Calculation of adequacy indices for interconnected Spanish electric systems in presence of RES, hydro and pump units

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***Abstract*— This article presents the recent developments in the methodology for the calculation of LOLE and EDNS in the Spanish electrical systems; these solutions can be directly applied or easily adapted to fit any other system as well. Starting from an existing probabilistic methodology, a new tool was created to address not only thermal power units but to include new features such as renewable generation technologies, higher degree of interconnections, and pumped hydro storage. Several areas of improvement have been identified and addressed.**

A recursive algorithm to treat the mutual support among interconnected systems is developed; stochastic contribution of wind power and other RES is added or improved; pump storage hydro units are considered, thanks to an optimization of the hydro resources; conventional hydro is modelled based on the historical availability of primary resource.

***Index Terms*— Loss Of Load Expectation (LOLE), Expected Demand Not Supplied (EDNS), Renewable Energy Sources (RES), generation adequacy, generation planning, security of supply, Monte Carlo analysis**

I. Introduction

IN Spain, as in most European countries, the development of renewable energies in electricity generation is of utmost importance in order to meet the EU renewable energy targets and reduce external dependency, among other benefits of RES. Particularly, in the seven systems of the Canary Islands, high solar and wind resources allow for a large development of both technologies, and very large penetrations are expected in the medium term. Further development of RES is also foreseen in the mainland Spanish system, as well as in the three main electrical systems of the Balearic Islands.

Large scale integration of stochastic wind production requires additional balancing generators capable of ensuring a safe operation of the system; pump storage hydro units are planned in some of the Canary systems, as well as in the mainland. Hence, detailed pump storage hydro modelling has been developed.

Additionally, the high variable costs of isolated systems, which typically run on heavy oil, gas oil or coal, in steam or open cycle turbines, suggest the need of new interconnections between neighbouring systems. In fact, more than two neighbouring systems are expected to be interconnected soon in the Canary and the Balearic Islands. In these extra peninsular systems, as well as in the autonomous towns of Ceuta and Melilla, the system operator REE[1] must assess system adequacy and suggest the additional back-up power ensuring system security [1], [2]. Therefore, a thorough analysis of adequacy in N interconnected systems has been done and implemented in the model for the case of N=4 systems.

Finally, REE is performing adequacy studies at European level in the context of ENTSO-E's Ten Year Network Development Plan [3], which aims at designing a safe, efficient and sustainable European system. In order to use the former Loss Of Load Application (LOLA) tool [4] for the continental Spain, its complex hydro system has been implemented in an improved new version of the software, named iLOLA.

The following sections explain the modelling of each of the new elements that need to be considered for the medium and long term adequacy studies performed by REE.

II. Previous work for the calculation of LOLE

A. *Summary of REE's model LOLA*

The Loss Of Load Application (LOLA) was in-house developed by REE back in 2007, in order to address the TSO needs to obtain the probabilistic system adequacy indices [5] LOLE and EDNS in Spain's extra-peninsular systems. The hourly LOLE index quantifies the probability that in an hour the demand cannot be met with the available generation. The available generation is obtained by performing the convolution of all the thermal power availability functions, which are built taking into account historical Forced Outage Rates (FOR) for each unit and the expected maintenance periods. An example result of this calculation is shown in *Fig. 1.*

[1] Red Eléctrica de España (REE) is the Transmission System Operator of the Spanish electric systems, including the mainland continental system and the extrapeninsular systems (The Balearic and the Canary Islands, and the autonomous towns of Ceuta and Melilla).

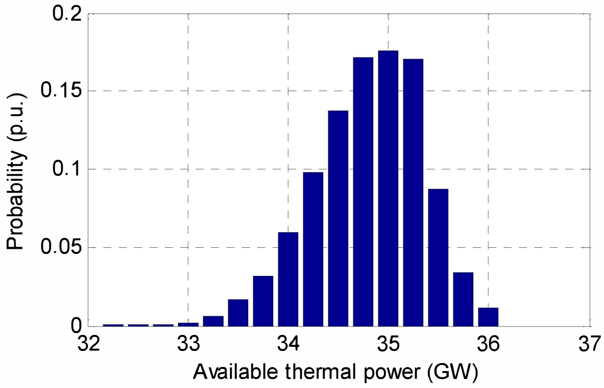


Fig.1 Thermal power availability function of the Spanish peninsular system

Computation time grows exponentially with the number of thermal groups when performing the convolution using a Full Combinatorial Analysis. In order to reduce this time, several alternative approaches were developed, including a novel Limited Combinatorial Analysis (an automatic selection of the significant combinations of units failed/not failed), and a Monte Carlo Analysis.

For conventional generators that only have two possible states ON/OFF, the Monte Carlo method [6], [7], [8], [9] produces random combinations of the available units, following the expression $S_i^n = IF(random > FOR_i; 1; 0)$ where *i* represents each unit in the system, *n* the number of the sample, and *S* is the state of the unit, 1 for available and 0 for failed.

Given that the probability of occurrence of every combination is $p(s) = \frac{1}{number\ of\ samples}$, an estimation of the LOLE can be obtained drawing many random samples for each hour and adding up the probabilities in the case that available power is lower than the hourly demand. When using 100,000 samples per hour, and repeating the calculations for every hour of the year, the variability in the LOLE was empirically found to be below 0.01 h/month, meeting the needed accuracy. LOLE variability for 10,000 hourly samples was found to be below 0.02 h/month, which slightly reduces accuracy but allows a faster computation time in large systems, below 20 minutes in the case of the Spanish peninsular system.

Given that some Spanish extra-peninsular systems are interconnected, a methodology was developed to model their probabilistic mutual support. The solution adopted studied only two systems simultaneously, performing their combinatorial analysis considering the power surplus or deficit available or needed, respectively, in each random sample. Transmission capability of the interconnector is considered. The results are presented per system, and for the interconnected system.

In the LOLE estimation process, additional indexes are also calculated (Expected Demand not Supplied, Loss of Reserve Expectation, Expected Reserve not Supplied, Available Power distribution functions) and graphed.

B. *New needs*

The context in the extra-peninsular systems is growing more complex, with renewable energies quickly developing (wind turbines, PV solar), hydro pump units, and a growing number of interconnections among the systems. A simplified approach to this new reality was not possible using the existing version of LOLA, and there was an urgent need to tackle the adequacy analysis in presence of all the new elements. Some different approaches to the problem of modelling wind, hydrothermal and other energy sources were found in the literature [10], [11], [12], [13], but a precise adaptation to the Spanish systems was necessary.

III. MODELLING OF NEW ELEMENTS

A. *Stochastic contribution of wind power*

In order to obtain an hourly probability function of the total available generation in a system, wind power availability must be modelled. All available historical data of several years were used, each system having its own records. The wind power availability refers to actual wind production in percentage terms of the installed wind power.

Although technically possible, it is not practical and it would not be statistically significant to consider different wind power probability functions for each hour of the year. On the other hand, it would be inaccurate to consider a unique probability function covering all the hours of the year: wind power availability differs in summer and winter, as it can be seen in *Fig. 2*, or in the daytime and the night.

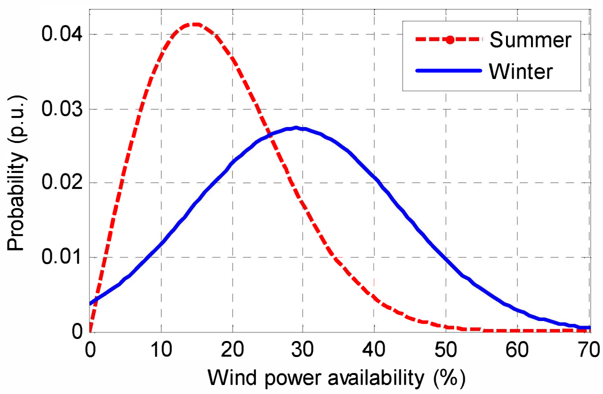


Fig. 2. Wind power availability in summer and winter

The solution adopted by REE divides the year in *n* periods, each one with its own probability function of wind power availability. The number of periods *n* is an input of the application, and practical results have shown that dividing the year in 6 periods is most reasonable. Using the historical data, each hour of the year is assigned to its corresponding period based on similarity patterns referred to the mean available power. This automatic assignation can be nevertheless overruled by the user. An example of the results can be seen in *Fig. 3.*

Month	Hour 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
2	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4
3	6	6	5	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6
4	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	3
5	2	2	2	2	2	2	2	1	1	1	2	2	2	2	3	3	3	3	3	3	2	2	2	2
6	2	2	2	2	2	1	1	1	1	1	1	1	1	1	2	2	2	3	3	3	3	3	2	2
7	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	3	2	2	2	2
8	3	3	2	2	2	2	2	1	1	1	1	2	2	2	2	3	3	3	4	4	4	3	3	3
9	2	2	2	2	2	2	1	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	3	2
10	3	3	3	3	3	3	3	3	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
11	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5
12	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

Fig. 3. Wind periods for the Spanish peninsular system.

Probability functions for each period are created from the available data of all hours that belong to such period, and sampled afterwards in the Monte Carlo simulation in order to provide the random contributions of wind power, which will then be added to the previously sampled combination of thermal generators.

B. Stochastic contribution of other RES

The following technologies could be included in this category: mini hydro, cogeneration, photovoltaic solar power, thermal solar power, industrial urban waste, etc.

Estimated hourly production time series must be generated beforehand with the average hourly RES power availability and its standard deviation.

The hourly probability functions of the other RES are then fitted to a normal distribution, and samples are generated following such distribution. This sampled value is then added up in the process of calculation of available power.

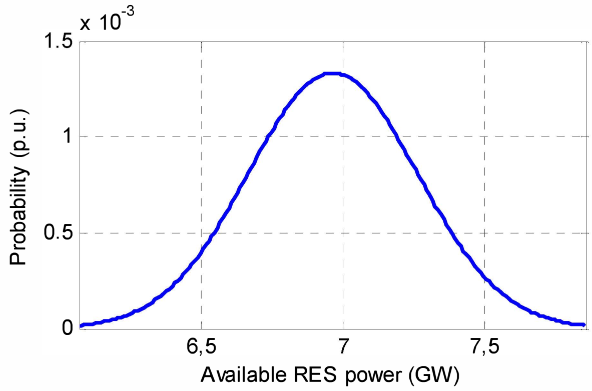


Fig. 4. Other RES availability function for a sample hour of the year: μ=7 GW and σ=3%.

C. Pump storage hydro units

Pump storage hydro units are manageable resources of energy that can be used to balance supply and demand. These units can store energy by pumping water to the upper reservoirs in the off-peak hours and produce energy in the peak hours using the water previously stored.

Given this behaviour, the Monte Carlo methodology with decoupled hourly calculations is not applicable for this analysis. A new methodology that allows optimizing the water reservoirs across different hours of the same day had to be implemented. This algorithm, graphically shown in *Fig. 5*, is executed in two different steps. For each sample of thermal, wind and other RES:

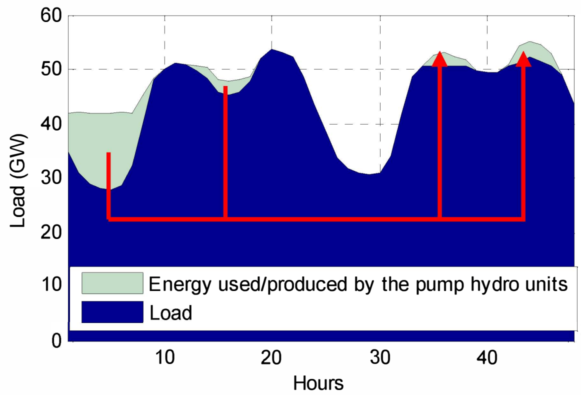


Fig. 5. Pump storage hydro units methodology.

1. The excess of available power on the previous day has to be analyzed to estimate the amount of water that can be pumped to the upper reservoirs on a certain D-1 day (hours 1 to 24). The constraints of reservoir capacity, maximum pumping power and efficiency of the pumping cycle are respected.
2. Once the algorithm has calculated the amount of water available in the reservoir, this water is used throughout the D day (hours 25 to 48) applying the maximum reliability principle. This principle minimizes the total daily LOLE, distributing the available energy across the day in order to flatten the net load curve.

D. Conventional hydro

Conventional hydro is a very important technology in the Spanish peninsular system, representing 12% of the total installed power in 2012. Consequently the modelling of this technology becomes critical. After a review of the literature on adequacy indices and generation planning no adequate methodology was found for the Spanish hydro system and a novel methodology had to be developed.

As for wind power, hydro power has an important seasonal component and an additional stochastic component within each season depending on the humidity of the year. Therefore a stochastic treatment had to be implemented to cover all the possibilities of hydro power availability.

Using several years of historical data of maximum daily power that can be maintained for four hours –such information is provided daily by hydro energy producers–, probability functions are created for each month. In *Fig. 6,* hydro power availability functions fitted from historical data are represented for two different months. It can be seen that there is a big difference across different months. Also, in the same month, the effect of dry years and normal ones is significant.

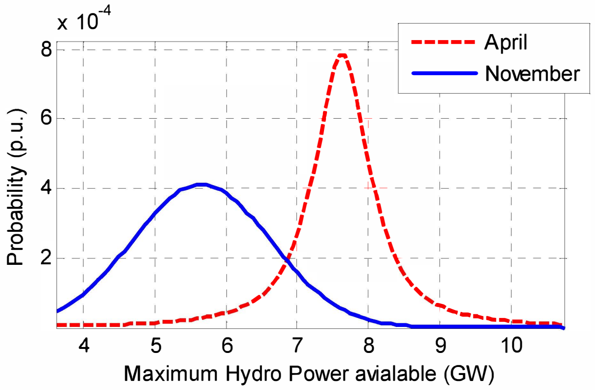


Fig. 6. Hydro power probability functions obtained from historical data of the Spanish peninsular system.

The methodology developed treats each day separately, generating samples that follow the hydro power availability functions. Two different methodologies were developed to allocate across the day the power obtained by the Monte Carlo methodology:

1. Optimistic approach: it uses this maximum power all day long. Although such a power can in fact only be maintained during 4 hours, it is assumed that the rest of the hours will not contribute significantly to the LOLE index.
2. Pessimistic approach: the amount of hydro energy available that can be used each day is limited to four times the value of hydro power sampled. This energy is then optimised during the day of analysis applying the maximum reliability principle to the demand not covered by thermal, wind power and the other RES power.

As LOLE can be either underestimated or overestimated depending on the selected methodology, sensitivity studies have been made in order to validate the most suitable methodology for the Spanish case. *Fig. 7* and *Fig.8* show for a given week the differences of hourly LOLE obtained with both methodologies applied to the Spanish system.

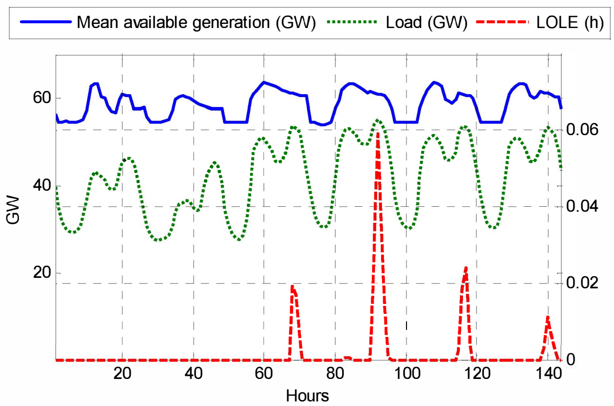


Fig. 7. LOLE results using the optimistic hydro power methodology.

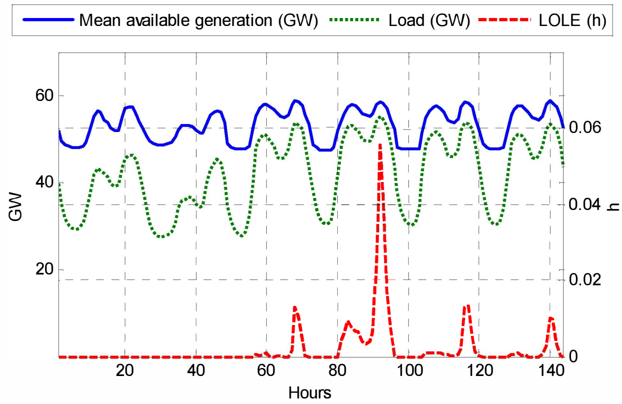


Fig. 8. LOLE results using the pessimistic hydro power methodology.

As it can be observed in both figures, the main contribution to LOLE is concentrated in the hours of peak load. The difference between both methodologies lies in the hours around the peaks and/or the morning hump of the load. The optimistic approach doesn't show any LOLE in these hours – hydro power is available all day–, while the pessimistic does show some, because of the lower availability of hydro power outside of the peak hours. Despite the low differences between methods, the pessimistic approach is considered optimal to perform adequacy studies.

E. Multiple interconnections

Nowadays, most systems, especially those isolated or not reaching the 10% interconnection capacity with neighbouring systems [14], are designed to face every possible contingency without any major help from the surrounding systems. However, the mutual support between systems is of utmost importance, especially in the context of a truly integrated European electricity system. Hence, a method to treat this mutual support has to be incorporated to the model.

In previous versions of the LOLA model, this problem was solved only for two interconnected systems, using a simple algorithm based on the idea that if one of the systems needs generation support, and the other system has excess available power, support is provided with the constraint of the maximum capacity of the interconnection.

However, this algorithm was incomplete to deal with the increasing number of interconnections among the Spanish peninsular and insular systems, specially the Balearic Islands, which will be mutually interconnected and linked to the mainland. Furthermore, the mainland is already interconnected with three other systems: Portugal, France and Morocco.

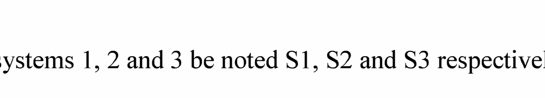
As the number of interconnected systems grows, the complexity increases exponentially, as there is more than one single way to provide and model the mutual support. For instance, in the unlikely event that several systems lack generation at the same time, a potential surplus from other neighbouring systems will have to be shared. In practice, these situations of multiple deficits are so unlikely, that more in-depth approach to the problem would not improve LOLE results significantly. Therefore, rather than performing a time-consuming calculation that complies with an additional optimization function (such as to keep an equal share of the EDNS among all systems in deficit, or assign all EDNS only to a selected system), the developed algorithm finds one of the many solutions that minimize the total EDNS.

A generic algorithm capable of calculating the support between N systems was created based on graphs theory. Specifically, the Ford-Fulkerson algorithm [15], [16] was adapted to fit this problem. The result is an iterative algorithm that distributes the excess of generation to the systems in need following the next steps:

1. Each system is studied isolated, trying to meet its load with its own available generation.
2. If any of the systems is not able to meet its load, the algorithm selects the one with the highest monthly LOLE index and looks for interconnections with every other system that has excess of available generation.
3. Power is then transferred from the systems with excess of generation through every possible interconnection proportionally to the capacity of the connection, and limited to their respective maximum capacities.
4. If the system being analyzed still does not cover its demand with the contribution of the other systems, step 3 is repeated until one of the next possibilities happens:
   a. There is no more available interconnection capacity with any of the systems with excess of generation.
   b. There are no more systems with excess of generation.
   c. The demand can be covered with the help of the other systems.
5. If there are still systems in need, and systems with excess of power and free capacity in the interconnections, the algorithm returns to step 2.

Given the nature of the problem, there might be different valid solutions for the same initial configuration, as it was previously stated. The algorithm will always converge to a solution that will minimize the total EDNS, and hence the LOLE of the entire system.

An example of LOLE calculation for three systems is now presented. The difference between available generation and load, as well the capacity of interconnections, both in a given random draw, are depicted:



Let systems 1, 2 and 3 be noted S1, S2 and S3 respectively.

Step 1: S1, S2 have excess generation, no action is required. S3 lacks power supply and there is available capacity in S1, S2 and free transmission capacity in the interconnectors: energy flow is possible in order to reduce the deficit in S3. The power transmitted through each interconnection will be calculated iteratively.

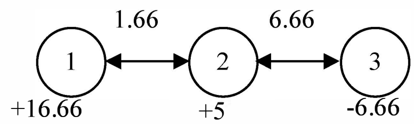
Step 2: There is a free capacity of 10 MW from S2 to S3 and $5\ \mathrm{MW} = \min(5\ \mathrm{MW}, 10\ \mathrm{MW})$ from S1 to S3. S3 requires 10 MW, which are provided by the interconnections proportionally to the capacity of the lines.

From S1 via 1-2-3: $10 \cdot \frac{5}{15} = 3.33\ \mathrm{MW}$,

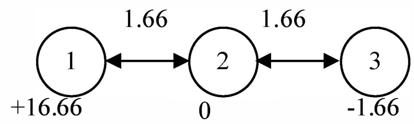
From S2 via 2-3: $10 \cdot \frac{10}{15} = 6.66\ \mathrm{MW}$, but limited to 5 MW.

Step 3: These are the resulting balances and free capacities in the lines (values are in MW):

Step3.1: supply from S1



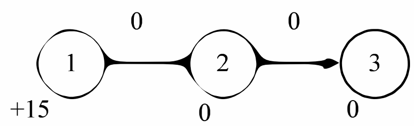
Step3.2: supply from S2. The results after the first iteration are the following:



Step 4: There is still demand to be met in S3. Total free capacity to S3 is now only 1.66 MW via 1-2-3, and support can be given:

From S1 via 1-2-3: $1.66 \cdot \frac{1.66}{1.66} = 1.66\ \mathrm{MW}$

The balance in the nodes and the free interconnection capacity is recalculated.



Step 5: As there is no system with lack of power, the problem is solved and there is no need to iterate.

The apparently intricate logic of the algorithm makes it possible to extend the method to a generic situation with N interconnected systems. The case for N=4 systems was programmed in the iLOLA software, making it possible to study the interconnected systems of Mallorca-Menorca-Ibiza-Mainland. Also, this algorithm allows studying the continental interconnected systems of Morocco-Spain-Portugal-France. The same algorithm can also be used to share a previously defined [17] operational reserve between systems.

IV. Further Work

Several fields remain to be further investigated. The interconnections algorithm could be extended to more than 4 systems if necessary. Economic analysis of the value of transmission capacity in reducing LOLE could be performed using the output of the algorithm. This would imply introducing generation costs data to the model. Additionally, this algorithm could be changed to select another of the multiple equilibrium solutions minimizing the total EDNS that also complies with additional criteria such as an order of preference among systems or a solution that is compliant with operational restrictions.

Another field of improvement is implementing correlations among different variables in the sampling process. For instance, it could be possible to generate correlated samples of combined solar and wind production. Any other correlation between wind, RES productions or demand can be implemented. These potential correlations, however, should be previously analysed.

Also, the operation of the pumped hydro storage plants must be further studied, to implement a more realistic model without the need of a Unit Commitment optimization, which would add accuracy but penalize dramatically the computation time.

Finally, it is possible to further develop and use this probabilistic model to study the best compromise between security of supply, integration of renewable energy sources, and back-up costs.

V. Conclusions

The large scale introduction of renewable energy generation technologies in the Spanish electric systems, and also other non-thermal technologies (such as storage and hydro units, which are gaining weight in some extra-peninsular systems), make it necessary to develop new methodologies to estimate their contribution to security of supply. Also, the development of multiple interconnections between systems has to be properly addressed.

All these challenges were identified, addressed and solved by developing new methodologies and algorithms, successfully implemented in the software iLOLA. Using a Monte Carlo approach, the influence of all these factors is considered in a probabilistic way, and calculation speed is not jeopardized. A novel model was in-house developed and implemented, that takes into account the contribution of large scale RES, the future existence of pumped hydro energy storage plants, and multiple interconnections in different configurations. The methodology also allows including the complex stochastic contribution of large hydro power in the main continental Spanish system with a novel algorithm.

This model has allowed Red Eléctrica de España to overcome the traditional deterministic methodologies and to analyse system adequacy in all the isolated and interconnected systems of the Balearic and the Canary Islands, as well as the interconnected continental system, with a more suitable probabilistic approach. The use of iLOLA -and probabilistic models in general- to calculate adequacy indices, is a key step to analyse security of supply in complex interconnected systems with high RES penetration.

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BIOGRAPHIES

Rubén López was born in Madrid, Spain, in 1979. He studied at the Madrid Polytechnic University, where he graduated in Industrial Engineering and mastered in the area of Energy and Power Stations in 2004.

Mr López has experience in the development of different tools, such as power plant monitoring tools, demand forecasting software, and system adequacy modelling.

He is currently a member of the Network Planning Department of Red Eléctrica de España, where Mr López works in the areas of long-term load demand forecasting and generation capacity planning. He is currently corresponding member in the ENTSO-E group of System Adequacy and Market Modelling, and is partner in several projects with the Portuguese National Grid, related to the development of the Iberian Electricity Market (MIBEL).

Javier Revuelta (b. 1980) received in 2003 the degree in Electrical Engineering from the Universidad Pontificia Comillas -ICAI- of Madrid. He joined in 2004 Red Eléctrica Internacional, subsidiary of the Transmission System Operator of the Spanish electric system REE, and in 2009 the Network Planning department of REE.

His work has been related to system operation tools, generation planning and scheduling, wind integration, and wholesale markets. He has participated in projects in the Maghreb, Central America and Mediterranean countries. He led the market integration studies within ENTSO-E's Ten Year Network Development Plan 2012.

Mr. Revuelta has published 17 articles or presentations in international conferences or magazines, including three articles in IEEE Xplore. He currently studies a full time MBA program at Insead Business School.

Ignacio Cobo was born in Madrid, Spain in 1990. He will receive his master degree on Electrical Engineering from the Universidad Pontificia de Comillas -ICAI- in 2013.

He joined Red Électrica de España in 2012 for a 6 months internship in the Network Planning department. His main contribution was the modelling and technical implementation of the software LOLA. He also participated in RES integration studies, system planning activities, and regulatory proposals.

Mr. Cobo has conducted his graduation project on a novel methodology for short term load forecasting with the collaboration of the IIT of Comillas and the Spanish energy firm Endesa.