorting to storage and to demand response to reduce the impact of production variability in wind farms and solar plants is leading to the development of new technological solutions and business models and, on top of all of it, of analysis methodologies.

Seeking an Integral Model

There is no such thing as two identical power systems and, thus, each system poses different challenges to the people in charge of studying the proper way to operate and plan them. At the same time, this has led to the development of tools to support decision-making in these fields, which are different from one another based on geographical location.

However, although we cannot deny that each case is different, it is certainly possible to discriminate between two main trends when classifying the models for evaluation, optimization and analysis of the operation, planning and expansion of the generation facilities: on the one hand, capacity-constrained systems and energy-constrained systems. In a few words, in the first case scarcity problems arise because there is not enough installed capacity available (MW) to satisfy demand at a given moment (e.g. due to the outage of two nuclear plants and/or minimum wind output); aggregating all the hours, the system could certainly have enough energy available to satisfy demand on that day (more than enough thermal capacity in the valley), but it lacks installed capacity to satisfy peak demand. In energy-constrained systems the situation is quite the opposite: rationing is applied due to a lack of available energy; the system could certainly satisfy peak demand, but would not be able to satisfy demand during the remaining hours of the day/week.

- Most European power systems (with the exception of the Nordic system until relatively recently) and North American systems have traditionally been capacity-restrained. In other words, the instantaneous relationship (e.g. hourly) between capacity and energy available in these systems (due to a lack of large hydraulic reservoirs) has led operators and market participants to be primarily concerned about modeling the very short term in great detail (ramps, very fast reserves, start-up costs, availability of thermal units, etc.). As a result of this, highly sophisticated tools are being developed in these systems for modeling the so-called unit commitment problem in the short term (from an hourly period up to 5 minutes). The Security Constrained Economic Dispatch models in use in markets managed by ISOs in the United States, or the old Goal program in place in England until the disappearance of the pool with the advent of the NETA, or the model for matching supply and demand currently in use in Ireland (and all the tools developed by and for participants operating in these markets) are a good example of this. In addition, since there is little uncertainty beyond the short term as to fuel availability in the generation units of these -mostly thermal- systems, these systems do not require much sophistication for analyzing the medium and long term.
- On the other hand, as opposite to the systems described above, a large proportion of Latin American systems have traditionally fallen in the category of energy-constrained systems, i.e. satisfying peak demand in a particular instant on an isolated hour has not traditionally been a problem. Due to the availability of reservoirs with a large storage capacity, it has not been necessary to model the short-term operation in much detail up to date. However, as opposite to the systems previously described, in these systems it has been of critical importance to suitably represent uncertainty and to determine the optimal management strategies for hydro resources and their medium, long and very long-term interaction with thermal facilities –a highly complex task at both methodological and computer level.

The penetration of non-conventional energy sources is considerably changing this paradigm in both contexts, which leads us to not only anticipate, but also already observe, a clear convergence process.

- In some European systems (Germany, Spain, and Portugal, Denmark and its connection to the Norwegian system) the development of wind and solar power has evolved so fast and so much (e.g. nearly 30GW of installed solar generation and a maximum output of 24GW in Germany for a yearly peak demand of around 60GW, or above 20GW of wind generation in Spain for a peak of about 40GW), that a great effort has been and is still necessary to adapt tools to this new reality. For instance, since the problem occurs in the few hours when thermal demand reaches its highest peaks[3], models which aggregate periods, for instance, are not valid. Given the increased need for plant-cycling -i.e. when thermal plants need continuously to be started and shut down or run at minimal power for several hours, see Batlle and Rodilla (2012)-, representing chronology is becoming increasingly necessary. Looking forward, models will need to consider the role to be played in the medium term by storage (with a regulation capacity which in any case should not be higher

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[3] Please note that in the new context peak demand is no longer the hour when the demand is the greatest, but the hour when net demand is the greatest (demand-generation of non-manageable ERNC, i.e. wind and solar).

than weekly), as well as demand management (still underdeveloped in Europe but otherwise relevant in some United States markets).

- In the case of Latin American systems, progress may be expected in the opposite direction. Due to the increasing difficulties faced when undertaking new investments in hydro plants with significant reservoir capacity, the large storage capacity which some of these systems still have may be reduced in relative terms. It will be therefore necessary to further develop the already advanced planning support tools nowadays available, which are capable of analyzing large systems representing the uncertainty associated with flow rates, in order to gradually incorporate granularity in as much detail as that used for representing the short term, since wind and solar output-related uncertainty is especially relevant in the short term (within a day or a week), even if it may be subject to certain seasonality.

An additional problem associated with NCREs which sets the two different types of systems apart is the need to have flexible generation capable of modulating output fast (i.e. capable of providing pronounced ramps). In systems with a strong hydro component, this problem does not exist, thanks to the almost infinite capacity of this technology to provide energy almost instantaneously. On the other hand, in systems with a strong thermal component, ramp management is a critical aspect already considered by short-term analysis tools, but which will also need to be considered by tools supporting expansion analysis.

On top of this, as if the problem were not complex enough, it will be necessary to sufficiently represent the capacity of the transportation network to accommodate these new developments in the generation facilities. As an ultimate objective, not only will generation planning tools need to consider network-related restrictions, but generation and transportation will need to be planned in an integrated manner.

Therefore, the ultimate objective for both systems is to further develop currently available tools, in order to facilitate the study of the new context which will likely affect power systems when the penetration of renewable energy sources puts the current capacities of power systems under their maximum stress levels.

The objectives of this report are: (i) to make a quick review of opportunities and challenges for the integration of renewable energy sources (hydro, wind, biomass, solar, etc.) in Latin America; (ii) to describe the requirements of the operating and planning computer models in order to suitably represent the attributes (benefits and costs) of these sources; (iii) to analyze the computer tools used nowadays in a selected sample of countries; and (iv) to suggest potential improvements for those tools.

Document Structure

The report is structured as follows:

- Section 1 provides an overview of renewables in Latin America.
- Section 2 includes a conceptual analysis of how the penetration of NCREs impacts power systems.

- Section 3 provides a brief description of some solutions being or which could be applied to optimize the penetration of NCREs while maximizing it.
- Section 4 discusses some basic conceptual aspects that should be considered when dealing with the problem of long-term power system planning.
- Section 5 provides a general review of the main computer approaches being applied or studied in order to support decision-making for expanding electricity systems, for both the generation and the network side (transmission and distribution).
- Section 6 analyzes a series of experiences from a selection of Latin American countries. The aim is to briefly describe how each country is conducting its planning processes, focusing on the computer tools being used.
- Finally, Section 7 provides conclusions and improvement recommendations.

This document does not include an analysis of energy policy elements necessary to commercially promote the development of the new renewables. These mechanisms rely heavily on the regulatory, economic and political context of each country and have already been thoroughly studied by different experts (e.g., Mastropietro, P. et al (2013)).

2 RENEWABLE ENERGY IN LATIN AMERICA

2.1 Renewable energy in Latin America: conventional and non-conventional

Latin America and the Caribbean are rich in natural resources, not only of a renewable origin. Since natural resources have historically been primarily harnessed through the establishment of hydro plants, this region can nowadays boost one of the cleanest electricity mixes in the world in terms of GHG emissions.

Figure 1 below shows total installed capacity and hydroelectric share in the region.

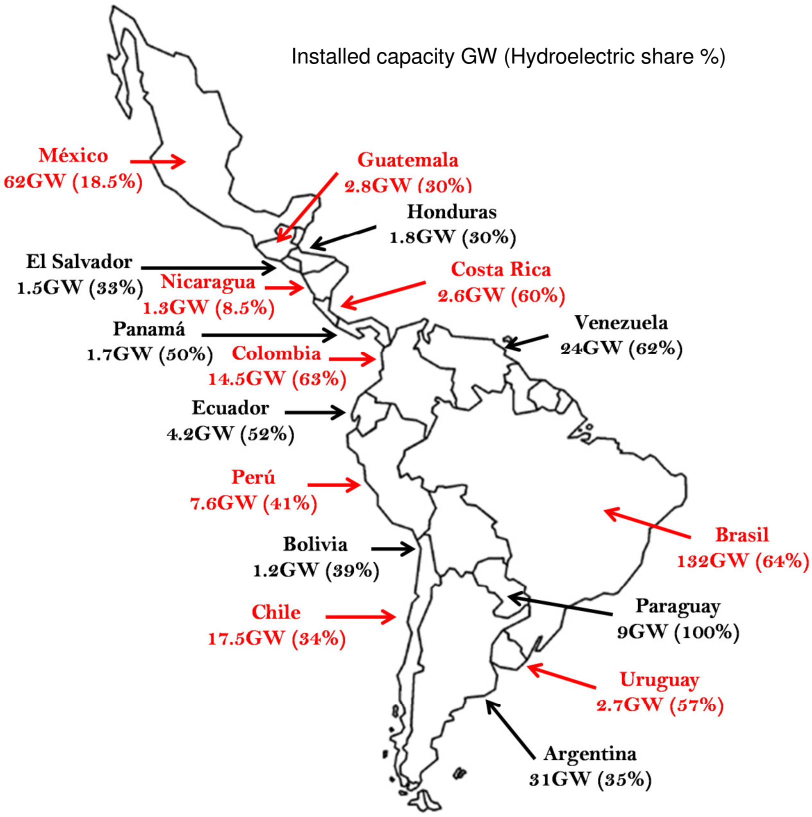

Figure 1. Installed capacity and hydroelectric share in Latin America (source: IDB, 2013)

While the availability and quality of data on the real potential of each of these resources varies considerably, the potential for exploiting new renewable energy sources, such as wind, biomass, geothermal and solar, is enormous at first sight.

However, in spite of this potential, the penetration of these non-conventional renewable energy sources is still reduced. Because none of these countries are included in Annex B of the Kyoto Protocol and have therefore not undertaken formal GHG reduction obligations/commitments, and because of the situation of the global economy and the lower per-capital income in these countries (which rules out the possibility to further increase the price in the electricity bill paid by users), the development of these technologies has not been a priority at least until costs have come close to those associated with setting up new conventional generation facilities.

However, this situation is well on its way to change and this decade started with a significant penetration of these new sources in the region. The main reasons for this change are discussed below.

2.2 The role of the new renewable sources in Latin America

From an electricity *supply reliability* perspective, the new sources enable diversifying the current mix, which is strongly based on hydroelectric generation and, therefore, vulnerable to climatic phenomena like El Niño/La Niña.

In addition, the increasing lack of clarity in the policies for granting permits for the construction of new hydro plants, combined with the increasing influence exerted by opposing groups to prevent the construction of reservoirs, has led to delays in the construction of these plants, which has negatively affected supply reliability.

In contrast, NCREs are smaller projects which are geographically scattered, subject to fewer barriers for obtaining environmental permits, which enable the diversification of the energy mix. In addition, the construction period of these sources (18-24 months) is much shorter than the five-seven years which are at the least necessary to complete a hydroelectric project. This results in greater flexibility for the installation of new capacity, which is an important aspect considering that demand growth is uncertain. In addition, they are also an appealing solution for providing isolated communities with access to electricity.

From an economic perspective, especially in the current context where financing capacity at global level has significantly declined, the smaller scale of the NCREs is a clear advantage considering the large capital investment involved in large hydroelectric projects under construction in the region –e.g. Belo Monte plant (11,233 MW) in Brazil or Pescadero Ituango plant (2,400 MW) in Colombia and potential projects like Aysén in Chile (2,000 MW).

In addition, replacing the use of imported fossil fuels (liquefied fossil fuels, coal or gas) with the production of local renewable sources enables: (i) GHG emission reductions; (ii) foreign currency savings; and, although the efficiency of policies in this respect may be the subject to long discussions, (iii) stimulating the settlement of local manufacturers, creating more employment and contributing to economic growth.

Another relevant economic reason for the establishment of NCREs is their location: sometimes, as they tend to be scattered, they can be located closer to load centers, which diminishes losses and efforts in transmission and distribution systems.

In addition, due to the reasons discussed below, the negative impact of volatility and dispatch unavailability of these resources on purely thermal systems (with power limitations, as already said), is of little relevance at least in the early stages thanks to their large storage capacity (of course depending on the system, the situation for instance in the North of Chile is quite different from the situation in Brazil). In other words, reservoirs work as “energy warehouses” which manage water, wind and biomass energy.

Finally, as discussed below, for many countries in the region the output regime of NCREs can complement the hydroelectric output regime, which enables the creation of invaluable synergies for the system.

3 IMPACT OF NON CONVENTIONAL RENEWABLE ENERGY ON POWER SYSTEMS

This section discusses in the first place and in deep detail the main impacts of NCREs on the planning, operation and control of power systems. Afterwards, there follows a brief discussion on the new requirements that these technologies will create for operators and planners of transportation networks, for both transmission and distribution.

3.1 Impacts on the operation of generation facilities

3.1.1 Wind and solar generation variability

Both wind and solar power are *non-controllable and intermittent*. Being non-controllable implies that the possibility that a given unit may not be available when needed is significantly higher than for controllable plants, like, for instance, a conventional thermal plant. For instance, Figure 6 shows the typical hourly variability of wind speed in Brazil. As for the European experience, for instance, EURELECTRIC (2010) shows that, on average, only 4% (2.5% in Spain and 5.5% in Germany) of the wind installed capacity has a probability of above 95% of being available at all times.

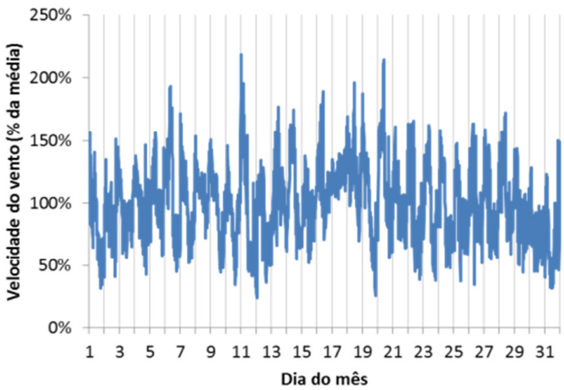

Figure 2. Typical hourly wind speed in Brazil

Such variability also occurs on a seasonal level. Figure 3 shows the output profile of PV solar generation in Germany throughout 2013.

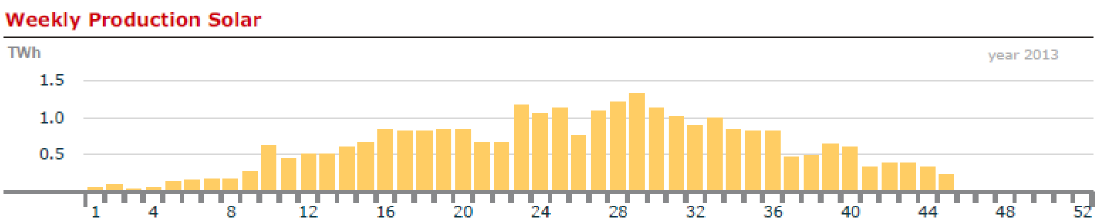

Figure 3. Weekly solar output in Germany in 2013 (Burger, 2013)

Figure 4 shows the typical seasonality of wind and hydroelectric output in Brazil and its great variability based on hydrologic and wind scenarios taken from historic measurements[4].

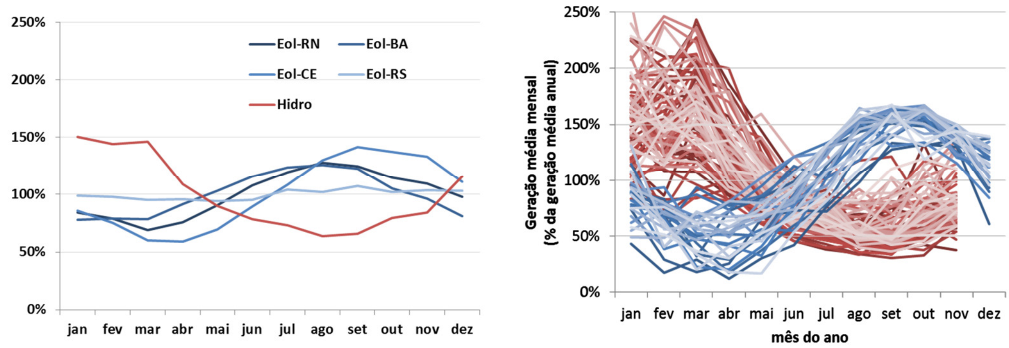

Figure 4. Typical hourly wind speed in Brazil

Wind generation variability decreases with spatial aggregation. Wind energy output over larger geographic areas has less variability than the output of a single wind farm. An example of this is provided by Figure 5, which shows the effect of wind output aggregation in Brazil (frequency distribution in blue shows the portfolio effect).

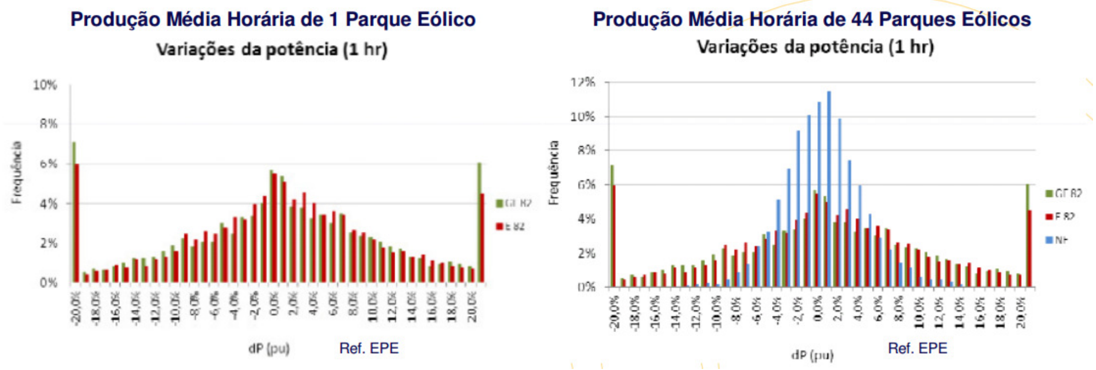

Figure 5. Effect of wind output aggregation in Brazil

Although wind output forecast techniques are significantly improving over the years, predicting wind's output is much more difficult than predicting demand. In general, only very near-term wind predictions are highly accurate (Xie et al., 2011). In particular, the error for 1- to 2-hour ahead forecasts (for a given wind farm) can be about 5-7%; for day-ahead forecasts, the error increases up to 20% (Milligan et al., 2009).

As regards solar power, variability is subject to a diurnal and seasonal pattern, where peak output usually occurs in the middle of the day and in the summer, so, for low penetration levels, it is quite well correlated with the hours of high demand of many electricity systems.

In particular, when peak demands result from the consumption of air conditioning devices in the summer (which is the case in most US systems), (photovoltaic) solar penetration reduces the net peak demand (demand minus solar output). However, it is worth noting that as solar penetration increases, the net peak demand starts moving

[4] In the case of wind output, the historic measurement record covers only 4 years.

towards the afternoon-night, when there is no solar generation. That is why its contribution in this respect is limited.

The following figure shows net demands for summer and winter in Spain. The sequence below shows how as solar penetration increases, net peak demand slightly diminishes.

The most interesting situation occurs in winter, when the synergies between the demand profile in Spain and the solar output profile are almost inexistent, and, as shown in the figure, the sun is not capable of reducing net demand at all. In fact, since in Spain the annual peak occurs in winter (which is frequent in the European continent), we may notice that the annual peak is not reduced as a result of solar penetration.

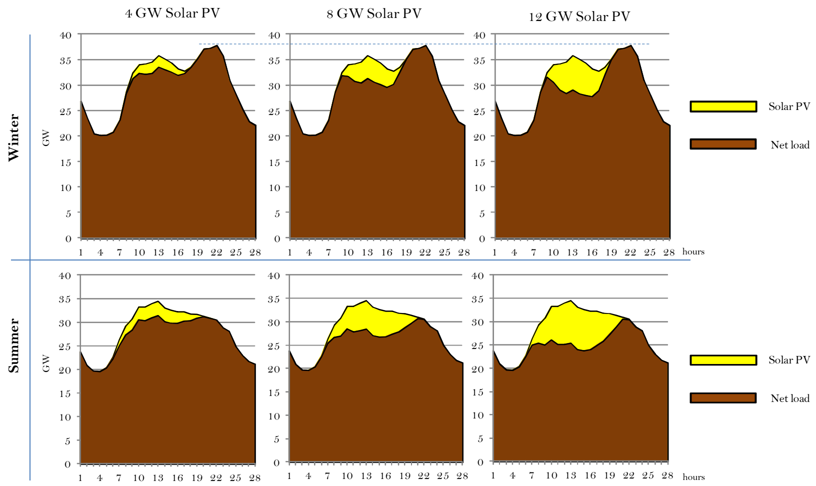

Figure 9. Contribution of solar generation to reducing peak generation needs

On the other hand, due to a lack of thermal or mechanical inertia in PV systems, and the impact of clouds, great changes in capacity may be observed in quite short intervals. Spatial diversity, as with wind, can mitigate some of this variability.

Compared to wind energy, PV solar output is generally more predictable because satellite data can be used to monitor the direction and speed of approaching clouds.

3.1.2 Taxonomy of impacts

In a vertically integrated electric power industry, the complete decision making process is organized in a hierarchical fashion with multiple couplings. Longer-term decisions (such as capacity expansion of generation or transmission) provide information and condition to a certain extant the short-term decisions, such as the hydrothermal coordination or the programming of the different plants. In power systems open to competition, most of these decisions regarding decentralized generation are made by multiple agents in a decentralized fashion, therefore replacing centrally coordinated plans of capacity expansion or operation.

From a supply reliability perspective (NERC 2009), different timeframes are also to be considered. From the seconds-to-minutes up to the real-time timeframe, reliability is mostly controlled by automatic equipment and control systems. From the minutes through one-week timeframe, operational planners need to decide what units will be used in order to maintain reliability through normal conditions, as well as contingencies

and disturbances. For longer timeframes, system planners must ensure that existing transmission and generation facilities are adequate to keep a reliable operation of the system.

The effects of penetration of intermittent generation affect decisions made at all timescales and across geographic regions, since a variable and only partly predictable source of power generation, with zero variable operational costs, will be brought about to a power system that has to balance generation and varying demand at all times. At high levels of penetration, the overall characteristics of the power system can be significantly altered. These changes need to be considered and accommodated into the current planning and operation processes, which were not designed to incorporate large volumes of intermittent generation. Multiple new issues must be addressed: (i) increasing power system flexibility by a better utilization of transmission capacity with neighboring areas; (ii) active demand side management; (iii) optimal use of storage (including pumping); and (iv) changes in market rules to schedule changes in output programs which are closer to real time. The future mix of generation technologies will have to accommodate the strong presence of intermittent generation and be able to cope with more cycling, fewer hours of operation and different patterns of electricity prices.

System operation encompasses a diversity of time spans. Common to all of them is that the installed capacity is given and the decisions to be made only include how to operate the generation plants. The discussion will focus on studying the effect of intermittent technologies on the reserves scheduling and the proceedings for guaranteeing system stability. The transmission network will be left aside of the analysis at all times.

From the innumerable impacts, a critical issue is discussed below: how the high penetration of renewable energies could affect operating reserves provision services.

3.1.3 Additional requirements of operating reserves

A critical issue in power system operation with a large volume of intermittent production is the number of operating reserves that will be needed to maintain reliable and efficient power system operation. The practical implications are (Holttinen et al., 2011): (i) more expensive operation, as a number of plants have to be maintained in a state of readiness and kept from being used normally to generate electricity, regardless of the regulatory framework; and (ii) a long-term impact on the generation mix, as appropriate investments have to be made to have these plants installed and ready when the level of penetration of intermittent generation makes these plants necessary.

A review of the numerous studies that have been conducted on the relationship between intermittent technologies penetration and the need for additional reserves has led to a set of general conclusions, which have to be adapted to the distinct characteristics of each power system (especially, those of Latin America):

- The observations and analysis of actual wind plant operating data have shown that wind does not change its output fast enough to be considered as a contingency event.
- Both the uncertainty in forecasts and the variability of wind generation may affect the required number of secondary reserves, but not significantly in most cases. Fast response reserves –primary response and regulating reserves– should be ready to respond to quick fluctuations in solar or wind production. However, power systems

have always needed this type of reserves to cope with demand fluctuations and unexpected contingencies. Therefore, the practical relevance, on both costs and reserve capacity, of the penetration of intermittent generation may be considered minor.

- More important is the impact of errors in the prediction of the output of wind and solar on conventional plants which are scheduled from one day to the next –which in many countries is also known as day-ahead scheduling. This requires having ready a significant number of flexible generating plants with relatively short start-up times and/or fast ramping capabilities, such as combined cycle plants or gas or hydraulic turbines, to provide load following and tertiary reserve supply. The level of these reserves is usually determined on the day-ahead, where wind forecast errors are still relatively high, although forecast models are improving, see Figure 6. In a properly designed system, it will be necessary to have a sufficient number of this type of state-of-the-art flexible plants in place in order to deal with the not-so-infrequent case of relatively long periods of low wind and solar production. It should be noted that the need to have reserves available does not necessarily mean that these state-of-the-art plants will actually be used for electrical power production, but rather, that these plants can be rapidly deployed when necessary.

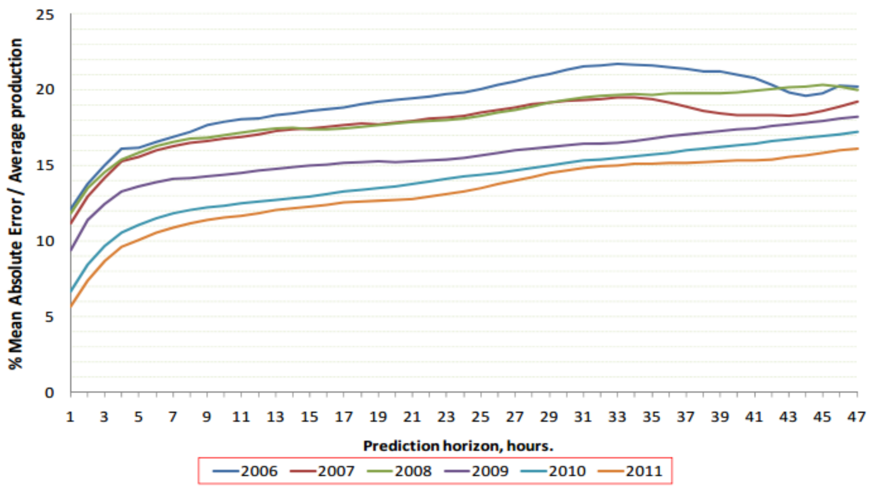

Figure 6. Wind forecasting error evolution in Spain (source: Spanish electricity network)

Requiring reserves implies that an increasing number of thermal units will have to be mandatorily scheduled. This reduces the capability of generators to manage their generating portfolio (the possibility to trade their energy in the daily market is reduced), and thus the amount of energy available to offer is reduced, which may increase market prices.

Findings from several studies conducted worldwide point at the fact that reserve requirements increase as wind power penetration increases, for instance, in Parsons & Ela (2008), Holttinen et al. (2011) or EURELECTRIC (2010). Figure shows findings for Ireland: the impact of electric power penetration on reserve requirements is closely tied

to an increase in wind forecasting errors as we grow apart from real time. Figure shows a selection of several international experiences.

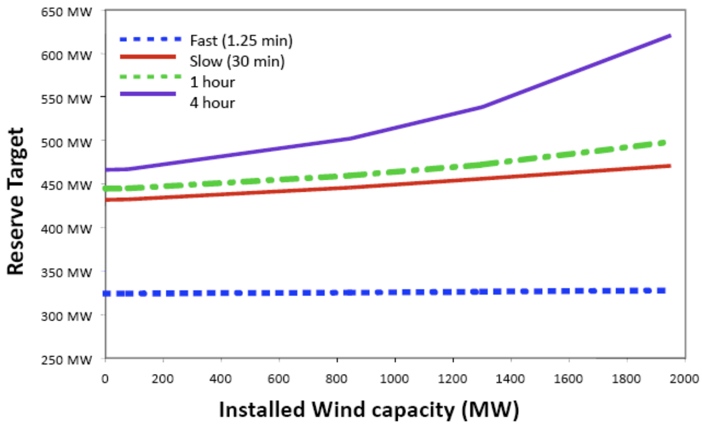

Figure 7. Reserve requirements by wind power penetration[5]

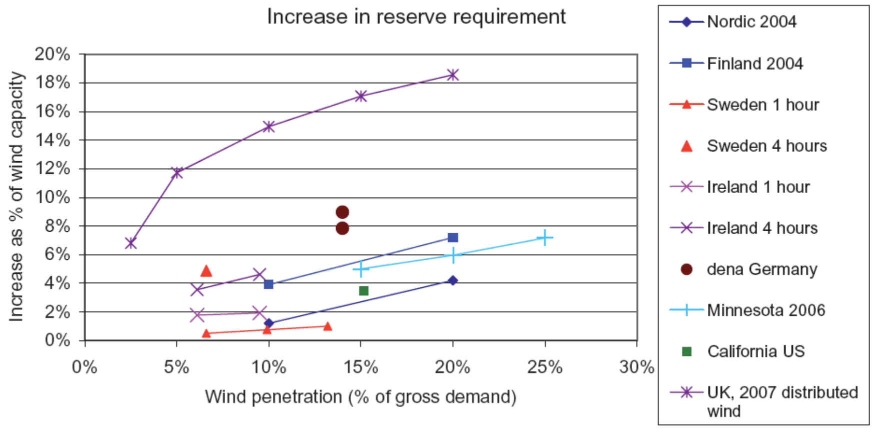

Figure 8. Increase in reserve requirements due to wind power penetration[6]

As pointed out in Holttinen et al. (2011), an “increase in reserve requirements” does not necessarily mean a need for new investments, as countries already with much wind power have learned from experience. Note that most wind-caused reserves are needed when wind output is highest and, therefore, the conventional power plants must have more spare capacity to provide reserves. Critical issues appear to be the limited capability of some conventional thermo electrical plants to follow steep long ramps in case of large wind forecast errors. In Latin America the predominance of hydroelectric generation plays an important role in providing operating flexibility for the integration of renewables.

However, special attention should be given to the relationship between flexibility and reserves. It should be noted that the need for flexibility does not match the need for reserves, with the latter being lower due to the fact that part of the net demand variation (original demand minus intermittent output) may be foreseen. As already

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[5] Source: MIT 2011 Wind Week. Presentation by Prof. O’Malley. Available at http://web.mit.edu/windenergy/windweek/Workshop2011.html.

[6] Source Holttinen et al. (2011).

discussed, reserves are mainly related with forecasting errors, while flexibility in plant scheduling also deals with output deviations. This opens a question regarding how to accurately define the flexibility requirements of an electric power system and how to promote investment in the proper technology and the rendering of flexibility services.

3.2 Impact of the NCREs on the expansion of electric power systems' generation capacity

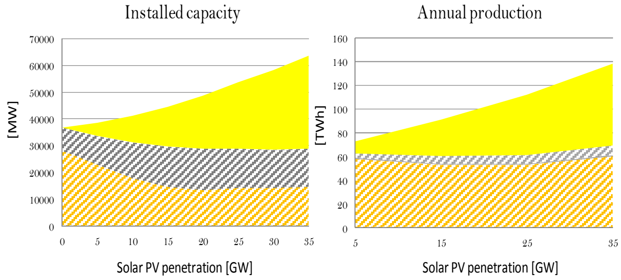
As a result of the already described characteristics of intermittent generation, the desirable long-term generation mix may significantly change. In addition, high levels of intermittent penetration will mean it will be advisable to invest in more flexible technologies. Furthermore, it is evident that reinforcement generation will be necessary for moments when the availability of resources is low. A large proportion of this reinforcement generation will be subject to very low use rates, as a result of being replaced with intermittent generation.

In general, as already stated, these requirements heavily rely on the fact that the energy facilities be purely thermal, or on the availability of a certain number of hydraulic resources which can be regulated.

In this respect, the following figure shows the evolution of optimal investment in combined cycle and gas-fired turbine plants for different scenarios of solar penetration in two systems respectively inspired in ERCOT and California in 2030. In the case of ERCOT (thermal system), due to the greater solar penetration, it is advisable to have increasing numbers of gas-fired turbine plants installed. On the other hand, when a hydraulic component is available in the system, the situation is quite the opposite: the greater the solar penetration, the lower the installed capacity of gas-fired turbines.

Both figures also show how the new thermal capacity required (the total number of installed MW) diminishes only for low solar penetration levels. That is why solar firm capacity is certainly limited.

New investments in the thermal system for different levels of solar penetration (ERCOT)



New investments in the thermal system for different levels of solar penetration (California)

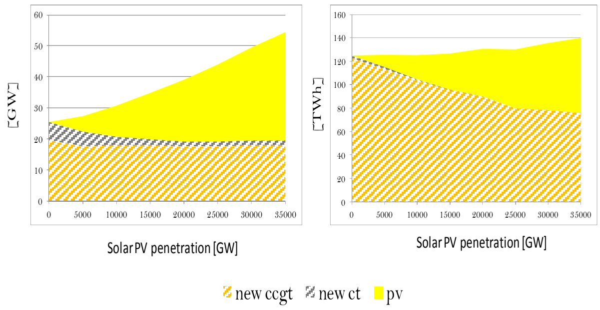


Figure 7. New thermal investment needs for large solar penetration

3.3 Impacts on transportation network planning

3.3.1 Transmission

Since most renewable generation technologies provide intermittent output, combined with the fact that the primary energy resources are not consistently distributed, the integration of large numbers of this type of technologies may well be expected to lead to a significant increase in energy flows between the different areas of electric power systems which are highly diverse, as well as an increased variability in the conditions of those systems. For transporting large amounts of energy from distant areas (as is the case of offshore wind power production, solar production in dessert areas, etc.), simply reinforcing the existing transportation networks may not be enough. Therefore, some kind of superstructure may be necessary, probably enabled for much higher voltage levels and direct current technologies. The development of networks in this new context, and particularly for regional systems like that of Central America or the Andean community[7], should ideally be planned in a centralized -or at least coordinated- manner, considering a large number of potential system scenarios and technological alternatives during the planning process.

The large number of small renewable plants with variable output and demand, and scattered across different countries, creates multiple challenges when it comes to planning the transportation network. On top of these challenges, there is the need to

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[7] The Electrical Interconnected System for Centro American Countries (*SIEPAC - Sistema de Interconexión Eléctrica de los Países de América Central*), which is almost 100% operational, and the Andean Electrical Interconnected System (*SINEA - Sistema de Interconexión Eléctrica Andina*), the feasibility of which is currently being studied with IDB's support, are Systems which precisely seek a regional generation expansion planning, developed by supraregional entities like SIEPAC.

account for the development of other energy sources, which turns planning into a highly complex issue. From a regulatory perspective, the challenge lies in building a planning scheme which should be efficient and provide for a proper allocation of costs among the renewables (Barroso et al, 2009).

3.3.2 Distribution

When NCREs penetration in the distribution systems is relevant, operating costs increase if a business-as-usual strategy is maintained, that is to say, if nothing but installing the new equipment is done. In fact, the increased presence of NCREs has two types of impact in the cost structure of the distribution operation. In the first place, heavy investment is required to connect this distributed generation facilities to the distribution network, to enable a proper management of the increased variability in flow rates and fluctuations in net demand and peak demands, and to install the IT necessary to optimize the daily operation of a network with plenty of NCRE installed capacity. In the second place, these new generation technologies, combined with storage and active demand response equipment, offer at the same time a series of new instruments for the operation of the networks which enable the operators of the distribution network to be more successful in achieving reliable, secure and efficient electricity power distribution. These new distributed resources will enable an active management of the distribution systems and a decrease in distributors' overall costs. For instance, managing NCREs and consumption in order to solve specific network congestions may delay the need to invest in new networks.

There is already a large number of studies on the increase in distribution network operating and planning costs as a result of the penetration of distributed generation. The output of these facilities alters the flows within the network, modifying energy losses. This effect may be positive or negative, depending on a number of elements, namely, penetration level, concentration and location of the generation facility within the system, as well as the characteristics of the technologies themselves. See, for instance, Ackermann and Knyazkin (2002) , González - Longatt (2007), de Joode et al. (2009), Cossent et al. (2010), and Yap (2012).

For low penetration levels, distributed generation tends to reduce losses, as local generation is absorbed by local load. As penetration increases, generation starts to exceed local demand (especially for low-load lines and/or when demand is low), which reverses flows and increases losses.

The need to reinforce the network will greatly depend on how the system is managed. DG GRID (2006) illustrates the main benefits stemming from an active management of the network for different levels of penetration and concentration of distributed generation. In the United Kingdom, for instance, up to 50% (15-40 %) of the cost of reinforcing the system for an installed capacity of 5GW (10GW) could be saved. In addition, a configurable network, that is to say, a network that may change its topology by opening and closing switches in the lines and, thus, dynamically change its topology in response to load and supply behavior, may reduce losses and increase the penetration of intermittent renewable generation (Lueken et al. (2012).

3.4 Summary and Impacts in Latin America

The new renewable sources are non-dispatchable and their output varies very fast throughout the day (and cannot be controlled by operators). Both aspects have a great impact in the operation of electricity systems, such as a greater need for generation reserve in the system in order to guarantee operational reliability.

In electrical power systems with a large component of hydro electrical output, such as many Latin American systems, issues associated with the integration of intermittent resources are minor, especially if the hydro plants have a significant storage capacity. As a result of this, the integration of the new renewable sources has not had a major impact in terms of operation up to date.

However, increasing difficulties associated with the construction of new hydro plants and, especially, the construction of new hydro plants with reduced (or null) storage capacity[8] associated with thermal generation penetration and the considerable growth of the new renewable sources, will increase the operation complexity in the region. This will call for changes in planning and operation, as we will discuss in the following sections.

[8] In the past 15 years, most of the hydro plants built in the region are "flow-of-river" type, i.e., with no storage capacity and considerable output variability.

4 RESOURCES FOR IMPROVING NCRE INTEGRATION

Certain technical resources may help operators successfully deal with intermittent generation. An example of these resources are hydroelectric systems with storage capacity, plant flexibility, improvements in wind forecasts, and, in a relatively near future, energy storage by batteries and electric vehicles.

4.1 Synergies between NCREs and hydro plants

Based on historic records of flow rates, winds, and periods of sunshine, complementarity occurs on different timescales and between different generation sources. There follows an illustration and an example of said complementarities and a discussion is presented regarding how this phenomenon may affect the development of NCREs.

4.1.1 Output complementarity among NCREs

The following figure shows the temporal (intraday) complementarity existing between solar and wind generation for a province in Brazil.

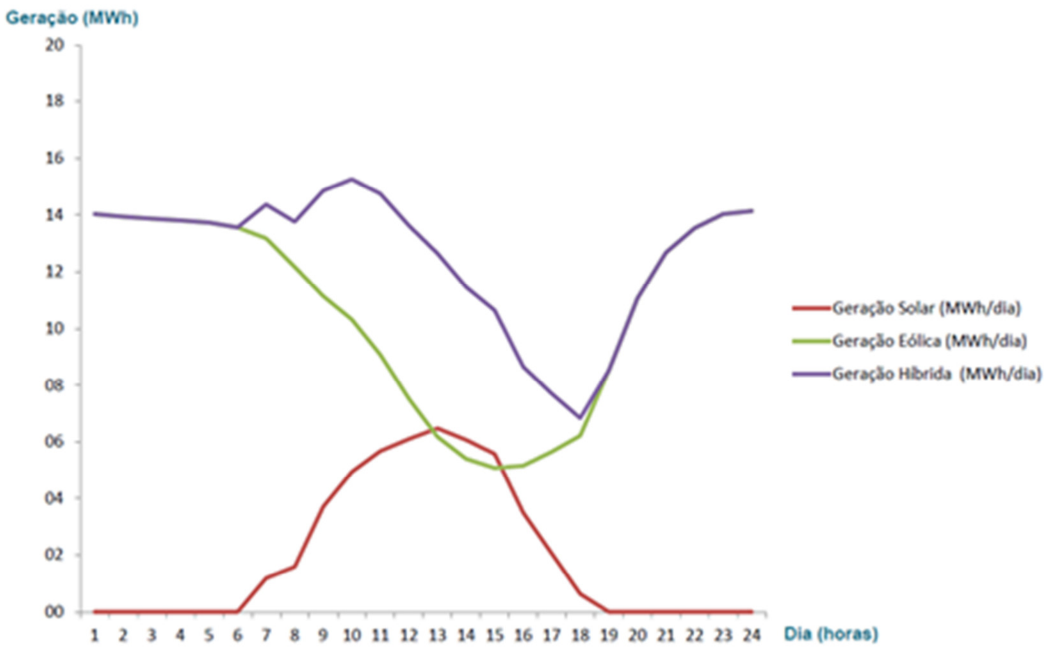

Figure 10. Hourly complementarity between wind and solar in Brazil

In addition, the following figure shows the spatio-temporal and energetic complementarity existing between biomass and the output of mini-hydro plants in one same region in Brazil. Figure 10 shows the output profile of co-generation from cane biomass, typical flow rates of mini-hydro plants and the average marginal cost (spot prices). Electricity output from biomass occurs during dry periods (higher marginal costs than the yearly average). This means that said output "is worth more" in economic terms.

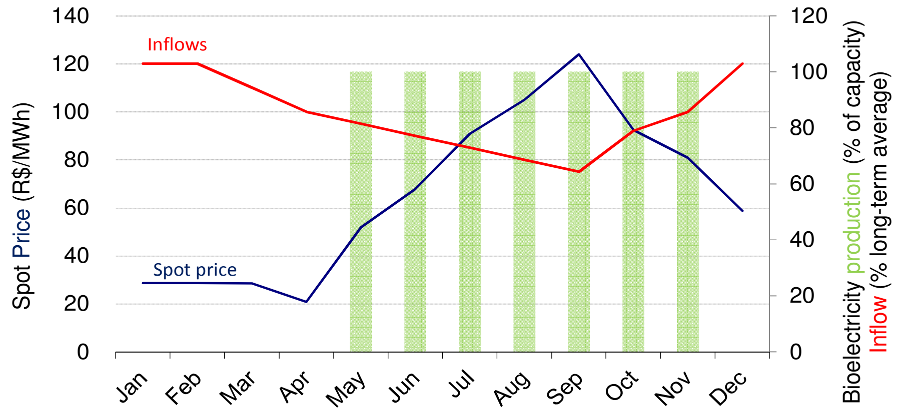

Figure 8. Seasonal complementarity between biomass and mini-hydro plant in Brazil

Figure 11 shows typical output profiles for wind farms located in the North-Eastern region and of mini-hydro plants located in the South-Eastern region of Brazil. The typical monthly profile is shown for said resources and their confidence intervals, which represent about average uncertainty. We may also notice great complementarity.

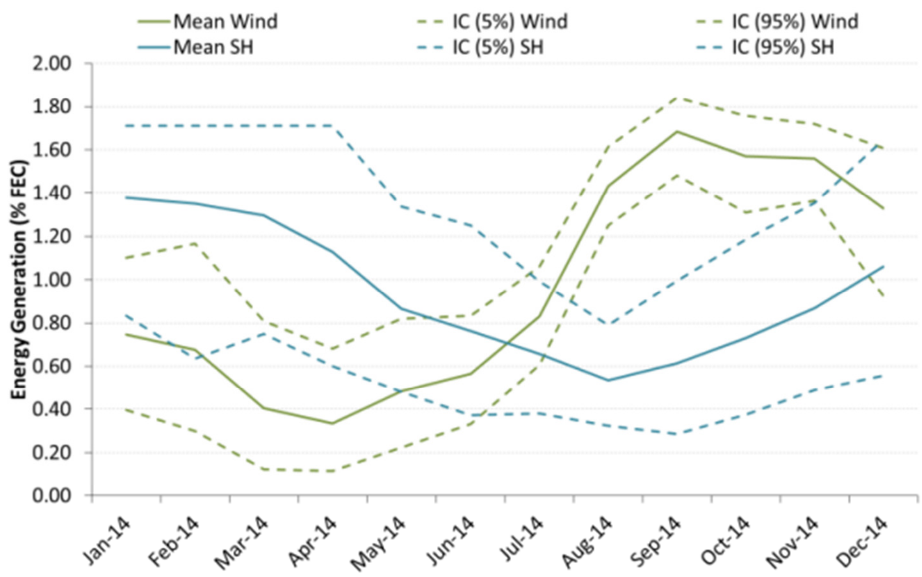

Figure 9. Seasonal complementarity between wind and mini-hydro in Brazil

4.1.2 Complementarity between NCREs and hydro

For the case of Brazil, Odilon et al. (2009) show that the San Francisco river, the main source of hydro electrical production in the North-Eastern region, has reduced flow rates in the summer, which is precisely when wind speed increases. The following figure shows wind and flow rate complementarity.

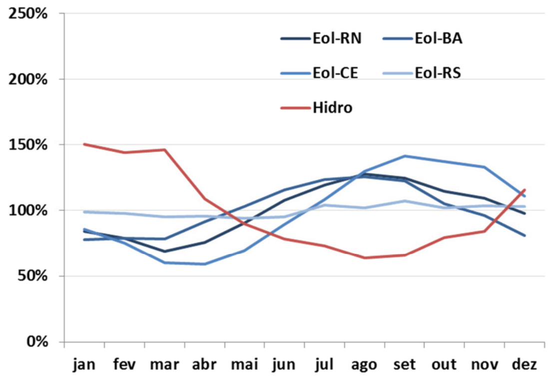

Figure 10. Seasonal complementarity between wind and flow rates in Brazil

The same complementarity may be observed in Colombia, as described by Otero (2011). Figure 13 provides an example of this complementarity for the Nare river and winds in La Guajira in Colombia.

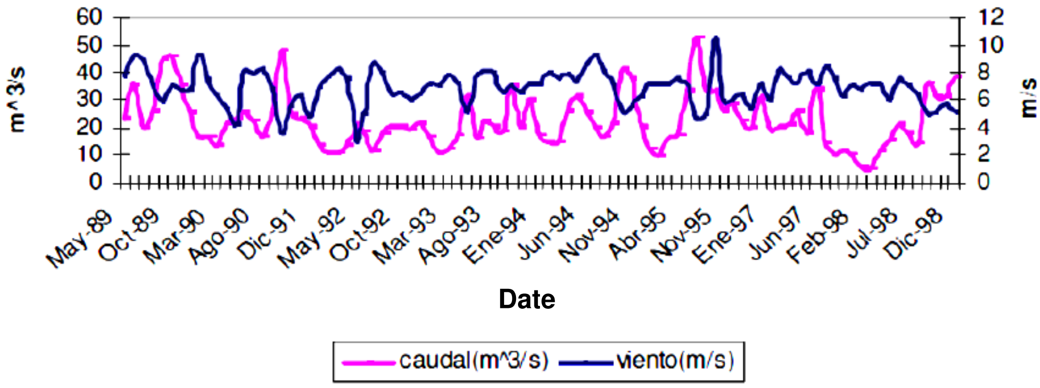

Figure 11. Seasonal complementarity between wind and flow rates in Colombia

Figure key: Pink curve - flow rate; blue curve - wind

The final paper of the study conducted by the World Bank, *Wind Energy in Colombia – A Framework for Market Entry*, also provides a detailed analysis of complementarity between wind and hydro energy resources in this country, stating that wind power appears to be available when its contribution to the system is most needed, that is, during the dry periods and when demand peaks (Vergara et al, 2010). Complementarity was also explored by analyzing the joint operation of a simple system consisting of a wind farm operating in tandem with a hydropower plant of similar size for each of the rivers studied and for a range of reservoir sizes. Results suggest that firm energy from the joint operation of wind and hydropower plants surpasses the isolated operation of the hydropower plant and of the wind farm. This result holds for a wide range of possible reservoir sizes studies and locations.

In fact, the presence of intermittent resources may boost the qualities of hydropower dispatch. The figure below shows, for a simulated operation inspired by the Californian system (Batlle et al., 2013), how photovoltaic penetration allows hydropower output to make a more effective peak shaving, eliminating the need to produce costly state-of-the-art plants.

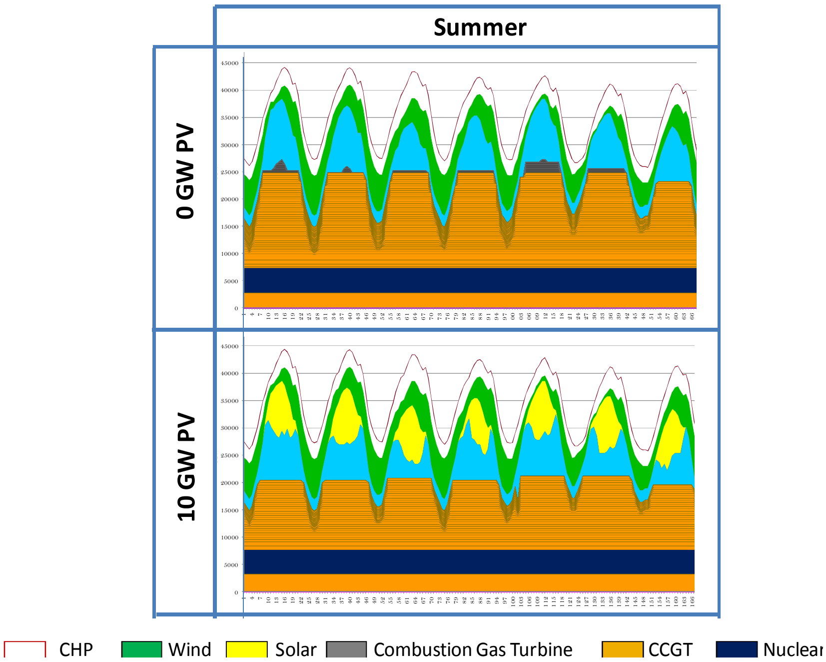

Figure 12. Coordination between solar output and hydropower management (Batlle et al., 2013)

Hydroelectric plumbing, where it can be applied, may provide economically feasible reinforcement to intermittent generation. It is difficult to find locations for new hydro plant projects, at least in more industrialized countries. Thermo-solar systems enable a certain degree of storage, and direct conversion of solar power into fuels could be the final solution. However, the technologies which could contribute great storage capacities to the existing capacity do not seem likely to be available at competitive prices in the short term; the same applies to electric vehicles.

4.1.3 Benefits resulting from synergies

As shown in the previous examples, the advantage of complementarity between sources is by no means insignificant. Complementarity reduces the impact of the intermittence of resources, increasing power supply reliability, optimizing the utilization of hydropower resources. In addition, the different patterns observed in different regions, turns this local complementarity in an element which should condition the development of the NCREs, discriminating in favor of those locations where the synergies with other resources already available is greater.

Complementarity between renewable resources is still an open issue which needs to be studied in greater detail. Likewise, progress should be made in designing regulations aimed at targeting investment in order to maximize the utilization of the existing synergies (for instance, by setting localization signals, whether directly, or through regulated payments for accessing the network).

4.2 Other resources

Active demand management is another potential source of flexibility, see NERC (2009). Demand management by means of time-of-day tariffs, such as the so-called real-time pricing (RTP) or cutoff agreements with certain consumers, would enable a reduction in the cost of both wind power integration and forecasting errors. Though a price signal by means of a RTP, consumption could be guided based on wind power output. For

instance, if wind power output is high, consumption would increase as prices would decline, and the other way around.

The greatest impact of intermittent generation on the electric power system operating costs affects the time scale of thermoelectric plants unit-commitment and derives from potential errors in wind output forecasting. Consequently, improvements in wind output forecasts based on daily timeframes offer an interesting opportunity to reduce costs and risks associated with this uncertainty. Forecasting technology is far from being perfect, but may be considered highly cost-effective. Wind forecasting is a highly complex issue. It depends on small pressure gradients which appear in large areas, chaotic and turbulent processes and also the local topography. The relationship between wind output and wind speed is by no means linear and, therefore, errors in wind speed forecasts get highly amplified when calculating expected output. Improving forecasts requires improving models and a larger number of site measurements. The benefits of wind output aggregation at power system control level and the need for large investments in observational and data-gathering networks favor centralization of the wind forecasting activities.

Rework of operation processes

Integrating large volumes of intermittent generation would be much easier if some institutional and organizational problems were properly addressed. This section will discuss two approaches:

1. Extending the geographic areas which are responsible for offsetting solar and wind production variability and uncertainty would smooth out the impacts and pool existing resources more efficiently and reliably;
2. A suitable management of intermittent generation requires scheduling markets closer to real-time, rather than the typical day-ahead scheduling, in order to reduce the negative impact of uncertainty in the operation of the system.

Both approaches should be implemented in a coordinated manner and simultaneously. There follows a detailed description of them.

Integration and coordination of balancing areas

As described in NERC (2009), ancillary services are a vital part of balancing supply and demand and maintaining bulk power system reliability. Since each balancing area must compensate for the variability of its own demand and generation, larger balancing areas with sufficient transmission proportionally require relatively less system balancing through operation reserves than smaller balancing areas, as explained in Parsons & Ela (2008). With sufficient bulk power transmission, larger balancing areas or wide-area arrangements can offer reliability and economic benefits when integrating large amounts of intermittent generation. In addition, this can lead to increased diversity of variable generation resources and provide greater access to other generation resources, increasing the power systems ability to accommodate large amounts of intermittent generation without the addition of new sources of system flexibility. Different coordination mechanisms between different areas have been implemented worldwide since long. Therefore, the opportunities resulting from participating (whether physically or virtually) in wide-area arrangements deserves evaluation.

Reduced scheduling intervals

Arrangements for the provision of the different kinds of ancillary services (and in particular operating reserves) widely depend on the individual power systems. In some cases the commitments for energy and some operating reserves are made at the day-ahead time range, while in others balancing energy transactions are scheduled one or two hours before real time. More frequent and shorter scheduling intervals for energy transactions may assist in the large-scale integration of intermittent generation. If the scheduling intervals are reduced, for example, from one hour to ten minutes, or intraday (or even continuous) markets are established to adjust previous positions in day-ahead markets, this will help to reduce the forecast errors of wind or solar power that affect operating reserves.

Given the strong level of presence of wind and solar generation in some power systems, there should be a level playing field for balancing responsibility, which applies to all producers, including wind and solar generators (although perhaps with some less stringent requirements) in order to stimulate all market participants to carry out thorough and proper scheduling and forecasting and thus limit system costs.

In summary, the need for additional flexible resources in power systems with great penetration of intermittent generation can be reduced through an accurate combination of: (i) adequate transmission capacity; (ii) larger balancing areas; and (iii) more frequent scheduling (within and between areas). Consequently, the need for ancillary services would be less, and the costs of running the power system would be lower. As an example that this can be accomplished, mandatory Framework Guidelines have been recently adopted in the European Union. This document contains all necessary elements, namely: A pan-European intra-day platform to enable market participants to trade energy as close to real-time as possible to rebalance their positions, with the participation of the system operators to facilitate an efficient and reliable use of the transmission network capacity in a coordinated way.

5 LONG-TERM PLANNING: CONCEPTUAL ASPECTS

The core objective of planning is to establish the right set of reinforcement for the generation mix and the transmission and distribution networks that guarantees supply in an economic and reliable manner through the period contemplated (in general, 5 to 20 years).

The entire planning methodology can be represented by the following process:

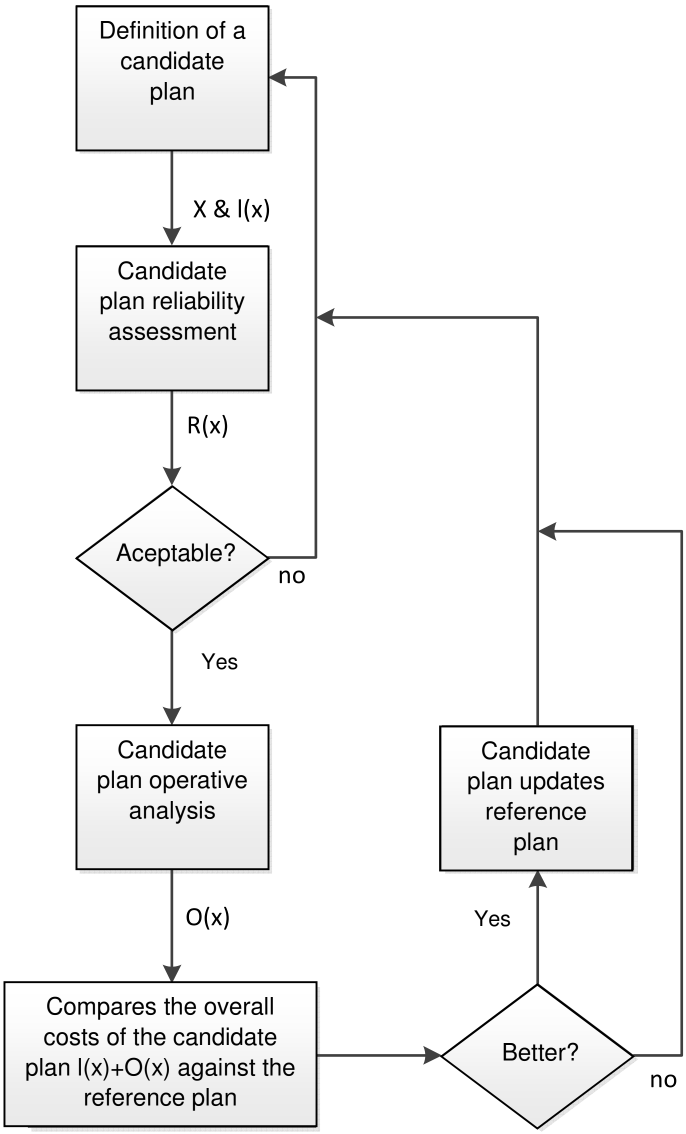

Figure 16. Planning process

This planning process comprises the following stages:

a) *Definition of a candidate plan* – A plan is a set of dates indicating when investments are to be made and generation and transmission equipments are to come operational. In addition, the plan must comply with *investment restrictions*, such as minimum and maximum deadlines for coming into operation, mutually excluding projects, etc. In the figure above, the candidate plan is represented by the *x* vector; and the total investment cost by the I(*x*) function;

b) *Supply reliability analysis* – In this step, the planner calculates the supply reliability indices which would result from the implementation of the candidate plan *x*, for instance, the average unsatisfied demand resulting from severe drought and/or generation and transmission equipment failures. These indices are represented by the R(*x*) function.

c) *Reliability criteria* – Afterwards, the acceptability of R(x) reliability indices is checked against the planning criteria. Among the criteria used is, for instance, loss of load probability (LOLP): loss of load probability below 0.1%; or not observing overloads on the network in case of outage of any circuit (the so-called "N-1" criterion); etc.

d) *Operating analysis of the candidate plan (economic dispatch)* – Although the candidate plan x is acceptable under the reliability criteria of the previous step (c), the operation of the generation-transmission system is simulated for several hydrologic scenarios, equipment failures, etc., and operating indices, like operating costs of thermal plants, are calculated. These indices are represented by the O(x) function.

e) *Comparison against the reference plan* – In this step, the attributes of the candidate plan are compared against those of the reference plan, which is the best plan obtained up to date. For instance, an attribute could be the present value of total costs (PVC), calculated by adding investment costs I(x) and the expected value of the operating cost O(x); another attribute could be the variance of this total cost, taking into account, for instance, uncertainties in hydrologic conditions and in demand growth rates. If, under comparison criteria, the candidate plan is better than the reference plan, the reference plan is updated.

Relevance of planning schemes

In several countries across the region –e.g. Colombia, Chile, Peru or Brazil- there is no centralized decision-making on reinforcement generation: investors are free to build new generation capacity (in Colombia, like in most European countries, once installed, they are also free to offer the amount and price they deem appropriate in the short-term market). In the case of transmission, although in some cases the market participants may propose network reinforcements (which ultimately need to be accepted by the system operator), all the countries in the region adopt the centralization process where the planner proposes the construction of the network reinforcement capacity. Therefore, an important question is what is the role of planning in the creation of a free-competition environment.

Therefore, generation capacity expansion planning in these contexts must have an indicative nature. The main objective of an expansion plan in a liberalized market is therefore to guide the market participants, providing them with the necessary information for them to plan their investments. This indicative planning is especially relevant at this moment, when so many governments are acting as regulators and making key decisions, especially as regards network expansion, and especially, considering that, at least for the time being, the penetration of these technologies is being guided by government intervention, see Mastropietro et al. (2013), which affects the future penetration of NCREs. As already discussed, the impact of these new energy sources may be so critically relevant that it is of vital importance for investors to have a clear picture of what the future scenario will look like. In the case of hydropower plants, the plan enables the identification of the generation alternatives which can be offered for private development.

6 COMPUTER TOOLS FOR ANALIZING POWER SYSTEMS' FUTURE

6.1 Generation planning

From the conceptual process (a)-(e) presented in Figure 6, it may be concluded that the success of a planning methodology depends on five main issues:

i. How the candidate plans x are produced and investment costs I(x) calculated;
ii. How the supply reliability rates R(x) are calculated;
iii. Which is the acceptable reliability criteria;
iv. How the operating costs O(x) are calculated;
v. Which are the applicable criteria for the evaluation of candidate plans benefits.

The answers to these questions depend mainly on the planning computer tools. There are many "classic" tools for this type of study, as explained in detail in Connoly et al. (2010) and Bhattacharyya et al. (2010).

Each tool may be more o less suitable for a certain system according to the following aspects: (i) how balanced is the combination of the number of relevant variables to represent in each system and the level of detail contemplated in each of them[9]; (ii) the formulation of the associated optimization problem; and (iii) its resolution algorithm.

Ideally, a planning tool should represent all the investment and operation aspects of a system in an integrated and detailed way. However, this implies several computer problems that are being solved, but which still need considerable investigation. Thus, until now, the integral planning process has usually been conducted in two sequential stages. Planning tools are generally divided in two main types:

- Optimization of generation capacity expansion. It is made with tools that heed the whole chain on Figure 6 and produce an expansion plan that combines economic criteria -minimum investment and operating costs-, and reliability criteria -for example, through the definition of target reserve margins- according to the planner's criteria. These tools represent the short-term operation in a simplified manner, through monthly (or quarterly or biannually) stages, with aggregate representations of system resources, representation of the demand by blocks (rather than the complete load curve), and most importantly, ignore output uncertainty (hydroelectric and new renewables), and bypass of equipment failures;

- Operation planning analysis: Using an expansion plan proposed on the previous stage, the economic dispatch is optimized or simulated in detail, with the intention of verifying the accomplishment of the objectives originally proposed.

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[9] For example, if the objective is to analyze future expansion plans in Brazil, a detailed representation of non-convex costs of thermal plants (start-up costs, efficiency losses for operating at minimal power, operation and maintenance variable costs, etc.) is less relevant than a proper representation of uncertainty related to the potential output of hydro. The situation would be different, for example, in the case of Uruguay, where the possibility to regulate hydro resources is lower, which makes it necessary to improve unit commitment representation in expansion planning tools.

One of the key issues that is currently under analysis is the fact that –especially in capacity-constrained systems- NCRE penetration makes it necessary to avoid breaking down the process in two stages, by using integrated models capable of considering short-term operation with a higher level of detail.

The WASP model (Wien Automatic System Planning Package) is the most used tool for producing expansion plans -see Connoly et al. (2010). WASP considers every technology[10] and outlines the plan for investment in new capacity, minimizing investment and operating costs, considering a wide range of limitations to investment (emissions, maximum capital expenditures, etc.) and ensuring a certain target reserve margin. Expected operating and unavailability costs are estimated through a non-chronological probabilistic simulation technique which incorporates the effects of random events, such as forced outage of thermal generation units and critical hydrological years. The objective is the minimization of investment, operating and scarcity costs, at present value. The optimum expansion plan is obtained as a result of a dynamic programming algorithm.

This tool was developed and maintained by IAEA (*International Atomic Energy Agency*). One of the reasons for its great success and dissemination is that WASP is freely distributed by the IAEA among its members. WASP has yearly stages with 12 demand blocks, and it is generally used for studies of timeframes of up to 30 years.

The figure below represents a WASP model scheme.

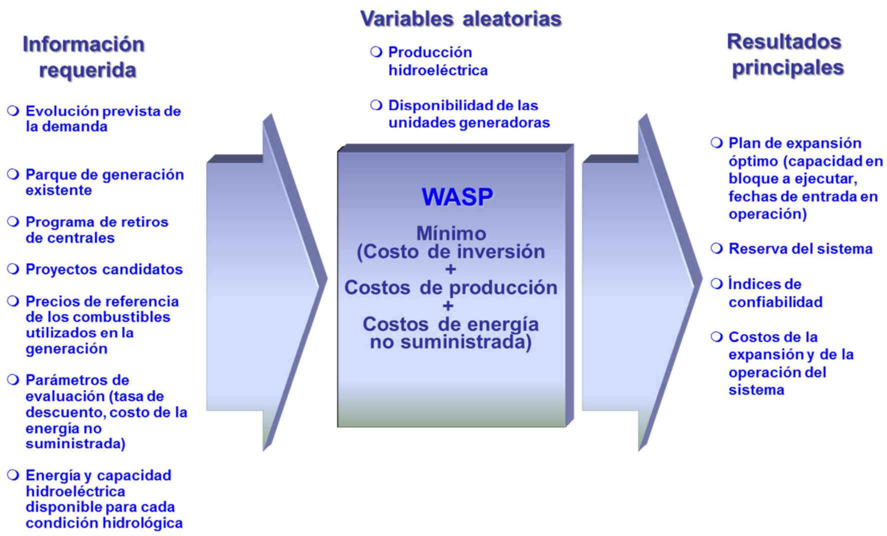

Figure 13. WASP tool (source: SENER)

Figure key:

Información requerida	Information required

[10] The representation of technologies that imply output uncertainty, i.e. hydro and NCREs, is made in a very simplified manner, where the output is defined through a profile introduced by the user.

Evolución prevista de la demanda	Expected demand evolution
Parque de generación existente	Existing generation facilities
Programa de retiros de centrales	Plant removal programs
Proyectos candidatos	Candidate projects
Precios de referencia de los combustibles utilizados en la generación	Referential prices of fuels used in generation
Parámetros de evaluación (tasa de descuento, costo de la energía no suministrada)	Evaluation parameters (discount rate, non-supplied energy cost)
Energía y capacidad hidroeléctrica disponible para cada condición hidrológica	Energy and hydro power capacity available for each hydrological condition
Variables aleatorias	Random variables
Producción hidroeléctrica	Hydro power output
Disponibilidad de las unidades generadoras	Availability of generating units
Mínimo	Minimum
Costo de inversión	Investment cost
Costos de producción	Production costs
Costos de energía no suministrada	Non-supplied energy costs
Resultados principales	Main outcomes
Plan de expansión óptimo (capacidad en bloque a ejecutar, fechas de entrada en operación)	Optimum expansion plan (executable block capacity, start-up dates)
Reserva del sistema	System reserve
Índices de confiabilidad	Reliability rates
Costos de la expansión y de la operación del sistema	Costs of expansion and operation of the system

There is a large variety of tools that address the operation planning analysis, but none of them stands out from the rest and defines a "standard" to be followed. Nowadays, it is possible to find commercial packages – used by many countries in the region - that accurately reveal the stochastic hydrothermal dispatch, including transmission restrictions (taking into account uncertainties regarding flow rates, output of new renewables, failures bypass and multiple cascade reservoirs, each one represented individually).

6.1.1 Representation of renewables in analysis models

Connoly et al. (2010) indicate that "*The 'best' energy tool will be defined by the problem you wish to solve (i.e. your perspective) more than the abilities of the tool*". This assertion is especially relevant when discussing which tool should be selected to represent a whole energy system. However, if the intention is to develop the planning process of an energy system, the capacity of the tool is key to obtain a proper solution.

In this sense, most of the tools analyzed by Connoly et al. (2010) misrepresent some aspects that are becoming more important as NCREs penetration grows, such as:

a) Greater temporal granularity (even contemplating an hour-by-hour breakdown) in the representation of generation facilities short-term operation;

b) Chronology of decision-making regarding the operation, which is key to represent the temporal correlation between NCREs and hydro power output and the impact of operation limitations and non-convex costs of thermal plants (costs and minimum start-up periods, operation at minimal power, etc.);

c) Uncertainty in the resolution of unit commitment. This uncertainty, within a context that considers a significant penetration of NCREs, is mainly linked to the short-term volatility of the output of these new generation plants.

These aspects become more relevant as the system is more capacity-constrained, i.e. they are extremely relevant for an entirely thermal system in contrast to those that have a considerable seasonal reservoir capacity.

As it has been repeatedly mentioned, the challenge consists on improving this representation in operation planning analysis tools (or economic dispatch), and ultimately, to be able to consider a sufficient level of detail within optimization models for generation capacity expansion.

6.1.2 Desirable attributes for operation and planning tools

Although in each particular case it is necessary to achieve a certain balance between computer costs and levels of detail - as previously described-, there follows a list of some attributes that tools for analyzing the operation, planning and expansion of regional systems should contemplate. Thus, the key will consist in the ability to make an early analysis of which variables should be represented in greater detail, in accordance with the settings of each system.

- Parameters, variables and technical restrictions regarding the operation optimization issue:
  - Thermal generation: thermal efficiency (i.e. MBtu/MWh) and CO2 emission (TonCO2/MWh) rates, non-convex costs –start-up costs-, operation at minimum power, ramps, variable O&M costs, etc.
  - Hydro generation: maximum capacity, reservoir and water release functions, flow rate limitations, cascading, etc.
  - NCRE generation: Hourly and chronologic detail of variability and correlation, and complementarity of the output in relation to short-term demand needs.
  - Demand reaction: potential demand resilience, non-supplied energy costs.
  - Storage: efficiency rate (i.e. pump units), useful life of equipments (in case of batteries).
  - Transmission: sufficient grid representation, losses account.
  - Needs and limitations of operating reserves.

- Timeframe
  - Granularity (i.e. hourly detail).
  - Chronology.
  - Lifespan (i.e. ten, twenty, thirty years).
- Representation of uncertainty
  - Uncertainty related to the future structure of generation facilities: additions and removals of generation plants.
  - Stochastity related to energy resource availability: flow rates and hydro inputs, wind, biomass, solar output, etc. Seasonal nature[11] and space correlation.
  - Uncertainty about demand growth rate (it contemplates a shorter construction timeframe which is a great benefit of new renewable sources).
  - Uncertainty related to the timeframes associated with the construction of generation facilities.
  - Uncertainty about fuel costs.
  - Uncertainty related to financial costs (i.e. rates of return).
- Representation of *energy policy* criteria:
  - Objectives/restrictions regarding GHG emissions
  - Objectives/restrictions regarding renewable sources penetration
  - Objectives/restrictions regarding diversification of energy sources in the country, including international interconnections.
- Solution methodologies for operation and planning studies
  - Stochastic scheduling (i.e. proper treatment of uncertainty related to the management of reservoirs).
  - Global mixed scheduling (proper representation of limitations and non-convex costs of thermal plants and of generation investment discrete decisions).
- Computer requirements
  - Parallel processing techniques[12].

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[11] For example, the seasonal nature of biomass production in Brazil complements the flow rate pattern.

[12] The growing availability of computer resources at reduced prices, especially in cloud computing, allows the new generation of planning tools to bring greater detail to the aspects of decision-making under uncertainty, which are key to planning studies.

6.2 Network planning

6.2.1 Transmission

Within the new context described, calculating the optimum network expansion strategy requires the use of highly efficient computer tools, capable of automatically generating the network expansion planning, taking into account a great number of possible scenarios (Oliveira et al., 2007).

The NETPLAN[13] or the TEPES[14] models are two examples of this type of tools.

The NETPLAN model in particular was recently used for planning the expansion of the transmission network of the WECC (*Western Electricity Coordinating Council*), which covers all the West coast of the United States and the Provinces of Alberta and British Columbia in Canada. With an installed capacity of 200 GW, a transmission network of over 15 thousand busbars and 20 thousand circuits, the WECC has currently a great penetration of renewables [15]. The figure below shows an example of said application.

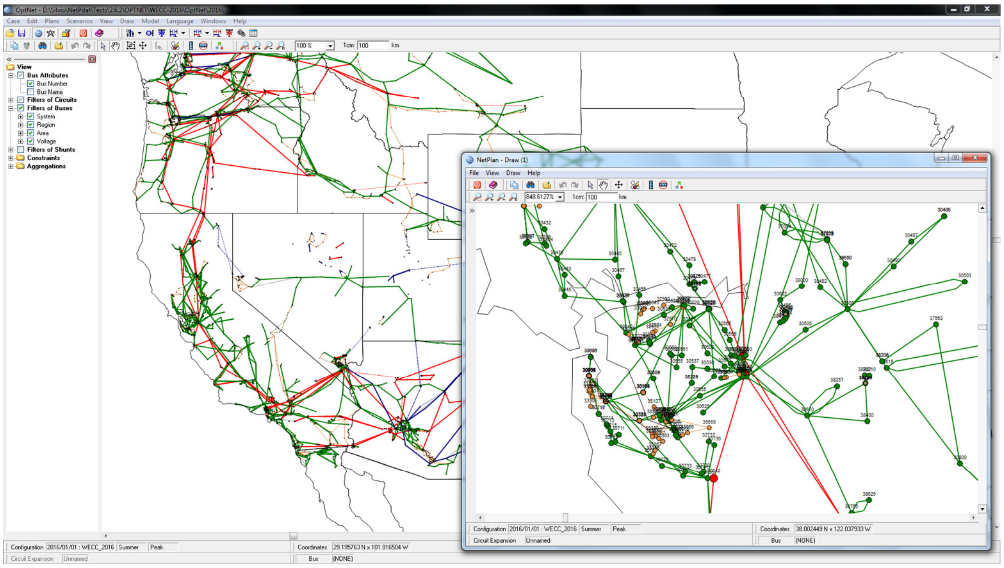

Figure 14. WECC planning

The TEPES model develops an optimization method based on breaking down functions into two modules: one module for the optimization of network expansion plans (based on optimization), and another module for the evaluation of each plan. Said model makes a Benders breakdown where the master problem proposes the investment decisions, and the sub-problems calculate their reliability (non-supplied energy and

[13] www.psr-inc.com.br/portal/psr_en/servicos/modelos_de_apoio_a_decisao/studio_plan/netplan/

[14] www.iit.upcomillas.es/aramos/TEPES.htm

[15] G. C. Oliveira, F. Thomé, R. Perez, L. M. Thomé, S. Binato and Mario Pereira, Transmission Network Planning Model Applied to WECC's System Expansion in the United States, XII Symposium of Specialists in Electric Operational and Expansion Planning, May – 20th to 23rd, 2012, Rio de Janeiro, Brazil y F. Thomé, Large-scale Mixed Integer Disjunctive Model for Transmission Expansion Planning under Uncertainty, INFORMS 2011 Annual Meeting, November 13th–16th, 2011, Charlotte, NC, US

network contingencies). The figure below shows one of the resulting plans calculated under the European Project DESERTEC[16].

Figure 15. Transmission expansion plan calculated with TEPES

Overall, the need to compare generation and transmission costs in an integrated way (between plants located near demand with lower transmission costs, and plants located far from demand and with higher transmission costs) is the key issue for an integrated planning of generation and transmission.

6.2.2 Distribution

Traditional models do not allow to consider the great variety of new dynamic resources, hence, it becomes necessary to develop new computer tools, even if that results in a considerable development effort to achieve the incorporation of essential technical features of distribution networks and NCRE connection.

A reference network model (RNM) is a tool for large-scale distribution network planning, with the ability to address problems in areas of hundreds of square kilometers that include several millions of consumers. The resulting reference network is structured in three hierarchical levels of voltage (high, medium and low), and complies with the same geographical criteria (orography, excluded areas, tramlines), reliability (supply continuity requirements) and technical restrictions (voltage and thermal boundaries) as the real network, and with minimum cost. In order to achieve this objective, a detailed geographic information system (GIS) and detailed electric modeling are required. Due to the complexity of the planning problem to be solved, a series of heuristic algorithms are applied, especially as the size of the problem grows.

The RNMs have been used in Spain for several years, as described in Gómez et al. (2013) and Mateo et al. (2011), and have also been used to carry on studies in other countries[17]. Since these are tools for panning large-scale distribution networks, the

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[16] Pre-feasibility analysis on power highways for the Europe-MENA region integration in the framework of the Dii Rollout Plan 2050 developed for Desertec Industrial Initiative (Dii).

[17] In Gómez et al. (2012) there can be found several case studies that show the applicability of these models for the evaluation of the impact of massive NCRE penetration. In case of lack of sufficient information on multiple real cases of distribution network costs for different levels of

RNMs may be used to estimate distribution efficient costs and to plan the already existing distribution networks. Unlike traditional planning tools, where it is the user that provides several expansion options, the RNMs automatically generate the required enhancement for the networks.

A good example of the potential of these models can be found, for example, in the analysis developed in one of the chapters of the solar study of the MIT, to be published at early 2014[18]. In said chapter, a RMN described in Mateo et al. (2011) is used to analyze the technical and economic effects of setting up a large amount of distributed photovoltaic solar generation. It shows how the intermittent generation impacts the network flow patterns, causing numerous problems (basically at local level) that will require considerable network improvements. To illustrate the potential of these models, the figures below show how the model is capable of defining the reinforcements that would be necessary in a life-size network in case of a great penetration of photovoltaic solar output forecast.

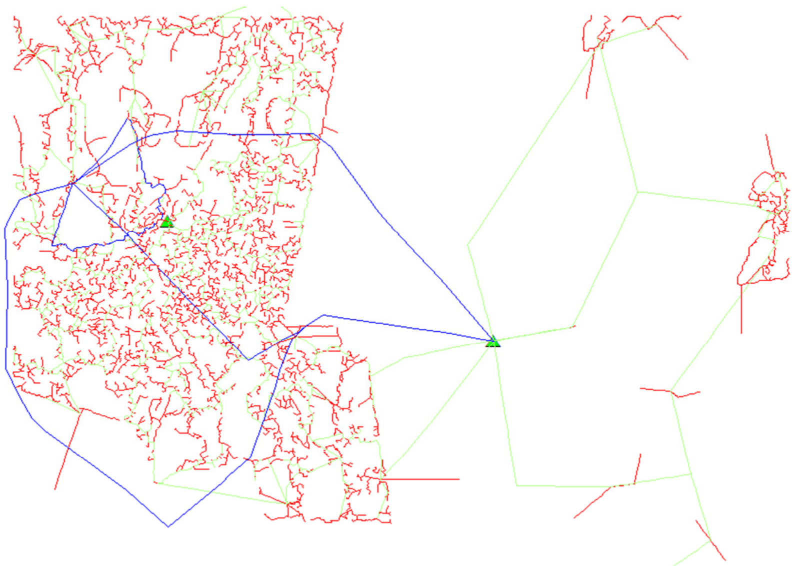

Figure 20. Lancaster base network

NCRE penetration that allow *benchmarking* techniques, RNMs are the only tool currently available that enable the controllers to make reasonable estimates of efficient distribution costs. However, the development of RMNs is very complex and they are still under study and investigation.

[18] “Integration of Distributed Photovoltaic Generators”, from the MIT *Future of Solar* study, that will be published in 2014

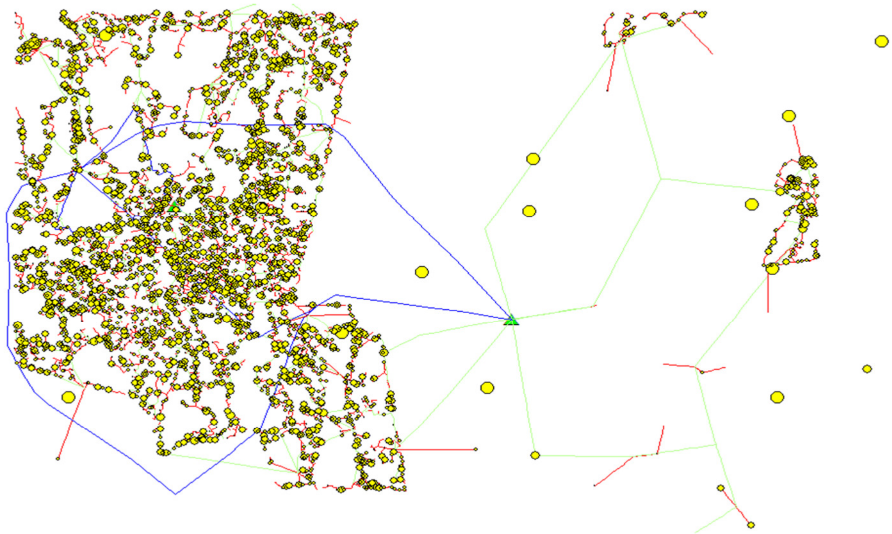

Figure 16. Lancaster base network with a high penetration of solar PV

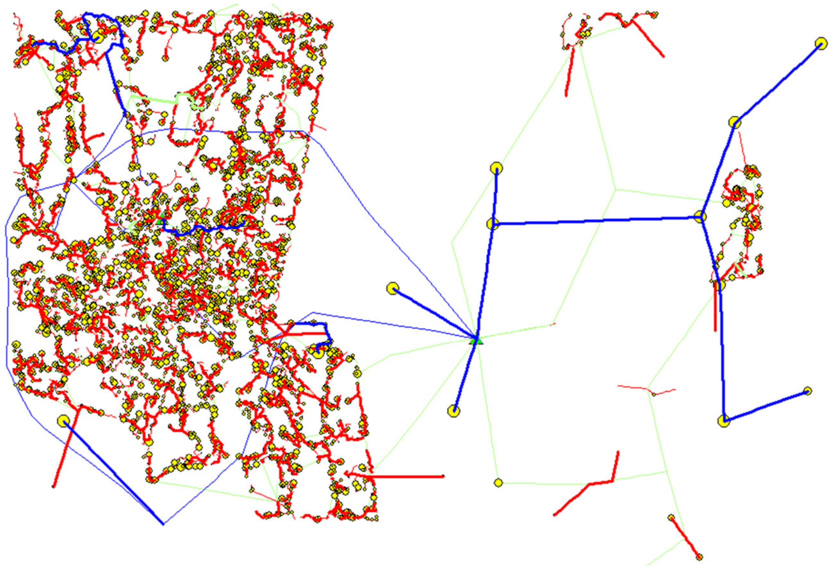

Figure 17. Lancaster network reinforcements needed

Therefore, based on these outcomes, the aforementioned tools enable not only to guide the distribution network expansion, but for example, to assess the impact of renewable generation on distribution costs.

7 EXPERIENCES IN LATIN AMERICA

This final section presents a compilation of experiences in some selected countries of Latin America. The objective is to make a brief description of how each country is handling its planning processes, focusing on computer tools and the challenges of planning within an environment with considerable penetration of new renewables.

7.1 Countries analyzed

The chart below shows the list of countries analyzed. These countries and regions were suggested by the Inter-American Development Bank (IDB), based on their respective NCRE integration plans. In aggregate, they accounted for an installed capacity of 235 GW by the end of 2012, which represents 93% of the installed capacity in Latin America, which is 253 GW.

Chart 1 – Features of countries and/or regions analyzed as of 12/31/12 (source IDB)

Country	Installed capacity [GW]	Share (% GW)			Official goal for new renewables
		Hydro power	Wind	Bio-energy	
Uruguay	2.7	56.8%	1.6%	9.3%	25% in 2015
Mexico	62	18.5%	2.2%	0.8%	35% non-fossil generation by 2024
Chile	17.5	34%	1.1%	1.9%	20% new renewables by 2025
Central America	12	36%	3.2%	6%	There is not any
Colombia	14.5	63%	0.1%	1.8%	3,5% by 2015 and 6,5% by 2020.
Brazil	132	64%	1.9%	8%	There is not any

The IDB provided valuable contacts[19] to the consultant to carry on short telephone interviews for a better understanding of current planning procedures, tools used and, above all, improvement needs in each country. These experts were contacted by the consultant and played a critical role in the following analyses. By all means, the consultant is entirely responsible for any error or inaccuracy in these analyses.

7.2 Details on selected experiences

7.2.1 Mexico

The generation installed capacity in the National Electric System (*SEN or Sistema Eléctrico Nacional*) in Mexico is mainly thermal, supplying demand through the use of liquefied fuel, coal and natural gas. Renewable energy has a 24% share (mainly hydro).

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[19] Virginia Echinope (Uruguay Ministry of Industry, Energy and Mining), José María Valenzuela (Mexico Secretariat of Energy), Carlos Barría (Chile Ministry of Mining and Energy), Javier Orozco (Costa Rican Institute of Electricity), Henry Josué Zapata (Energy and Mining Planning Unit of Colombia), Luiz Barroso (PSR, Brazil).

The development of energy sources originated from renewable resources has been labeled as a priority in Mexico, with the objective of diversifying its energy mix, currently depending on thermal generation of fossil fuel. Mexico wants to increase the share of renewable generation from the current 24% to a 35% by 2024. To this end, they have already initiated actions by developing a regulatory frame that seeks to reduce barriers and minimize costs in order to make these types of technologies economically competitive versus traditional options. To achieve this goal, there is an important instrument which is the "Law for the Use of Renewable Energy and Financing of Energy Transition" (*Ley para el aprovechamiento de energías renovables y el financiamiento de la transición energética*) of November, 2008 ("*LAERFTE*"), which defines several mechanisms to promote the development of renewable resources and efficient co-generation, for voltages up to 20 MW. As provided by the LAERFTE, the Secretariat of Energy (*SENER*) annually develops a Special Program for the Use of Renewable Energy. This program is the tool that defines public policies in this field, setting objectives for the use of said energy sources, and the actions required to achieve them.

Several studies indicate that Mexico has great potential to generate energy through renewable sources due to its high levels of solar exposure, its hydro resources suitable for the installation of mini-hydro and conventional hydro plants, its steam and water suitable for the development of geothermal fields, and its areas with intense and constant prevailing winds. Particularly, the wind patterns of the Southern region of the country are compatible with hydro generation.

In addition to these initiatives, the government also seeks to promote the installation of new base generation capacity, which implies that Mexico's future energy mix must evolve to a combination of new renewables with thermal and hydro power generation.

The *Comisión Federal de Electricidad* (Federal Electricity Commission - *CFE*) is responsible for creating the *Plan de Expansión de Generación de México* (Mexico Generation Expansion Plan) aimed at supplying the demand corresponding to Public Service. The supply of industry demand through local and/or remote self-supply is decided by the permit holders themselves, thus, it is not part of the Expansion Plan prepared by CFE. CFE annually publishes the document entitled *Programa de Obras e Inversiones del Sector Eléctrico* (Works and Investment Program of the Electricity Sector- *POISE*) which summarizes the outcomes of its studies on integral planning of the electricity system of the country.

Based on Article 36 *bis* of the Electricity Public Service Act (*Ley del Servicio Público de Energía Eléctrica* - *LSPEE*), the planning of the CFE electricity system is made in a "*determinative*" way by seizing the best energy investment and production options, both for short and long terms, that may enable satisfying future electricity demand with minimum global costs, and meeting an adequate level of reliability and quality. This results in a *mathematical formulation* with the objective of minimizing total updated investment, operating and failure costs. To this end, the investment, operating and non-supplied energy costs are considered, together with the provisions contained in the LAERFTE and its associated Rules, energy policy guidelines, and national regulations on financial, environmental and social matters.

The POISE is based on fuel prices and the country's macroeconomic scenarios prepared each year by the SENER, and it considers a planning timeframe of 15 years

(National Energy Strategy timeframe). The electric sector planning is performed based on the energy policy guidelines. The figure below shows the information flow for preparing the POISE.

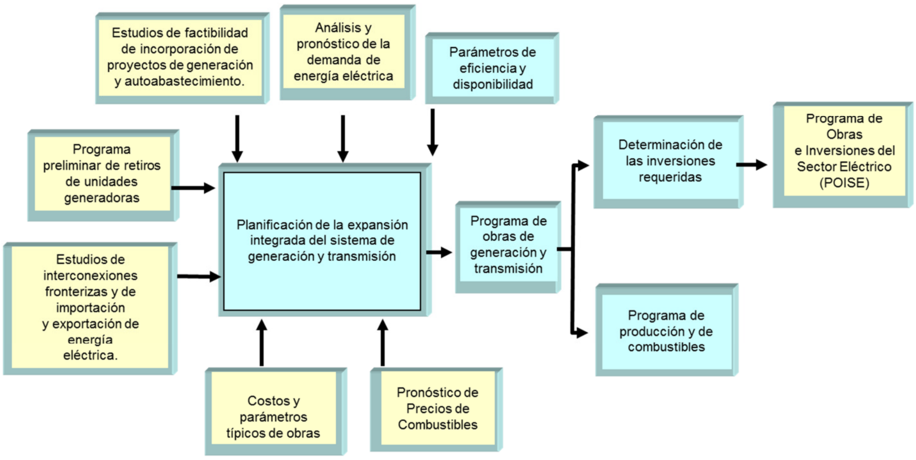

Figure 23. POISE preparation process (source: SENER)

Figure key:

Estudios de factibilidad de incorporación de proyectos de generación y autoabastecimiento	Feasibility studies on the incorporation of generation and self-supply projects
Programa preliminar de retiros de unidades generadoras	Preliminary program for generating unit removals
Estudios de interconexiones fronterizas y de importación y exportación de energía eléctrica	Studies of border interconnections and electricity imports and exports
Análisis y pronóstico de la demanda de energía eléctrica	Analysis and forecast of electricity demand
Planificación de la expansión integrada del sistema de generación y transmisión	Planning of the integrated expansion of the generation and transmission system
Costos y parámetros típicos de obras	Typical costs and parameters of works
Parámetros de eficiencia y responsabilidad	Efficiency and responsibility parameters
Programa de obras de generación y transmisión	Generation and transmission works program
Pronóstico de precios de combustibles	Fuel prices forecast
Determinación de las inversiones requeridas	Definition of required investments
Programa de producción y de combustibles	Output and fuels program
Programa de Obras e Inversiones del Sector Eléctrico - POISE	Works and Investment Program for the Electricity Sector

The planning process takes the minimization of total costs as a metric, considering reliability criteria (loss of lead probability and non-supplied energy), and it is based on a set of computer tools. The figure below shows the whole set of tools used:

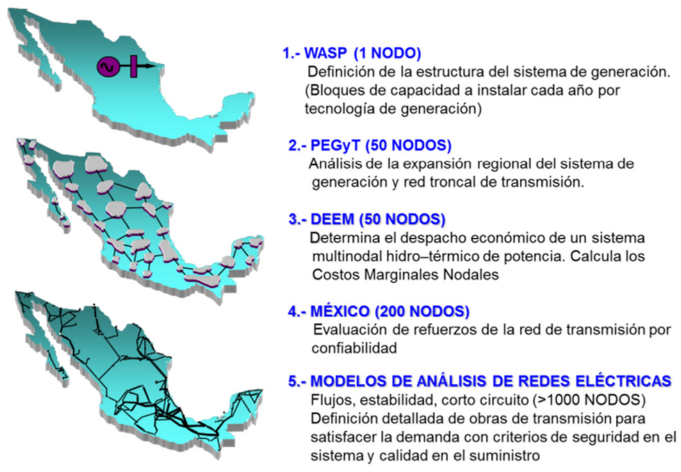

Figure 24. Tools used in Mexico (source: SENER)

Figure key:

1.- WASP (1 NODO) Definición de la estructura del sistema de generación. (Bloques de capacidad a instalar cada año por tecnología de generación)	1.- WASP (1 NODE) Generation system structure definition. (Capacity blocks to be installed yearly by generation technology)
2.- PEGyT (50 NODOS) Análisis de la expansión regional del sistema de generación y red troncal de transmisión.	2.- PGEyT (50 NODES) Analysis of regional expansion of the generation system and the main transmission network.
3.- DEEM (50 NODOS) Determina el despacho económico de un sistema multinodal hidro-térmico de potencia. Calcula los Costos Marginales Nodales.	3.- DEEM (50 NODES) Defines the economic dispatch of a multi-nodal hydrothermal voltage system. It calculates Margin Nodal Costs.
4.- MÉXICO (200 NODOS) Evaluación de refuerzos de la red de transmisión por confiabilidad.	4.- MEXICO (200 NODES) Assessment of reinforcements in the transmission network for reliability purposes.
5.- MODELOS DE ANÁLISIS DE REDES ELÉCTRICAS Flujos, estabilidad, corto circuito (>1000 nodos). Definición detallada de obras de transmisión para satisfacer la demanda con criterios de seguridad en el sistema y calidad en el suministro.	5.- ELECTRICITY NETWORK ANALYSIS MODELS Flows, stability, short circuit (>1000 nodes). Detailed definition of transmission works to satisfy demand implementing system reliability and supply quality criteria.

The WASP tool is used for planning and defining the optimum expansion mix. WASP is used in quarterly stages for a 15-year timeframe. With the objective of making operational and reliability analyses more detailed, a combination of tools developed in Mexico by the CFE and universities is used. The features of these tools are the following:

- The PEGyT tool is used for defining regional plans for expanding the generation capacity and the main transmission network, in order to satisfy forecasted demand in a reliable way and at minimum costs, within a long-term timeframe (up to 30 years).The electricity system is represented through 50 inter-connected regions. The solution method used is Benders' mixed integer deterministic linear programming with decomposition;

- The DEEM (*Despacho Económico Estocástico Multinodal* - Multi-nodal Stochastic Economic Dispatch) tool defines the economic dispatch of a multi-nodal hydrothermal voltage system. It considers a linear approach for the representation of the transmission network. For the national electricity system representation, it considers monthly demand curves divided in five steps, where the first one represents the system peak demand and the next ones, intermediate and base demands. This model calculates the Margin Nodal Costs for the Main System contemplating the random aspects of thermal and hydro power generation (flow-of-river plants, with monthly and annual regulation), using the Monte Carlo method to simulate the randomness of variables, and linear programming to solve the economic dispatch issue;

- The MEXICO tool defines the joint reliability of the generation and transmission of the electricity system, analyzing combinations of failure conditions on generation units and transmission lines;

The challenges faced by CFE and SENER in conducting planning in an environment with strong penetration of renewables lie in their capacity to develop a better and more detailed representation of the short-term operating dynamic (meeting demand on hourly time ranges). With the penetration of new renewables and gas-fired thermal generation, it will be essential to represent the interactions within the wind-gas-hydro mix (which will also include solar in the future), as well as the short-term dynamics (unit commitment limitations, ramps, load curve, etc.), and the uncertainties associated with hydro power and new renewable generation. These aspects are not represented in the DEEM tool, which works on a monthly time range. SENER is currently exploring (through cooperation agreements) the models which have been developed or are under development by the National Renewable Energy Laboratory (NREL) in the United States.

7.2.2 Uruguay

Uruguay boosts a strong hydro power system with storage capacity which has been essential for ensuring demand supply at minimum costs. Uruguay has an Energy Policy in place that promotes the development of non-conventional renewable energy. Said technologies (especially wind power) are expected to play a prominent role in the expansion of the power system; medium and large-sized hydro power resources in Uruguay are almost completely utilized and are therefore not likely to enable major expansions.

The Government has issued several Executive Orders creating a framework to encourage independent producers to develop generation based on renewable sources (wind, biomass, solar and small hydro power plants). The UTE (*Administración Nacional de Usinas y Transmisiones Eléctricas*), which is the state-owned electricity

company of Uruguay, will acquire energy from these projects -selected through a bidding process- and will charge regulated consumers any surcharges resulting from acquiring energy from the selected projects at the tendered prices.

Natural gas-fired thermal generation is also expected to play a relevant role. Uruguay has three gas pipelines connected to the gas network of Argentina, which may cutoff supply. Uruguay is working on the construction of a liquefied natural gas (LNG) re-gasification plant, which license has already been granted through a 20-year-term agreement and another pending project that contemplates LNG storage and re-gasification (the solution includes a ship for transporting LNG, and the plant's re-gasification capacity is 10 to 15 million m^3/day.

The Ministry of Industry, Energy and Mining (MIEM), among other duties, is responsible for designing and implementing the Government policies related to its energy mix. The *Dirección Nacional de Energía* (DNE) is the unit within the MIEM which is responsible for creating, proposing and coordinating the policies aiming at satisfying domestic energy needs. In this context, the DNE conducts energy planning for the whole country, and especially for the electricity sector.

The plans for generation expansion conducted by the MIEM are only indicative and contemplate the development of wind power, among other options. The metric used in the planning process is the minimization of total system costs, including investment, operation, maintenance, and fuel costs, and it imposes limitations (annual and weekly) on the expected amount of non-supplied energy. These analyses rely on two computer tools:

- The WASP tool is used for planning and establishing the optimum expansion mix. WASP considers quarterly time ranges for a 20-year period;
- The SIMSEE (electricity systems simulator[20]) tool developed by the Electric Engineering Institute of the University of Uruguay is used to simulate the economic dispatch in greater detail, especially representing hydro power and renewable non-conventional generation (misrepresented in WASP). This simulator enables the optimization of the operation of hydro power generation systems on weekly time ranges (which may be scaled up to hourly time ranges) for a timeframe of 20 years. Its solution algorithm is based on stochastic dynamic planning (SDP) with representation of stochasticity in hydro flow rates and also in wind generation.

The challenges faced by MIEM in conducting planning in an environment with strong penetration of renewables lie in its capacity to develop a better and more detailed representation of the short-term operating dynamic (meeting demand on hourly time ranges considering operating reserves available in the system). Representing the interactions within the wind-gas-hydro mix (which will also include solar in the future) is becoming increasingly relevant, especially considering that Uruguay's hydropower potential has been exhausted. For conducting those studies, it will be critical to represent short-term dynamics –non-convex costs, nit commitment restrictions, ramps, load curves, etc.- and the uncertainty associated with hydro generation and NCREs. These aspects are not represented in the SIMSEE tool.

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[20] See the following site for further details: http://iie.fing.edu.uy/simsee/simsee/index.php

On top of this, there is the uncertainty associated with the interconnections with Brazil and Argentina, because depending on their development, the optimum expansion decisions may significantly vary. Hence, apart from the issues previously described, it is necessary to improve the representation of the impact of these interconnections on the models.

The MIEM, through the DNE, is currently analyzing the development processes that other countries with high levels of wind power have gone through. For this purpose, it has commissioned Energinet, the system operator of Denmark, to conduct several studies, and has recently contacted the REN in Portugal, due to the similarities between said system and the Uruguayan –it has a considerable hydro component and great development of wind power, and it is a small-sized system connected to a larger electricity system (Spain).

7.2.3 Chile

Chile has a limited energy resource capacity, and depends mainly on the availability of hydro resources and hydrocarbon imports to meet most of its needs. The natural gas is imported through two LNG re-gasification terminals. There are six gas pipelines running from Argentina, although virtually no volumes have been traded in recent years. The electricity sector in Chile relies basically on two interconnected systems: the *Sistema Interconectado Central* (SIC - Central Interconnected System) – main Chilean electricity system, with 74% of the country's installed capacity and a strong hydro power share, which serves 92% of the country's population – and the *Sistema Interconectado del Norte Grande* (SING - Great North Interconnected System), mainly thermal, which serves major mining and industrial consumers.

Amendments to the Electricity Act between 2004 and 2008 introduced some incentives to generation. In 2008, under Law 20,257, a system establishing mandatory quotas of NCREs was set up, starting with a 5% quota in 2010 and rising gradually to a 10% quota by 2024, which must be met by trader generators. More recently, in October 2013, Law 20,698 introduced further changes to the new renewables regulations in Chile, raising NCREs target to 20% by 2025 and allowing the Ministry of Energy (MdE) to make annual public tenders for the purchase of NCREs so as to ensure compliance with this obligation.

A competitive regulatory framework for the generation market has been in operation in Chile for thirty years. The *Comisión Nacional de Energía* (CNE - National Energy Commission) develops indicative generation plans, mainly used for tariff calculation of nodal prices, which requires system marginal cost projections for the next four years. There is no binding planning for generators or other forms of direct state intervention to ensure supply.

However, the situation is different when it comes to transmission. Every four years, a Committee composed of representatives of the MdE, the CNE, as well as generation, transmission and distribution companies, commissions a study by an independent consultant for the purpose of assessing each section of the main transmission system and defining (in a binding manner) the extensions and expansions for each expected generation expansion scenario. These extensions are tendered. Additionally, based on the results of this study, the *Centros de Despacho Económico de Carga* (CDEC - Economic Load Dispatch Centers) must analyze the consistency between the study results and the actual developments on generation investments and demand evolution.

As a result of this analysis, they must submit a report to the CNE, including their proposals on the works to be undertaken or initiated in the next 12 months to meet demand.

In this context, the planning activities carried out by the Chilean bodies and associated tools can be organized as follows:

- *Expansion planning*: there is no development of a plan for generation expansion on a regular basis, and the planning activities in Chile are focused on transmission and are used for purposes of system reinforcement bidding.

However, the MdE performs its own planning studies, using a set of tools. The tool that has been used is PET (Power Electricity Timetable) – multi-nodal network centralized planning model that seeks to minimize investment and operation costs of the system, leading to an economical operation, along with a work plan for the generation facilities. The MdE is testing OPTGEN[21], a tool developed by PSR in Brazil, which determines the least-costly expansion of a hydrothermal system, representing the system operation in a detailed manner, taking into account the inflow uncertainty, greenhouse gas emission restrictions, and minimum capacity constraints, among others.

Operational planning: there is a wide variety of tools for operational planning. For that purpose, the CDEC-SING uses Plexos, a tool developed by Energy Exemplar. The CDEC-SIC uses PLP and PCP (long and short-term programming models, respectively), tools developed by companies and universities in Chile, as well as SDDP[22], a stochastic hydrothermal dispatch tool developed by PSR, which represents a hydrothermal system and new renewables in detail, and with their associated uncertainty. For its operational studies and nodal pricing reports, the CNE uses OSE 2000, a stochastic hydrothermal dispatch computer model developed by KAS Ingeniería[23]. This model is similar to the PLP model used by the CDEC-SIC. The MdE uses OSE 2000 as well, and has also used SDDP, the stochastic hydrothermal dispatch tool.

In general, we can notice that the presence of two systems in Chile with a different hydrothermal mix has posed different challenges for operation today: the SING, more like a thermal system, has characteristics similar to those of the European countries (really concerned about short-term dynamics), while the SIC, more like a hydro system, has the same characteristics as those of the rest of the Latin American countries (more concerned about the medium-term reservoir management). However, both systems continue looking for solutions focused on representing better and in more detail short-term dynamics – constraints associated with unit commitment, ramp, load curve, etc. – and the uncertainty of hydro power generation and new renewable sources (demand coverage in hourly time ranges). While this dynamic will be more important for the SING, the SIC will also face the same challenges. Due to the size of each system in terms of peak demand (about 2GW for the SING and 7GW for the SIC), the challenges

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[21] www.psr-inc.com

[22] www.psr-inc.com

[23] http://www.kasing.cl/diseno/kas_hacemos_modelo.htm

mentioned above are expected to be seen in the short run, given the high penetration rate of renewable energy expected for the years to come.

In Chile we can also notice a strong interest in a better generation planning that would provide input to produce more robust transmission planning studies.

7.2.4 Colombia

Colombia has a current supply portfolio based on hydro power and thermal generation fired by natural gas and coal. The country still has a significant hydropower potential, and coal and natural gas reserves. The most promising new renewable sources are wind, small hydro plants and biomass.

In Colombia there is no explicit mechanism that provides business support to the new renewable sources. While there are VAT and income tax benefits, the prices of the Wholesale Energy Market are the main mechanisms for attracting new renewable sources. In 2011, the *Comisión de Regulación de Energía y Gas* (CREG - Regulatory Commission for Energy and Gas) defined the methodology for determining the firm energy of wind power plants so that they can participate in the Reliability-based Charge scheme, thus creating another market for that technology.

On the other hand, Colombia has been one of the few countries which has maintained a body responsible for developing planning activities after introducing a reform process in its electricity sector. According to the provisions of the Electricity Act, the *Unidad de Planeación Minero Energética* (UPME - Mining and Energy Planning Unit), is responsible for developing – indicatively – the Generation Reference Expansion Plan. The UPME is a National Special Administrative Unit, of a technical nature, under the Ministry of Mines and Energy.

For the purpose of developing the reference expansion plan, the UPME uses the following computer tools developed by PSR when performing its analyses:

- OPTGEN is the tool used for planning and determining the optimal expansion mix. OPTGEN is an expansion optimization model which, from a set of candidate projects, determines the plan with the least overall cost (sum of investment costs plus the expected value of operating costs). OPTGEN adopts a solution method known as Benders decomposition, where the least overall cost function is built from the iterative solution of an approach to the expansion and operational problem. This process is quite flexible and enables the incorporation of computer models with different levels of detail[24] and different solution strategies, such as the cases with multiple dispatch scenarios and models based on stochastic optimization.

- Once the generation expansion plan is known, the hydrothermal dispatch tool MPODE[25] (SDDP, as it is known in Colombia) is used to simulate the economic dispatch in more detail, particularly representing the hydropower and non-conventional renewable generation, and to estimate the supply reliability rates. This

[24] Virtually, the only requirement needed is that the optimization tool uses continuous decision variables and that it can produce the marginal benefit vectors.

[25] *Modelo de Planificación Optima del Despacho Energético* (Energy Dispatch Optimal Planning Model).

tool enables the optimization of the operation of hydropower systems for electric power generation on weekly time ranges for a 20-year timeframe. Its solution algorithm is based on stochastic dynamic programming with representation of stochasticity both in hydro flow-rates and wind output. The tool has been used for several years in Colombia, both by market players and the System Operator (XM).

The challenges of planning for new renewable sources integration in Colombia are the same as those observed in other countries: representation of a greater granularity in the time ranges of the optimization models and relevant aspects to represent hourly demand coverage, in addition to the uncertainty associated with hydro plants and new renewable sources output. Given the gas reserves present in Colombia, another important aspect is the integrated representation of natural gas and electricity networks. A thermal power plant located in the "wellhead" requires reinforcements in the electricity network, as it is distant from the main load centers, and -the other way around- a plant located close to these centers requires investments in the gas pipeline network. This interaction between the gas and electricity sectors suggests that an integrated planning of these networks can lead to more economical solutions for consumers of both sectors.

Colombia continues to seek solutions to these challenges and to improve its planning practices. The UPME has shown interest in continuing with its current tools, focusing on refining them together with their developer.

7.2.1 Central America

Central America is a region with a strong hydro power share, where wind power has played an increasing role and where gas generation is also expected to play an important role through LNG. There is no uniform support scheme for new renewable sources among the different countries, but each of them has used its own mechanism to promote them, where auctions and tax benefits have played an important role in the development of these sources.

The region has a strong regional and integrated planning tradition. The *Consejo de Electrificación de América Central* (CEAC - Central American Electrification Council) – composed of the INDE (Guatemala), ENEE (Honduras), CEL (El Salvador), ENATREL (Nicaragua), ICE (Costa Rica), ETESA (Panamá) – is responsible, within its scope of activities, for the organization of the Regional Indicative Planning Working Group (GTPIR).

The GTPIR is composed of planners of each of the six electric utilities and energy ministries, and it operates as a technical committee under the CEAC, with the aim of developing regional indicative generation expansion plans, taking into account the effect of current and future interconnections. The GTPIR has undertaken the following activities:

- Analysis of the current situation of generation expansion planning.
- Defining the methodologies and criteria for regional planning.
- Creating and updating a regional database for generation expansion planning.
- Preparing indicative expansion plans.

Within these activities, the GTPIR creates the Regional Indicative Generation Expansion Plan with the aim of designing optimal expansion plans for power generation in Central American countries, through the analysis of various alternatives, taking into consideration the most relevant future scenarios. The latest plan available shows the findings from a follow-up study and update of the regional indicative plans, which in this occasion cover the 2012-2027 period.

To get the least-costly expansion plan, OPTGEN (a tool developed by PSR) is used. Then, Stochastic Dual Dynamic Programming (SDDP), a tool also developed by PSR, is used to simulate the system operation in detail for each of the plans derived from OPTGEN. Dispatch simulation is used both to validate the reliability criterion and to obtain the technical and economic parameters of the dispatch included in the analysis of results obtained for each plan. These two models are used by the GTPIR, as well as by all bodies within each country in the development of their own planning activities.

An important output of the GTPIR is the creation of an integrated database of each CEAC member state. Each of the companies develops its respective databases in SDDP with the aim of determining their indicative generation expansion plans. This database is very detailed and includes the following information:

- Characteristics of current and future generation facilities.
- Demand projection. Moderate scenario.
- Historical basis of flow rates of existing and future candidate hydro plants.
- Fuel cost forecast.
- Generation projects catalog.

The database – which is marketed as a product[26] – is really important and critical for the development of integrated planning activities in the region and improvement tests on current or new tools.

The challenges of planning for new renewable sources integration in Central America are the same as those observed in other countries: representation of a greater granularity in the time ranges of the optimization models and relevant aspects to represent hourly demand coverage, in addition to the uncertainty associated to hydro plants and new renewable sources output. The GTPIR continues to seek solutions to these challenges and, like Colombia, has shown interest in continuing with their current tools, focusing on refining them in terms of representation of the aspects required together with their developer.

7.2.2 Brazil

Brazil relies predominantly on hydropower, supplemented by natural gas, coal and nuclear thermal plants. The hydro power share is 75% of the installed capacity. Most of the more than 200 hydro plants in Brazil have large reservoirs of multiannual regularization, located in cascade along the same river basin. The main new renewable sources in the country are wind power, co-generation of sugarcane biomass and mini

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[26] Refer to http://www.ceaconline.org/documentos/Propuesta_de_Venta__BD_GTPIR.pdf

hydro plants. Brazil still has a significant hydropower potential, and gas and coal reserves. Energy auctions have been the primary mechanism for the integration of new renewable sources and, over the past 5 years, Brazil has purchased more than 11,000 MW of wind, biomass and mini hydro power which will begin to operate until 2016.

In Brazil, there is free competition in the generation sector, but this is not the case in the transmission sector. Therefore, the planning studies are indicative in terms of generation, and they are determinant in terms of transmission. The country has a strong planning tradition; the *Empresa de Pesquisa Energética* (EPE - Energy Research Company), created in 2004, is the body in charge of the planning activities, which purpose is to provide technical support to the Ministry of Mines and Energy (MME) for energy planning studies. The Figure below shows the information/decision flow of the planning process in Brazil.

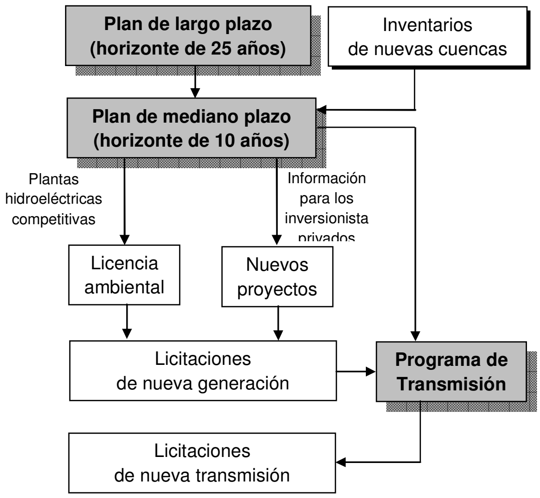

Figure 25 – Planning process

Figure key:

Plan de largo plazo (horizonte de 25 años)	Long-term plan (25-year timeframe)
Inventarios de nuevas cuencas	Inventories of new basins
Plan de mediano plazo (horizonte de 10 años)	Medium-term plan (10-year timeframe)
Plantas hidroeléctricas competitivas	Competitive hydro plants
Información para los inversionistas privados	Information for private investors
Licencia ambiental	Environmental permit
Nuevos proyectos	New projects
Licitaciones de nueva generación	New generation bidding
Programa de transmisión	Transmission program
Licitaciones de nueva transmisión	New transmission bidding

The first study is the Long-Term Plan with a 25-year timeframe. The purpose of this plan is to create a strategic vision for energy development options in the country: resources, new technologies, international situation, etc. The second study is the Ten-Year Generation-Transmission Plan which, as the name suggests, has a 10-year timeframe. The main input data for the Ten-Year Plan are the long-term study results,

used as "guiding principles", and the results of inventory studies of new hydrographic basins, from which the features of the candidate hydro projects are obtained. The main result of the Ten-Year Plan is an (indicative) schedule for incorporating new generation and new transmission reinforcements. The third type of study is the Transmission Expansion Program (PET). The PET has a 5-year timeframe, and includes the detailed studies of the circuits to be placed for bidding. The input data for PET studies are the Ten-Year Plan and the information on what plants won the bidding for new generation (so that the required transmission reinforcements can be built).

The EPE and MME use the computer tools developed by CEPEL (*Centro de Pesquisas em Energia Elétrica*), a government-owned electric power research center.

To get the least-costly expansion plan, MELP, a tool with similar functions to those of the WASP model, is used. Then, NEWAVE is the tool used to simulate the operation of the system in detail for each of the plans derived from MELP. NEWAVE is a long-term stochastic hydrothermal dispatch model with monthly time ranges, which represents the hydropower system through equivalent subsystems, i.e., creating aggregate reservoirs which represent the individualized hydro system in an “energetically equivalent” manner. The tool is stochastic in terms of the equivalent system representation of flow rates, and it is deterministic in terms of all other parameters. The aggregate representation of reservoirs in NEWAVE already represents a significant disadvantage compared to the tools used by other countries.

The challenges of planning for new renewable sources integration in Brazil are the same as those observed in other countries. Given the nature of its current generation system – hydro plants with a great storage capacity –, representation of a higher granularity in the time ranges of the optimization models and of relevant aspects to represent hourly demand coverage, have not been urgent issues. Nevertheless, the rapid wind power penetration and major integration of large-scale hydro plants without storage capacity will make these issues critical. The EPE and MME are looking to refine the current tools together with the CEPEL.

7.3 Summary

The table below summarizes the tools used by each country or region analyzed, as well as their needs and actions.

Table 2 – Summary of the tools used, needs and actions

Country	Body responsible for planning	Planning tool (developer)	Economic dispatch tool (developer)	Tools requirements to represent new renewable sources	Ongoing actions
Uruguay	Ministry of Industry, Energy and Mining	WASP (IAEA)	SIMSEE (local university)		Contacts with the system operators in Portugal and Denmark
Mexico	Secretariat of Energy and Federal Electricity Commission	WASP (IAEA)	DEEM (local university)	Representing short-term operation dynamic (hourly demand coverage), including unit commitment constraints, ramps, load curve, and the uncertainty of hydro power generation and new renewable sources	Contacts with the NREL, USA
Chile	Ministry of Mines and Energy	PET and OPTGEN (PSR)	Great variety: SDDP (PSR), Plexos (Energy Exemplar), OSE 2000 (Kas Ingeniería), PLP and PDP (companies and universities)		Requests to developers of current tools
Central America	CEAC GTPIR	OPTGEN (PSR)	SDDP (PSR)		
Colombia	Mining and Energy Planning Unit	OPTGEN (PSR)	SDDP (PSR)		
Brazil	Ministry of Energy and Energy Research Company	MELP (CEPEL)	NEWAVE (CEPEL)		

8 CONCLUSIONS AND RECOMMENDATIONS

With the penetration of new non-conventional renewable sources and gas thermal generation, the representation of the interaction between the wind and solar mix and the existing hydropower and thermal generation mix has become significantly complicated. In the Latin American region, the challenges faced by the countries when undertaking planning initiatives in a context of great penetration of renewable sources mainly lie in being able to better and more thoroughly represent the short-term operation dynamics (greater temporal granularity and better representation of thermal plant non-convex costs and restrictions), on the one hand, and the uncertainty associated with hydraulic resource management and the individual renewable resources (shorter-term), on the other hand.

Since Latin American power systems have a great hydropower component capable of being regulated (reservoirs), it has not been necessary to consider a better short-term representation of the operation issue up to date. However, due to the fast penetration of wind power and the more than likely development of PV solar generation, alongside the fact that most new hydropower plants cannot be regulated, we may already anticipate the need to make progress toward the development of these tools in order to incorporate the aspects listed in the above paragraph.

Research on these issues is still under development at global level, and we are still far from having a tool capable of considering all the relevant variables in an integrated manner. In the case of Latin America, apart from a good representation of the new NCREs, it will be important to adequately represent the uncertainty and correlation existing between the output of NCREs and that of conventional renewables (hydropower), and, most importantly, to properly represent hydropower generation, which is the prevailing energy source in the region.

The IDB can play a relevant role in promoting the development of the existing tools, by supporting the implementation of new functionalities in those tools. It is worth remembering that IDB was responsible for the development of the first integrated planning tool with a detailed representation of uncertainties and hydro generation in the early 90s (SUPER/OLADE/BID System, MODPIN model).

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- CEPEL (MELP and NEWAVE model): www.cepel.br