A Long-Term Prospective for the Spanish Electricity System

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***Abstract*-- The main objective of this paper is to present the preliminary results obtained within the SUSPLAN EU Project[2], regarding the integration of increasing levels of Renewable Energy Sources (RES) into the future Spanish energy system. Firstly, the optimal expansion of the Spanish electricity generation capacity from 2020 to 2050 is determined for four different storylines. Then, for each one of these storylines, a detailed analysis of the power system operation is performed for the years of 2020 and 2050. Two electricity models are used for that purpose: i) a long term generation expansion model, and ii) a medium-term system operational model. The results obtained showed that a high amount of RES generation could be integrated into the future Spanish power system but this should be accompanied with flexible generation and storage units for ensuring a secure system operation.**

***Index Terms*--Energy prospective, renewable energy sources, power system economics**

I. INTRODUCTION

The current international climate change strategy, added to energy supply security and economic competitiveness goals, has resulted in a binding target of 20% of renewable energy consumption in the EU by 2020[3]. Achieving this objective will demand a future massive penetration of renewable generation in power systems, an increase in final consumer responsiveness to system conditions and a smarter grid operation. The required adaptation process will not end in 2020 but will continue far beyond, especially if we consider future energy projects such as DESERTEC[4] – Solar and Wind Energy from the Deserts in North Africa and the Middle East – or gas supply in Europe coming from North Africa via Spain or Italy.

In this context, the SUSPLAN project - Development of Regional and Pan-European Guidelines for More Efficient Integration of Renewable Energy into Future Infrastructure – attempts to bring solutions for the environmental and energy challenges faced by the European community. Analyses carried out within the project are aimed at increasing the level of integration of renewable energy sources (RES) in the horizon of 2050 in the energy sector within a Europe-wide perspective. The project focuses on developing strategies, recommendations, and benchmarks for an optimal integration of these technologies.

In order to identify the optimal path for RES in terms of security issues and economic competitiveness, four storylines are considered in this project: Green, Yellow, Red and Blue. These are potential future scenarios that differ in technical development rate and public attitude towards the adoption of greener solutions. As a result of differences among general conditions, demand level and RES development, among other parameters, shall also vary with the storyline.

Analyses within the SUSPLAN are conducted by European regions/countries in order to connect regional implementation of energy infrastructures with national or European strategic targets. The research presented in this paper is focused on the Spanish case.

In Spain, renewable generation sources are being strongly promoted by public policies. Generous feed-in tariffs have allowed an important expansion of renewable generation, especially wind and solar power. For instance, currently, Spain has more than 18 GW of wind installed capacity [1] and it is expected that this capacity will keep increasing in the next years. Such an amount of intermittent generation will have significant impacts on the electricity system operation.

Having that in mind, the main objective of this paper is to find different potential future evolutions of the electricity generation mix in Spain, according to the four storylines considered in the SUSPLAN project. Those futures should meet the requirements imposed by the integration of high levels of RES generation and at the same time must be compatible with achieving a safe operation of the system.

Storyline analysis will be performed in two steps. First, the required development of RES and conventional generation shall be computed using a long term generation expansion model. Then, a detailed analysis of the operation of the power system in 2020 and 2050 is carried out considering the evolution of RES and conventional generation that has been

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[2] SUSPLAN (PLANning for SUStainability) is a project initiated in 2008 under the European Union's 7th Framework Program and is sponsored by the Directorate General Transport and Energy (DG-TREN). Webpage: http://www.susplan.eu/. The sole responsibility for the content of this paper lies with the authors. It does not represent the opinion of the European Commission. The EC is not responsible for any use that may be made of the information contained therein.

[3] European Commission. Available at: http://ec.europa.eu/energy/climate_actions/doc/2008_res_directive_en.pdf

[4] The DESERTEC Concept describes the perspective of a sustainable supply of electricity for Europe, the Middle East, and North Africa up to the year 2050. Webpage: http://www.desertec.org/.

previously computed. The medium term operation model allows the analysis of power reserves needs, thermal and hydro generation output, among other resources in the system. The operational analysis is essential in order to test that the capacity resultant from the expansion model can be safely integrated to the system.

Finally, this paper is divided into three sections besides this introduction. Section II contains the description of the four storylines, as well as the parameters/hypotheses assumed when defining each one of them. It also describes the methodology applied to carry out the research. Section III includes the results obtained from the analysis. Finally, Section IV presents the conclusions.

II. Storylines Characterization and Methodology

The four storylines analyzed in the SUSPLAN project are defined in [2]. Hypotheses regarding electricity demand, RES and electric vehicles (EVs) penetration, RES learning curves, fossil fuels and CO_2 prices will vary according to each storyline definition and the studied region/country.

A. Future energy contexts: Storylines characterization

Storylines differ in the technical development rate (slow or fast) and in the public or social attitude (positive or negative) towards the adoption of environment-friendly options. Fig. 1 shows the storylines division according to the assumptions made regarding technological development and public attitude.

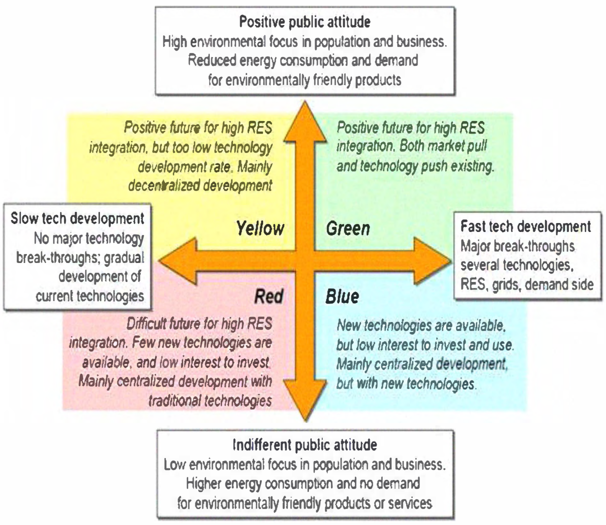

Fig. 1. Overview of the four storylines in SUSPLAN.

The Green storyline is characterized by a fast technology development and positive public attitude. Energy consumption growth in this storyline is considered to be low due to high consumer awareness, high potential for demand response and active demand management and the availability of more energy-efficient technologies. High technology development favors steeper RES learning curves and high EVs penetration. In the Green storyline, EVs penetration may partially counteract electricity consumption reduction.

The Yellow storyline is characterized by slow technological development and a positive public attitude towards environment-friendly options. Unlike the Green storyline, demand reduction is limited to customers' behavior inasmuch as there are fewer technologies to use. Slow technology development restrains RES penetration and EVs deployment in comparison to the Green storyline. Low deployment of EVs contributes to electricity consumption reduction.

The Red storyline corresponds to the less sustainable future context. In this storyline, technological development is low and public attitude is indifferent. Demand is relatively high due to low environmental concern and lack of low energy-consuming technologies. RES penetration is limited and learning curves are slow.

Finally, the Blue storyline is characterized by fast technological development and public indifference. Lack of environmental concern added to EVs consumption results in higher demand growth rates in this storyline. Fast technology development allows a higher deployment of RES technologies and EVs in comparison to the Yellow and Red storylines. Nevertheless, this deployment is inhibited by public indifference towards greener solutions.

B. Main assumptions for the Spanish case

The main assumptions considered for the Spanish energy system in each storyline are presented in Table I. Country-independent parameters, such as RES technologies costs, learning curves, CO_2 and fossil fuel prices are considered the same by all partners involved in the SUSPLAN project.

Other parameters, such as demand growth and number of electric vehicles will depend on the region analyzed. In this study, these figures have been defined after considering (i) prospective reports from the Spanish Ministry of Industry, Tourism and Trade (MITyC) and the system operator (REE) [3] and the Spanish Association of the Electric Industry (UNESA) [4]; and (ii) meetings with experts of the energy sector.

TABLE I
MAIN ASSUMPTIONS WITHIN THE FOUR STORYLINES

Storyline	GREEN		YELLOW		RED		BLUE	
Year	2020	2050	2020	2050	2020	2050	2020	2050
Annual Demand growth without EVs (2010-2020)/(2020-2050)	1%	1.5%	1%	1.5%	2%			
EVs penetration	10%	30%	-	10%	-	5%		20%
EVs (million)	3	10	-	3	-	1.5	-	6
CO_2 price (€/ton)	30	53	30	53	35	104	35	104
Gas price (€/MWht)	29				39			
Coal price (€/MWht)	7,6	3,3	7,6	3,3	10	11,3	10	11,3

It can be observed in Table I above that demand growth rates are considered the same for the Green and Yellow storylines on one hand, and for the Red and Blue ones, on the other. Total demand, however, is affected by EVs penetration.

As batteries deployment depends mainly on technology development, higher EVs penetration levels are assumed for the Green and Blue storylines. However, positive public attitude in the Green storyline allows a faster replacement of conventional vehicles for electric ones.

Higher fossil fuels prices in the Red and Blue storylines are a consequence of the larger use of energy from these sources, which is due to lack of environmental concern and high demand. Since consumers are indifferent, public intervention is necessary in order to influence energy production and consumption. Therefore, CO_2 emissions prices are also higher in these storylines.

With regard to generation technologies, other hypotheses are considered. In the Green storyline, it is assumed that nuclear power plants will no longer be operating after the end of their useful life (around 2030). In the Yellow and Blue storylines, it is considered that the existing nuclear plants are repowered and for that reason their useful life is extended for 15 extra years. In these three cases, the expansion model was programmed not to install new nuclear capacity.

In the Red storyline, due to high demand and low RES penetration, besides the extension of the useful life of existing nuclear units, the installation of new nuclear capacity was allowed, limited to a maximum of 15GW by 2050.

C. Methodology

In order to determine the economic and technical viability of RES targets for 2050, two electricity models have been used. Firstly, additional conventional generation capacity is computed by a long term generation expansion model. RES new installed capacity is an input of the model since it corresponds to fixed RES targets. For conventional technologies, the resultant installed capacity is the most economically profitable one that meets residual demand (the result of subtracting RES generation from total demand).

This expansion model is based on the model presented in [5]. The objective of this tool is to minimize the net present value of system costs considering as input data investment costs of each technology, fuel costs, CO_2 prices, demand growth and environmental constraints. Under the hypothesis of costs minimization, the model simulates the investments that would be made in generation capacity in order to supply demand in the period of study.

The model's main outputs are total annual installed power and energy production by technology, annual investment costs, marginal cost of electricity, optimal premiums to achieve specific RES targets and CO_2 emissions.

In order to take into account in the analysis the installation of new generation groups and the shutdown of power plants which useful life have ended, a large time horizon is considered. In the study presented in this paper, the model will be run for the period of 2020-2070.

Due to this long period of study (50 years), the detailed system operation, such as hourly demand, behavior of intermittent generation and ramps, is not represented by this model. For this reason, once the evolution of RES and conventional capacities has been computed, the analysis of the operation of the power system in 2020 and 2050 is carried out by another model.

This tool, described in [6, 7], is a daily operational model with a one-year scope. Firstly, operational decisions – daily unit commitment and economic dispatch – are deterministically optimized. Detailed operation constraints such as minimum load, ramp rate of thermal units and secondary reserve procurement are included into the daily optimization model. The stochastic nature of demand, hydrological conditions and rare events is taken into account by considering a multiplicity of yearly scenarios obtained by Monte Carlo simulation.

The main outcomes from the model are the hourly generation output by technology, including pumped storage hydro and EVs generation, pumped storage and EVs consumption, generation surplus, energy not supplied, total operation costs, up and down reserve marginal costs, and the system marginal cost.

In this paper, the operation model will be used in order to determine if the generation mix resultant from the expansion model is able to safely meet hourly demand while respecting system constraints.

III. Results Analysis

Considering that concerns regarding climate change and the environment, combined with the search for energy autonomy and economic competitiveness, will drive energy policies in most European countries, one could expect that the Green storyline is plausible future storyline in Europe. Surely, this is the storyline in which the energy system would be the most sustainable.

A high penetration level of renewable generation, especially wind and solar, is expected to be reached in Spain in the near future. Currently, Spanish wind installed capacity is superior to 18GW. Besides, in 2008, nearly 25% of electricity demand was supplied by renewable generation [8].

Having that in mind, the Green storyline is here deemed to be the base case scenario. The remaining storylines will be considered as alternatives to the reference storyline and their outcomes will be compared to the results obtained for the Green one.

A. Evolution of the installed power capacity

The year 2020 was considered the starting point of the analysis. Conventional capacity was assumed to be the same for all storylines; differences among them in 2020 are due to the higher or lower penetration of RES technologies according to the definition of each storyline.

Considering the assumptions presented in Table I and the installed capacity in 2020, the generation expansion model was run for the period 2020-2070. Fig. 2 shows the actual power capacity in 2008 and the estimated installed capacities power in 2020 and 2050, which is resultant from the use of the expansion model.

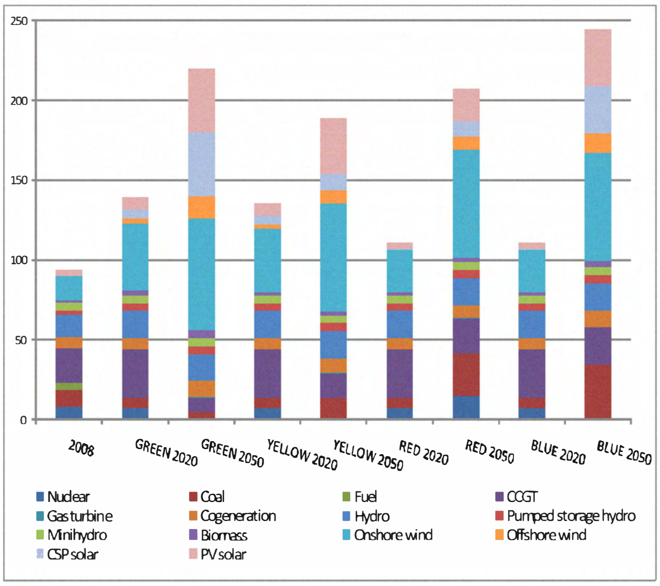

Fig. 2. Installed capacity (GW) in 2008, 2020 and 2050.

The smallest thermal gap (total installed power subtracted from the renewable capacity) in 2050 is observed in the Green storyline due to the substantial penetration of renewable generation and reduced electricity consumption in this scenario. The Yellow storyline also presented a relatively low thermal gap. On the other hand, the fact that consumption levels in the Blue storyline are high led to a large thermal gap despite the high penetration of renewable sources in comparison to the Yellow and Blue storylines.

Regarding costs, the same investment costs (in euro per MW) were assumed for thermal technologies in all storylines. On the other hand, RES investment costs used depend on the storyline considered – the Green and Blue storylines present lower investment costs due to fast technology development while the Red and Yellow present higher costs. Table II below shows the total new RES and thermal installed capacity between 2021 and 2050 and the average investment cost of RES, thermal and total new capacity.

TABLE II
TOTAL AND AVERAGE INVESTMENT COSTS OF THE NEW INSTALLED CAPACITY IN THE PERIOD 2021-2050

	GREEN	YELLOW	RED	BLUE
Total new RES installed capacity (GW)	174	129	114	154
Total new thermal installed capacity (GW)	24	34	71	68
RES capacity average investment cost (€/kW)	1,645	1,776	1,741	1,782
Thermal capacity average investment cost (€/kW)	762	899	1,215	1,018
Total average investment cost (€/kW)	1,539	1,575	1,538	1,548
Total investment costs (Billion €)	304	262	298	344

First, according to Fig. 2, the installed capacities for the Green storyline in 2020 and 2050 are, respectively, 140GW and 220GW. Therefore, for this storyline, total capacity increases 80GW. However, it can be observed that the total new installed power capacity (RES plus thermal) between 2021 and 2050 is 198GW. This means that part of new capacity, for all storylines, was installed in order to replace power plants which useful life has ended.

Average investment costs of RES technologies are greater than the average investment costs of thermal capacity. With respect to the average investment cost of RES technologies, the lower value is observed in the Green storyline due to the fast technology learning curve employed. Higher investment costs in the Blue one are due to the fact that more expensive RES technologies, such as solar and offshore wind, are deployed to a larger in this scenario than in the Yellow and Red storylines. As for the average investment cost of thermal capacity, the Red and Blue storylines present much higher costs than the Green and Yellow ones due to the higher share of coal capacity installed in these storylines. In the Red storyline, this is aggravated by the installation of new nuclear plants, characterized by high investment costs.

Finally, the lowest total average investment costs are observed in the Red and Green storylines, respectively, and are very similar. It means that total average investment costs in a scenario with higher RES penetration, fast technology learning and low thermal generation could be at the same level as investment costs in a scenario with low RES share, slow technology learning and high thermal generation.

B. Operation of the future power system

Once the economically optimal conventional generation capacity expansion was computed, the operational model was run for the years 2020 and 2050 for each storyline. It was noticed that the storylines with higher RES penetration, especially the Green and Yellow ones, presented very high ENS and operational reserves costs. For that reason, more backup and storage capacity was added to the previously computed capacity so that these costs could be reduced. The following Table shows the technologies and added capacities.

TABLE III
ADDITIONAL CAPACITY AND INVESTMENT COSTS REQUIRED DUE TO OPERATIONAL REASONS IN 2050

	GREEN	YELLOW	RED	BLUE
Coal capacity (GW)	5	1.5	0	0
CCGT capacity (GW)	10	6	0	0
Gas turbine capacity (GW)	2.5	2.5	0	2.5
Pumping storage hydro (GW)	3	3	0	3
Total additional investment (Billion €)	16.0	8.6	0	2.7

The main results from the operational model considering those additional generation capacities are shown in Table IV and Table V.

1) Technical aspects

TABLE IV

ENERGY PRODUCTION (% OF TOTAL DEMAND), DEMAND AND CO_2 EMISSIONS

Storyline	GREEN		YELLOW		RED		BLUE	
Year	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**
Wind generation	26.51%	29.91%	22.89%	30.30%	20.36%	29.23%	27.38%	24.87%
PS hydro generation	0.13%	1.89%	0.60%	1.23%	0.37%	0.54%	0.58%	0.79%
Other RES	24.42%	38.02%	21.61%	26.24%	14.96%	16.78%	20.46%	27.37%
EVs generation	1.49%	5.89%	0%	2.68%	0%	1.27%	0%	4.14%
Thermal generation	47.46%	24.28%	54.90%	39.55%	64.59%	52.18%	51.58%	42.83%
Total demand (TWh)	**313**	**544**	**300**	**495**	**330**	**610**	**331**	**647**
EVs consumption	4.55%	11.73%	0%	4.61%	0%	2%	0%	7.1%
PS hydro consumption	0.32%	3.24%	0.82%	1.96%	0.51%	0.73%	0.50%	1.2%
ENS	**0%**	**0.12%**	**0%**	**0.12%**	**0%**	**0.12%**	**0%**	**0.12%**
Generation surplus	**0.75%**	**1.71%**	**0.23%**	**0.20%**	**0.02%**	**0.48%**	**0.46%**	**0.03%**
CO_2 Emissions (millions of tons)	**54**	**75**	**62**	**122**	**83**	**120**	**64**	**173**

First, the composition of the generation mix in 2020 and 2050 is presented. Then, EVs consumption, PS hydro consumption, ENS and generation surplus are presented as percentages of the total demand. PS hydro refers to pumped storage hydro. Other RES includes conventional hydro, mini-hydro, biomass, solar thermal and solar PV. ENS corresponds to Energy Not Supplied due to the fact that, for some hours, demand is higher than generation. Finally, generation surplus (or spillages) refers to the case when, for some hours, there is too much generation to be injected into the grid, in other words, no generator can reduce its production and demand cannot be increased by pumped hydro. For this reason there is a "spillage" of hydro and/or wind energy.

a) Green storyline

Focusing on the Green storyline, RES share of total generation increases considerably from 2020 to 2050. According to the model, pumped storage hydro use increases in a significant way due to the high level of intermittency on the system. In this case, water is pumped when wind generation is high and demand is low and it is injected when demand is high and available RES power is low.

After adjusting the conventional capacity computed by the expansion model the levels of ENS become reasonable and comparable to other storylines with a higher share of thermal generation. On the other hand carbon emissions are much lower than the ones obtained in the rest of storylines.

b) Comparison among storylines

When different storylines are compared, it can be noticed that the impact of RES penetration on the operation of the system is lower.

In the Green storyline, PS hydro use decreases in 2050. Although wind generation share is higher in 2050, the total amount of energy from this source (in GWh) is lower than in the Green storyline. Additionally, the integration of EVs in 2050 contributes to mitigate power intermittency as it happened in the Green storyline.

For the Red and Blue storylines, PS hydro use increases from 2020 to 2050, although not in the same proportion as in the Green storyline due to the much higher penetration of wind energy in the latter.

Regarding generation surplus in 2050, the more significant increases take place in the Green storyline as a result of higher intermittency and unpredictability of RES generation.

2) Operation costs

Technical changes in system operation caused by a higher RES penetration due to the requirement of more flexible but expensive generation can result in increased system marginal costs. On the other hand, these technologies have zero fuel costs, which in a context of high RES integration, should lead to a reduction of average production costs and in some hours to lower marginal costs as well.

TABLE V
SYSTEM OPERATION COSTS (% OF TOTAL COSTS)

Storyline	GREEN		YELLOW		RED		BLUE	
Year	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**
Fuel and CO2 emission costs	90.3%	71.4%	93.8%	81.4%	96.1%	93.0%	93.8 %	86.9%
ENS	0	8.6%	0	6.1%	0	4.4%	0	3.2%
Spillages	2.3%	5.3%	0.6%	0.4%	0	1.1%	1.2%	0.1%
Up and down reserves	7.4%	14.7%	5.6%	12.1%	3.9%	1.5%	5.0%	9.8%
Total system operation cost (Million €)	5,475	10,980	6,557	14,913	12,812	25,485	8,817	36,791
Average fuel and CO2 emission cost (€/MWh)	16	14	20	24	37	39	25	49
System marginal cost (€/MWh)	53	63	56	65	73	97	67	110

Table V shows the main results produced by the operation model regarding costs. Fuel and CO_2 emissions costs, ENS, spillages and up and down reserves costs are represented as percentages of the total system operation costs. ENS cost was considered at the level of 1,500€/MWh. Spillages cost was evaluated at the same level of the system marginal cost. Finally, up and down reserve is the generating capacity available to the system operator within a short interval of time to meet demand in case of lack or excess of generation, respectively. Up and down reserve costs were estimated by multiplying up and down reserve requirements in each storyline by their respective marginal costs.

a) Green storyline

It can be observed from Table IV that fuel and CO_2 costs on total costs are reduced in 2050 due to higher costs of ENS, spillages and operational reserves needs, which increases with the larger intermittency of the system.

Average fuel and CO2 costs also decrease from 2020 to 2050. This is related to the higher share of RES and, consequently, to the much reduced amount of energy produced from thermal generators.

On the other hand, system marginal costs increase in 2050 with respect to 2020. This increase is due to the higher use of pumped storage, existence of a larger amount of ENS, and higher needs of up and down reserve, which push costs up.

b) Comparison among storylines

The lowest share of fuel and CO_2 costs on total system operation costs in 2050 is observed for the Green storyline due to the high RES penetration. On the other hand, due to the lower variability of production in the other storylines, ENS, spillages and up and down reserves represent lower percentages of total costs in the Yellow, Red and Blue storyline compared to the Green one.

Total system operation costs in 2050 are much higher in the Red and Blue storylines than in the Green and Yellow ones. Despite the higher amounts of RES generation in the Blue storyline, as mentioned before, the significant contribution of nuclear generation in the Red storyline helps to reduce electricity cost in the latter. Moreover, higher consumption levels in the Blue storyline increase the need for expensive conventional generation. Average fuel and CO_2 follow the same trend in these two storylines.

As for system marginal costs, increases from 2020 to 2050 are observed in all storylines. Lower marginal costs in 2050 appear in the scenarios with higher RES shares - the Green and Yellow ones. On the other hand, the Blue storyline presents the highest marginal cost due to the high use of expensive thermal generation.

IV. CONCLUSIONS

The preliminary results of the prospective analyses carried out within the SUSPLAN project has demonstrated that different assumptions about the future of the Spanish electricity system provide significant differences in the composition of the generation mix, including renewable sources, the expected carbon emissions, and the associated investment and operational costs.

The obtained results show that, despite its beneficial effect on carbon emissions and operational costs, the implementation of scenarios with a high penetration of renewable sources - up to 68% of the total electricity production by 2050 - would involve higher infrastructure investment costs and important challenges in the operation of power system. From these outcomes, it is possible to derive some recommendations or measures that could be taken in order to allow a higher integration of renewable generation.

First of all, it was observed that changes caused by larger shares of RES in the power system operation, such as higher ENS levels and generation surpluses (spillages), give raise to higher system costs. These costs should be minimized with the integration of backup conventional generation, storage capacity and/or other flexible resources.

In this sense, electric vehicles are a potential source of flexibility that could help the System Operator to integrate higher shares of renewables. Smartly charged EVs could reduce spillages, PS hydro use and ENS levels. These vehicles could also provide less expensive operation reserves, since they would be charged mainly in hours when electricity prices are low.

If sufficient flexible resources are in place, high shares of RES can be safely integrated into the system. A first estimate of the required amount of these flexible system resources has been provided by the expansion planning model. After analyzing the results obtained from the operational model, it was concluded that the amount of resources needed in order to provide backup capacity should be higher than those values initially provided by the expansion model.

Furthermore, developing more accurate forecasting methods could also favor a higher integration of wind energy by making wind generation more predictable.

Finally, the development of higher electric interconnection capacity could also play an important role in achieving a safer massive integration of RES. The excess of intermittent generation could be exported to other countries while energy needs in Spain could be supplied by them.

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