WIND INTERMITTENCY AND CO_2 REDUCTIONS: THE CASE OF THE SPANISH POWER SYSTEM

R.A. Da Silva-Álvarez[1], P. Montoro-Pintado[2] and F. Gutiérrez-Martín[3]

1. E.U.I.T.I. Universidad Politécnica de Madrid, Spain; email: ricardoadasilva@gmail.com
2. E.U.I.T.I. Universidad Politécnica de Madrid, Spain; email: pmontoro.pm@gmail.com
3. E.U.I.T.I. Universidad Politécnica de Madrid, Spain; email: fernando.gutierrez@upm.es

ABSTRACT

Renewable energy sources are believed to reduce drastically greenhouse gas emissions that would otherwise be generated from fossil fuels used to generate electricity. This implies that a unit of renewable energy will replace a unit of fossil-fuel, with its CO_2 emissions, on an equivalent basis (with no other effects on the grid). But, the fuel economy and emissions in the existing power systems are not proportional with the electricity production of intermittent sources due to cycling of the fossil fuel plants that make up the balance of the grid (i.e. changing the power output makes thermal units to operate less efficiently).

This study focuses in the interactions between wind generation and thermal plants cycling, by establishing the levels of extra fuel use caused by decreased efficiencies of fossil back-up for wind electricity in Spain. We analyze the production of all thermal plants in 2011, studying different scenarios where wind penetration causes major deviations in programming, while we define a procedure for quantifying the carbon reductions by using emission factors and efficiency curves from the existing installations. The objectives are to discuss the real contributions of renewable energies to the environmental targets as well as suggest alternatives that would improve the reliability of future power systems.

Keywords: CO_2 reduction, Wind power, Electric grid load balancing, Cycling.

1 INTRODUCTION

Current energy systems are no sustainable due to resource limitations, management aspects and external costs. Thus, an efficient utilization of the existing infrastructures should be first considered to address the increasing power demands and environmental concerns. Moreover, the potential of renewable energies is foreseen much higher than the global demands in many countries, and it is usually well distributed in the territories; however, the benefits of these energy resources, such as solar or wind, are overshadowed by their intermittent nature, the incompatibility with base load technologies, like nuclear, or the competence with ordinary thermal utilities, which can result in low utilization factors (e.g. nowadays, the power capacity in Spain exceed 100 GW, while the peak consumption reaches only about 45 GW) [1].

Table 1. Distribution of electricity generation per technology (Spain, 2011)

Primary energy	**Power capacity** (MW)	**utilization factor** (%)	**Generation** (GWh)	**energy mix** (%)	**Demand** (GWh)
Coal	12210	43,4	46427	16,1	-
Fuel + Gas	5425	15,8	7491	2,6	-
Gas CC	27123	23,2	55074	19,1	-
Nuclear	7777	84,7	57670	20,0	-
Hydro + pumping	17538	18,0	27650	9,6	-
Wind	20881	23,0	42060	14,6	-
Other (special regime)	15340	38,2	51383	17,9	-
TOTAL net	**106295**	**30,9**	**279711**	**100,0**	**270361**

This makes the management of the grid a very challenging task, which necessitates energy storage or load levelling options to improve the efficiency based on more holistic energy approaches, especially in relatively islanded systems like the Spanish grid. As electricity cannot be stored in large amounts (at least with current technology), we have to maintain the grid stability by fitting the instantaneous power generation capacities and the expected load demands, at the same time that we have to deal with growing needs of infrastructures and the integration of non-manageable resources, like solar thermal, photovoltaic and wind power [2].

The penetration of new renewable energies is considered a great advantage for the country, but it also affects the structure and operation of the power system, as we need large reserve capacities for the peak-periods when they are not available, while sometimes they are shut-down if exceeding the electricity demand. After introducing the special generation rules in 1997, the contribution of wind and solar technologies to the power capacity in Spain has considerably risen, leading the country to a prime position in the world, though it is still necessary at least to double this production to reach the energy targets for 2020 [3]. At the same time, a great number of natural gas powered utilities were built during the last years, till such point that the coverage ratio with conventional generation only is nowadays higher than 40% over the maximum of annual demands. Table 1 show the utilization factors for all the Spanish power technologies, where if we take into account that some utilities have priority of evacuation (special energies) we can foresee that they are conditioning the others, specially the operation of thermal utilities (if used only as rolling power). On the other hand, because of the intermittent nature of some renewable technologies, CO_2 reduction would be less than anticipated due to the cycling of the fossil fuel plants that make up the balance of the grid [4].

2 POWER INTERMITTENCY, RESERVE CAPACITIES AND CYCLING

For this study we have used the data provided by the Spanish power operator (REE), relative to the load demands and structure of power generation with a disaggregation of hours. Through this information one can approach the performance of the power system due to the penetration of intermittent renewable sources and their effect on the operation of ordinary thermal utilities responsible of fossil fuel greenhouse emissions. The effect of this intermittency must be corrected continuously to maintain the stability of the grid, by fitting the power generation capacities and the expected load demands; this is usually done by daily planning of the system or short term measures like reprograming the generation units for uploading or reducing the energy following unexpected variations of electricity generation, e.g. wind power (Fig. 1).

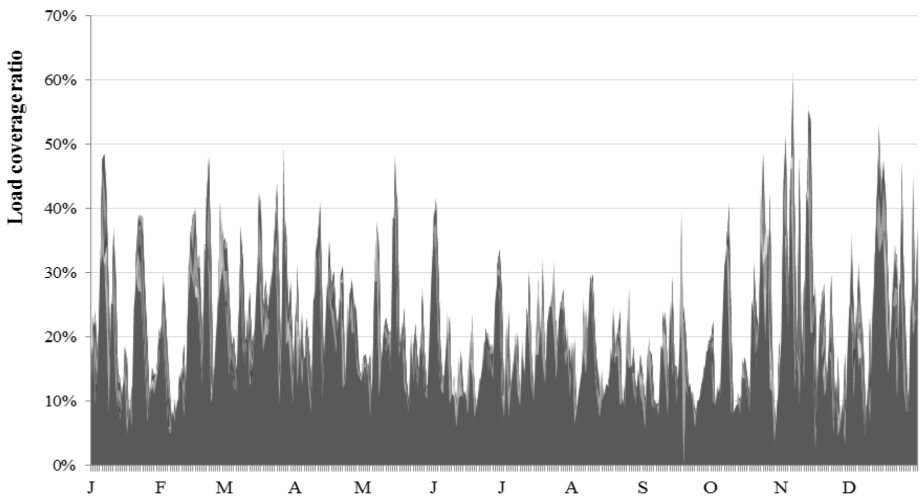

Figure 1. Variability of wind power generation in Spain (2011)

This brings to mention the concept of “rolling power” as the reserve thermal capacities to follow timely the power loading curves or compensate any deviation from the load programs. Both coal and gas fired utilities are widely used for electric grid load balancing, especially in those countries with great penetration of wind power as it is in Spain where this resource is the third major component of the power generation mix. Thus, when important fluctuations of wind production -expected or not- arise, they directly rebound on the load of more flexible fossil fuel plants that make up the balance of the grid; this is called “cycling” which consists in the variation of the plant loads causing in some cases the reduction of their rated energy efficiencies and fuel consumption. The effects of power intermittency, increasing reserve capacities and cycling can greatly affect the emission reduction targets, as they are based in simple estimations not taking into account the interaction of technologies in the power systems.

3 METHODOLOGY AND DATA SOURCES

The electricity market in Spain is based in hourly periods, where the programming of each power generation unit is modified according to the anticipated needs of the system. Then, we can assign different CO_2 emission values by knowing the resulting hourly productions, which are then aggregated daily, monthly or annually. In order to relate these emissions with wind intermittency, we used the real production of this technology to determine the coverage ratios regarding the hourly power demands in each period. All these basic data were found in the public web of REE [5].

The emission factors per technology can be estimated by using the average values proposed in the renewable energies plans (PANER), which are 0.961 and 0.372 kg_{CO2}/kWh for coal and NGCC power installations [6]. For coal utilities, we may also use more specific values for each generating unit by taking the published data relative to the use of autochthon resources in the Spanish power mix [7].

Together with the emission factors, we have considered the efficiency rates depending on the load operation levels of the installations. With these variables we are including the effect of the cycling in fuel consumption and related emissions, taking into account that many reserve capacities are used as rolling power (i.e. below their nominal loads). To compute these efficiencies we use a standard procedure that measures the relation of the electricity production vs. fuel consumption:

$$Y = A \times X^2 + B \times X + C + D / X \qquad (1)$$

where, Y is the fuel consumption rate in MWh(HHV) per MWh of electricity and X is the net production in MWh, while *A, B, C* and *D* are the polynomial coefficients, characteristic of each coal or gas unit, which are determined routinely by performance tests and vary along the lifetimes.

Because of the difficulties to obtain these particular coefficients for each power utility in this study, we have used several representative correlations for coal and gas technologies: for the coal plants we have established the difference between those units with capacities below or above 200 MW (according with the boiler sizes), while for GCC plants the differences are between 400 and 800 MW units (single or multiple shaft).

Therefore, once getting the net production ratios, we calculate the excess fuel required by the power plants working at different load regimes, by means of equation 1 and the consumption rates at full load operation; as a result, we obtain a dimensionless factor ($\rho \geq 1$) which relates the fuel rate in each period to its nominal value (Fig. 2).

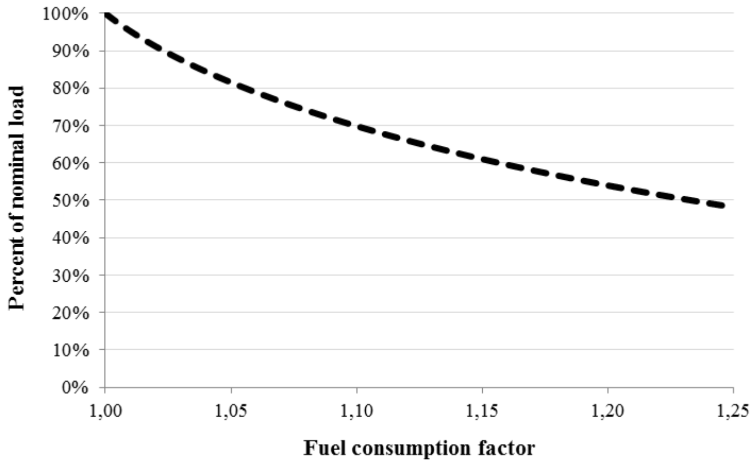

Figure 2. Fuel consumption curve for a thermal utility

Finally, the carbon dioxide emissions are calculated by multiplying these factors and net power productions for all the technologies/utilities considered in this study:

$$E(ton_{CO2} / h) = E_o \times \rho \times W_t \qquad (2)$$

where, E_o are the base emission factors (ton_{CO2}/MWh), ρ the coefficients for excess fuel (dimensionless) and W_t the net hourly generations in the different periods (MW). More precise and public information should be expected in the future, to quantify the real time emissions of different utilities which form the electric parks.

4 SCENARIOS OF WIND POWER INTERMITTENCY

4.1 Daily Scenario

This is a middle term scenario to analyze the daily generation curves, hour per hour, and how this variability affects the production of the units which constitutes the rolling power capacities of the system (Fig. 3).

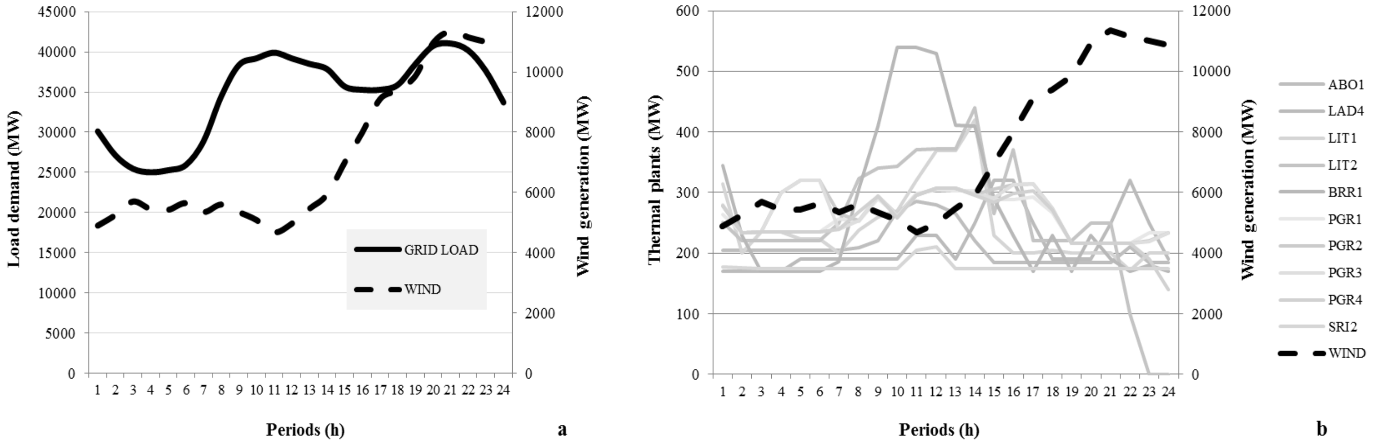

Figure 3. (a) Load curve and wind generation for a typical winter day;
(b) Comparative trends of several thermal utilities and wind power

The calculation of the fossil fuel capacities which are connected to the grid in the 24h periods is related to the hourly power demands and the reliability of wind production in each period; these `thermal reserves´ grow as wind power penetration increases and their deviation slopes from the forecasts are larger.

By supposing an existing trend between the wind penetration index and the thermal reserves for the different situations in this daily scenario, we can simulate new scenarios by substituting all wind generation with an equivalent fuel utility production and an available hydropower in the month under consideration; therefore, we are able to compare both current and no wind scenarios and their corresponding CO_2 savings.

4.2 Real Time Scenario

This is a short term scenario for analyzing sudden variations (no more than 4 h beyond) of wind generation, exceeding the expected values and requiring an immediate power tuning from facilities to achieve the grid balance. With this analysis, we try to quantify the effects on the emissions due to wind intermittencies which have not been planned in advance by the system operator.

In this case, we study the adjustment markets, representing the last opportunity to correct system unbalances which originate from unexpected variations of the load curves or the flowing energies (e.g. wind power) that have priority of evacuation to the grid. Any conventional technology can participate in these hourly markets, being the fossil fuel units more flexible for rising or decreasing power depending on the needs of the system. The total energy required and the hourly contributions of each generating unit in these markets are published by the system operator [3], allowing to get a good picture of the load distribution due to wind perturbations. To discriminate the effects of the two no controllable variables which affect these adjustments (i.e. the load demand or the renewable energy generation) it is necessary to analyze the daily wind forecasting with which the system operator do planning for electrical market. Looking at the anticipated wind curves, it is possible to perform a comparison with the true outputs of the days under study to determine those intervals in which the differences are fitting with the trends in the adjustment or imbalance markets in such periods (Fig. 4); then, we can estimate the proportion in which fossil fuel utilities varied their programs due to aleatory changes in the generation from windmills.

For example, if an imbalance hour required an extra of 100 MWh in the system, with two GCC units which generate 50 MWh each, and during that hour the difference between real and anticipated wind generation was just -40 MWh, there was a deficit of energy in the period due to wind shortage. The variation in this case follows the trend of the market but only a part of the requirements of the system in the period is raised by wind. Therefore, if we make a straight partage to the total wind difference, 20 MWh out of the 50 MWh increased grid inputs from the GCC units is due to the intermittence of wind.

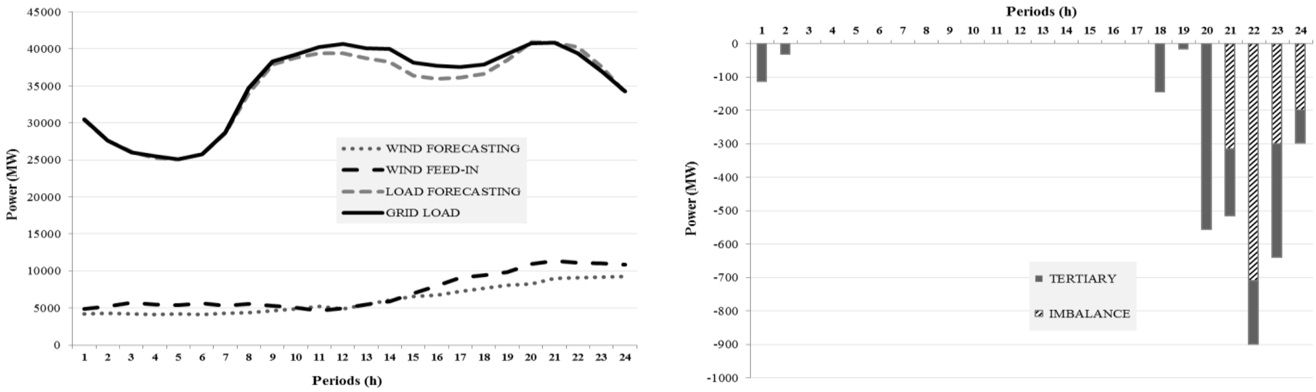

Figure 4. (a) Comparison of the load and wind forecast; (b) Hourly power requirements in the coupling markets fitting with the differences of the curves in figure 4(a)

5 ANNUAL ANALYSIS

The analysis of the data for the year 2011 and the corresponding results are summarized in the next figures. Fig. 5 is a dispersion graphic showing the emissions of CO_2, calculated from the final hourly programme for each generation plant, where we can fairly see its decreasing trend as wind penetration increases. However, we can also notice a slight decrease in the slope of the line, pointing out that the CO_2 reduction of each MWh is not proportional with the energy it replaces (fossil to wind).

As shown in Fig. 5(a) the quantity of CO_2 avoided per fossil megawatt substituted decreases as penetration of wind power increases. The high dispersion of the tons values around the trend line through wind production arises from its inherent variability at any penetration level and shows the concurrence of other technologies in the system -like the hydropower- as well as the daily grid load variations.

In Fig. 5(b) we try to demonstrate the relationship of substituting a wind megawatt by thermal megawatt at different wind power feed-in levels: to obtain this value, we divide tons of CO_2 by MWh fossil in the real system and we make the same quotient for the simulated system with no wind; then, we compare these values to find the ratios of CO_2 reduction by substitution of each MWh fossil by an equivalent MWh from wind. E.g., a wind MWh introduced in the grid can eliminate nearly all the CO_2 related to a thermal MWh in low penetration scenarios, whereas the reduction of CO_2 reach only 76% in high wind penetration scenarios.

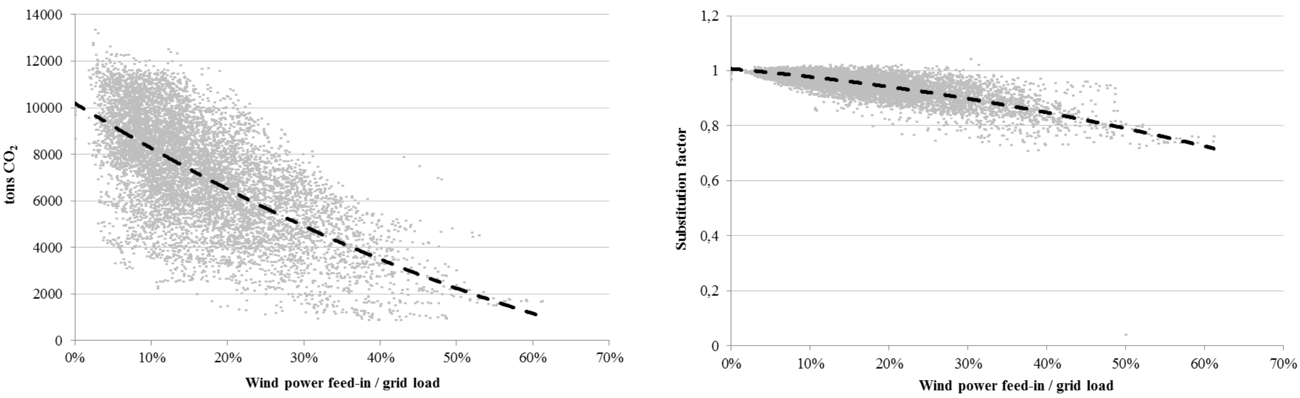

Figure 5. (a) Emissions of CO_2 vs. Wind penetration in Spain (2011); (b) Factors for CO_2 by substituting fossil and wind megawatts

These results reflect the effects of cycling as regard the emission reduction targets with the introduction of renewable sources. In the periods where the wind generation curves are variable and intermittent, the system requires the presence of enough reserve capacities, making the fossil fuel units running below their nominal loads; this reduces the efficiency and increases the fuel consumption, while in many cases we could optimize the number of utilities connected to the grid so that the remaining units are allowed to run more efficiently.

Fig. 6 shows the daily balances for CO_2 through 2011, due to not expected variations of wind forecasting in the real time scenario. The random nature of these results demonstrates that short-term intermittency in the Spanish system doesn't substantially contribute to the total CO_2 emissions in the year. In this case, the CO_2 generated vs. CO_2 savings result in a 12617 ton balance, i.e. no more than 0.02% of the total CO_2 emissions.

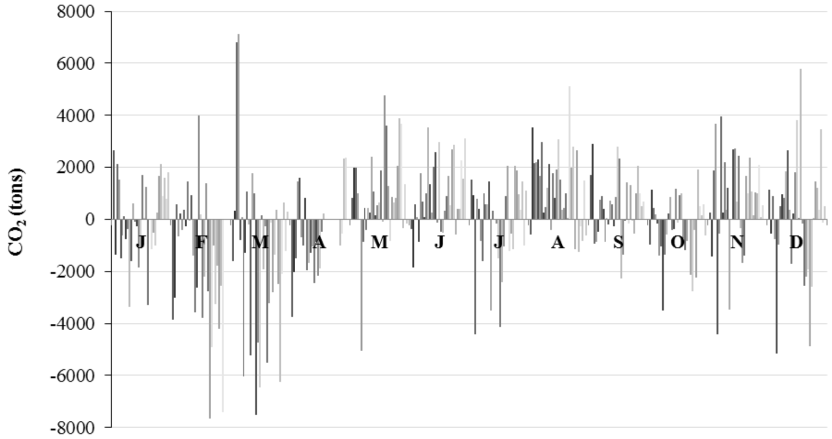

Figure 6. CO_2 balances due to real time imbalances

6 CONCLUSSIONS

Wind intermittency affects negatively the expected greenhouse gas reductions, taking into account that the fossil fuel utilities which make up the balance of the grid are running below their nominal loads during the periods of high wind generation. This is due to the fact that wind power substitutes each MWh of energy, but this does not mean that it avoids the same emissions as the efficiencies of thermal units are reduced at partial loads (cycling); nevertheless, our results show that the CO_2 reductions, even at high wind penetration, are still relevant and in any case near zero or negative as foreseen by some other studies [8, 9].

Promoters of renewable technologies, including governments of such countries -like in Spain- which have leaded initiatives in this field, must be aware of all the problematic posed by the integration of these energies in the electric grids. Thus, the same technological and regulatory leadership demonstrated in this area, must be now be oriented to palliate these questions and search for solutions in the line of the European targets for a sustainable energy future. Renewable energy is one of the best options in the way to this objective, though there are still some barriers to overcome and the environmental gains could be less than expected, as shown in this study, due to the complex interactions which appear during transitions from current fossil economies. Other means to make the substitution of ordinary for renewable energies more proportional would be storage systems which can greatly mitigate the fluctuations of wind power, improving the reliability of this resource; the utilization of hydrogen for this purpose is considered of great interest in the medium or long term [10].

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