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Combined penetration of wind and solar generation with plug-in electric vehicles

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Abstract

Combining large penetration of wind and solar generation with Plug-in Electric Vehicles (PEVs) seems a promising solution for energy cost saving and emissions reduction. PEVs connected to the grid with smart charging strategies can be an effective way to integrate non-dispatchable renewable generation, smoothing the load curve, contributing to the system stability by providing regulation services, and moving unhealthy emissions away from city centers.

This paper analyzes the combined penetration of PEVs, and wind and solar generation using a Unit Commitment model for the Spanish power system, providing some insight on how the penetration of these technologies affects relevant variables such as energy and reserve, thermal plants behavior (such as starts-up and shut-downs, technological energy share, generation costs or emissions) and systems costs. Results show that PEV increase total demand, but its optimal charging smooths the net demand (to be supplied by thermal units) and the final electricity prices. In addition, solar generation penetration leads to a larger net demand with more variability but with lower production costs than wind generation penetration, due to their different hourly profiles. Finally neither solar nor wind generation penetrations are totally profitable for the system with the assumptions made, since their investments costs do not compensate the production cost decrement, but grid parity is almost reached for both technologies.

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Keywords: Electric vehicle; wind and solar power integration; emissions; unit commitment;

1. Introduction

Progressive replacement of conventional Combustion Vehicles (CVs) with Plug-in-Electric Vehicles

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(PEVs) may lead to important benefits to current cities, making them smarter in the sense of [1][b], reducing noise and emissions as analyzed in [2]. However, this new electricity demand must be efficiently managed with intelligent charging strategies so that the system does not suffer from excessive plants stress, worsening their schedules and increasing their ramp requirements, [3].

In addition, using PEVs batteries as intelligent distributed energy storage systems can help to the integration of new renewable energy, as has been pointed out in several works, for example in [4], where an analysis of the combined penetration of wind, solar and PEVs was performed. Indeed PEVs facilitate the integration of non-dispatchable[c] wind and solar generation by consuming at valley hours, generating at peak times, and even providing regulation services to compensate the increased needs of regulation capacity that this intermittent generation may cause.

Therefore, the analysis of the net benefit of the combined expansion of non-dispatchable generation and PEV becomes a very relevant topic to investigate. Since the problem to face is large and complex, many aspects such as generation investments, market electricity impact and relevant externalities have been considered and modeled. References [2], [3] and [4] present an extensive literature review of the authors on previous related research works.

This paper extends the analysis performed in [3] by looking with more detail at the impact of different levels of wind and solar generation, for a fixed large PEVs penetration, on the operation and schedules of conventional thermal plants, electricity prices, CO_2 emissions and system costs. Market results have been obtained from a detailed hourly hydro-thermal Unit Commitment model (UC, already used and described in [3], [2] and [5]) with weekly water management [5]. It provides, among others, energy and reserve prices and schedules, and thermal units emissions, without considering network constraints or distribution grid problems [6]. Simulations have been performed for the first week of May 2011, selected due to reasonable amounts of both wind and solar generation. The extension to the whole 2011 is under progress.

This paper is organized as follows. Section 2 briefly describes the model, the main input data and the case studies analyzed, section 3 presents the main results, and section 4 concludes the paper.

2. Model and data

2.1. Model description

Simulations have been performed with a UC model which is a hydro-thermal-PEV UC for the joint energy and reserve dispatch that minimizes the total system costs, including production variable costs, startups, shutdowns and CO_2 emission costs for each thermal unit (see [2], [3] and [5]). Inelastic net demand (demand minus non-dispatchable generation such as wind or solar generation) is supplied by thermal units, hydropower generation, pumping cycles (generating or consuming), and PEVs (generating or consuming). Both, PEVs generation and consumption for a PEVs penetration of 45% (100% meaning that all CVs have been replaced by PEVs) are analyzed in this paper, taking into account different levels of wind and solar generation. Price is set as the dual variable of the demand balance equation, corresponding to the system marginal cost. Minimum and maximum prices were set to 0€/MWh and

[b]Within smart cities, PEVs are expected to serve several purposes: the displacement of harmful emissions away from the cities, the integration of renewable sources, and the contribution to the network reliability and security of supply, and to demand-response schemes.

[c]Non-dispatchable generation cannot generally be turned off unless the energy is discarded. It is typically generated from sources that are highly depending on meteorological conditions, such as wind or solar generation.

180€/MWh, corresponding to the presence of spillages and to the non-served energy cost, respectively.

In the UC model developed, reserve availability requirements can in general be supplied by thermal units, hydropower generation, pumping generation (only when turbining), and PEVs, although in the analysis performed in this paper PEV reserve has not been considered. The dual variable of the reserve balance equation provides a unique reserve price market for both the upward and downward reserves (as it is the case of the Spanish market).

Hydro units are modeled following [5], without topological relations, and using historic bounds on productions and cleared reserves per week for weekly optimization. Water and PEVs are dispatched in a two step process. They are optimally allocated on the first step, and remain fixed on the second one, so that the final prices correspond to the marginal cost of thermal plants, as occurs in practice in the Spanish system since hydro bids are based on the thermal substitution cost.

Only the V2G charging strategy of PEVs (optimal charging with generation[d]) has been used, with PEVs decisions centrally optimized by a hypothetical Electric Vehicle Operator, minimizing the total system cost. PEVs with same behavior have been grouped by fleets, as in precedent authors' works, [2]. A minimum charge of 80% is guaranteed before unplugging PEVs, and PEVs batteries efficiency has been set to 90%, [7]. PEVs do not supply electricity to the grid unless the batteries charge is above 60%.

2.2. Input data and case studies

Simulations are based on the structure of Spain's thermal generation (nuclear, national coal, imported coal, combined cycle and fuel gas) in 2011, and demand and reserve requirements for the first week of May 2011, which represents a warm and windy week (average temperatures overcame 3.5ºC historical values, and maximum wind speed was about 115 km/h in the 6th and 7th of May at the north of Spain). Reserves requirements (to deal with the additional wind or solar intermittent generation) have not been increased with respect to the historical ones. Although this is coherent with the Spanish System Operator practice (probably due to a possible overestimation of reserves, see [9]), some increment for very large renewable penetration should be expected. System demand, non-dispatchable generation (wind, solar and others), and the weekly parameters for hydro units are taken from [10], [11] and [12], see Fig. 1.

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[d] However, the model accepts four different PEVs charging strategies, [2] and [3].

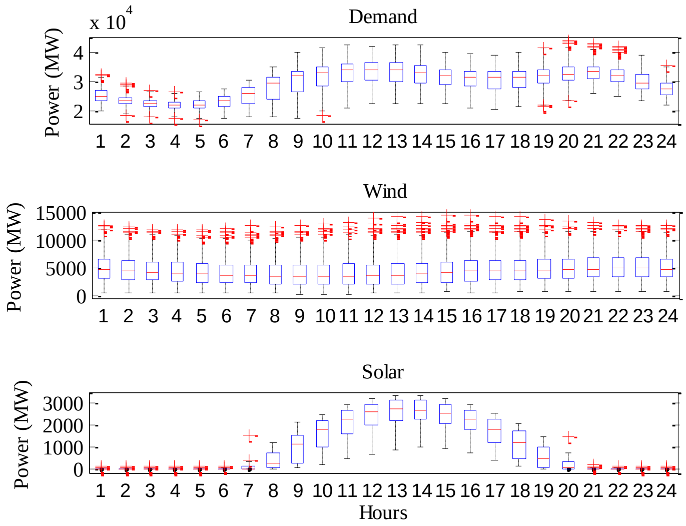


Fig. 1: Box-plots of hourly demand and solar and wind generations.

Wind and solar investment costs have been set to 1,500€ per installed kW, [13], and 2,500€ per installed kW, [14], respectively. Wind and Solar capacity factors (ratio of the actual to the potential output, computed for the whole 2011, see Table 1) are respectively 22% and 20%. Lifespan has been set to 20 years. Wind penetration levels, for the different scenarios considered, are identified with labels ΔWn, where n is a factor that increases the base case production (see Table 1) in multiples of 8 GWh. For example, ΔW1 corresponds to a wind generation increment of 8 GWh with respect to the base case. Solar generation capacity increments follow the same logic, so that ΔS2 means a solar production increment of 16 GWh with respect to the base case. As already mentioned, for simplicity the percentage of PEV penetration level has been fixed to 45%, where 100% means that all CVs have been replaced by PEVs.

Table 1. Base case annual values

	Demand	Wind	Solar
Energy (TWh)	256.1	41.5	7.6
Installed capacity (GW)	-	22	4.05
Capacity factor (%)	-	22%	20%

3. Case studies results

3.1. Thermal units commitment

Fig. 2 and Fig. 3 show thermal gap (net demand minus hydro generation, that is, demand to be supplied by thermal units), for the selected week and for the different solar and wind penetration scenarios, to be supplied only with thermal generation.

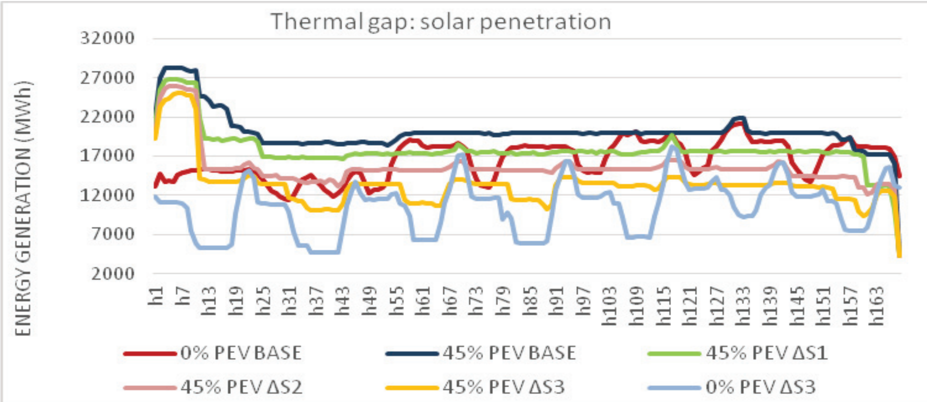


Fig. 2: Thermal gap for solar penetration scenarios

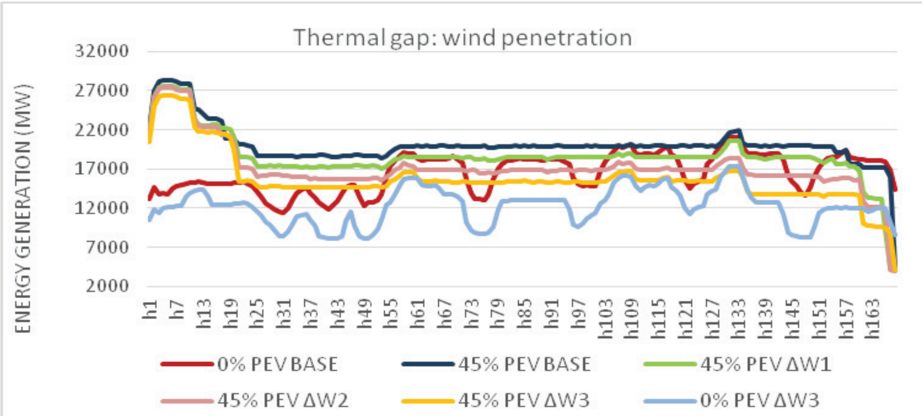


Fig. 3: Thermal gap for wind penetration scenarios

Base case with 0% PEV (that is 0% PEV with no additional solar or wind) corresponds approximately to the real 2011 existing situation, and shows the original peaks and valleys of the thermal gap. A penetration of 45% of PEV increases significantly the total energy consumption but smoothes the thermal gap thanks to the optimal allocation of PEV charging periods. However, increasing solar or wind generation has different impact on the thermal gap. While both technologies reduce it, and so the total thermal production, the reduction is allocated differently, even when the utilization factors are very similar for both technologies. This is due to the hourly production pattern of solar technology with respect to the more constant hourly wind production pattern, which concentrates on peak hours where the thermal generation is larger and thus more expensive. For this same reason the solar generation increases the thermal gap variability, but decreases the final energy production cost, as will be seen later in Table 4.

Fig. 4 shows the technologies supply for both solar and wind penetration scenarios.

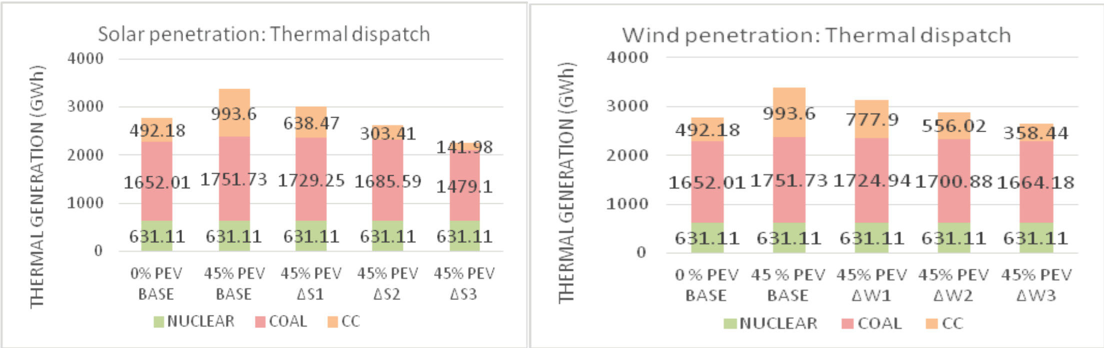


Fig. 4: Thermal production by technology for a) solar and b) wind penetrations scenarios

When PEV penetration goes from 0% to 45% both the energy consumption and the thermal gap increase significantly. Nuclear plants, with the cheapest variable costs, keep their production constant for all scenarios since they are always producing at their maximum capacity. Coal plants, with the cheapest variable costs after the nuclear ones, increase their production up to their maximum capacity (also considering the reserve commitment), and the additional energy needed is supplied by Combined Cycles (CC), in particular for large demand and low solar hours. When renewable generation increases, both coal but mostly CC reduce their production. This reduction is greater for the solar cases since solar production is greater for high demand hours when thermal generation is also higher.

3.2. PEV behavior

Fig. 5 shows the daily patterns of solar and wind generations versus the charge-generation pattern of PEVs resulting from the UC model described.

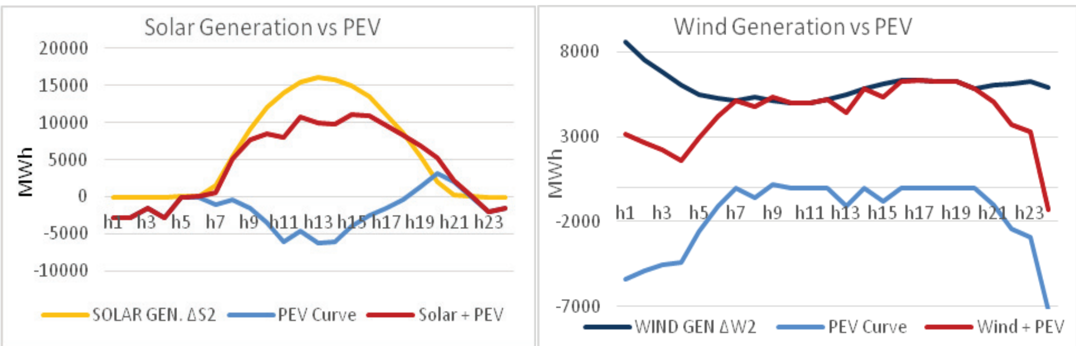


Fig. 5: PEV generation-consumption vs a) solar and b) wind generation

For the solar scenarios, PEVs charge partially at night to be ready for commuting trips early in the morning. However, most charging takes place at high solar production hours to store the extra solar energy. At dusk, when solar production decreases but demand is still very high, PEVs supply part of this energy to the grid, behaving like pump-storage units. PEVs behavior changes for wind scenarios, where PEVs charge mainly at night and almost do not generate. This entails that the storage capability of PEVs is more suited for solar penetration scenarios. In any case the possibility of optimally allocating the PEV consumption and the higher efficiency of PEV significantly reduces the need for storage-generation pumping hydro units, see Fig. 6.

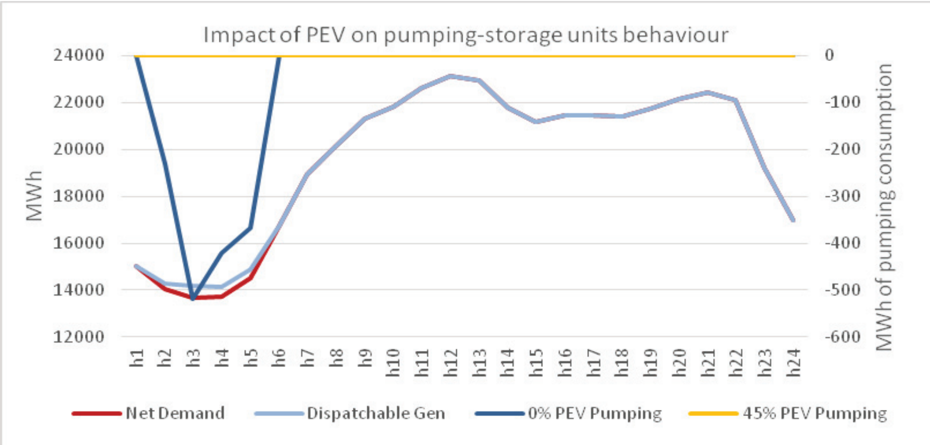


Fig. 6: Impact of PEV on pump-storage units' behavior

3.3. Reserves

Fig. 7 shows the upward reserve allocation for the different solar and wind penetration scenarios.

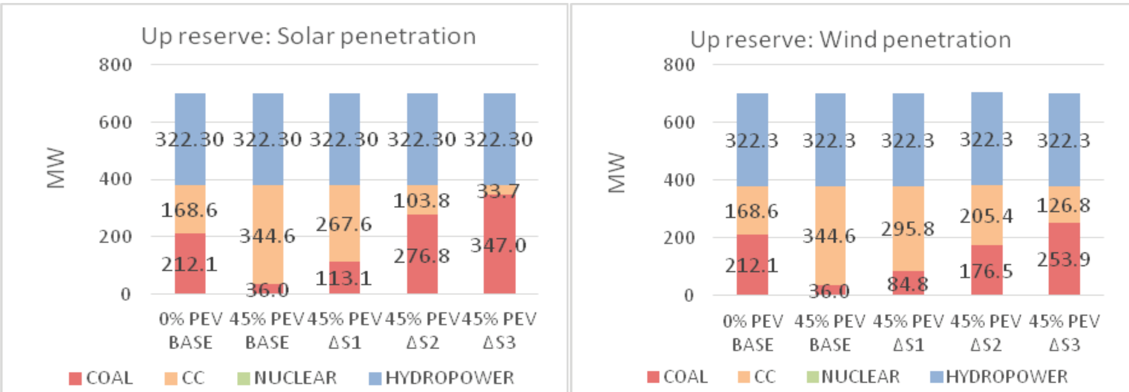


Fig. 7: Hourly average upwards reserve allocation for a) solar and b) wind penetration scenarios

When PEV penetration goes from 0% to 45% with no additional wind and solar installed capacities, the energy consumption and the thermal gap increase and coal plants produce at their maximum capacity (Fig. 2 and Fig. 3), providing almost null reserve. However, when solar and wind increase, the thermal gap decreases and coal plants reduce their production, increasing the reserve they provide. Again, solar production pattern allows for more thermal gap reduction, and so the reserve provided by coal plants is larger for solar penetration scenarios than for wind ones. Downwards reserve shows a similar behavior.

3.4. Operating costs analysis

To help understanding the following sections, Table 2 collects the average costs and emissions of the thermal technologies.

Table 2. Average thermal technologies costs and emissions per plant

Technology	Startup Cost [€]	Shutdown Cost [€]	Fuel Cost [€/MWh]	CO_2 Emissions Cost [€/MWh]	CO_2 Emissions [TCO_2/MWh]
Nuclear	93,467.55	18,693.51	10.45	0	0
Coal	26,897.08	4,168.60	30.23	9.77	1.01
CC	54,142.73	7,212.77	43.04	3.95	0.39
FG	24,135.81	1,953.26	72.51	6.09	0.61

Fuel cost

Fig. 8 represents the contribution of each thermal technology to the total fuel cost (fuel cost allocation) for the week under study.

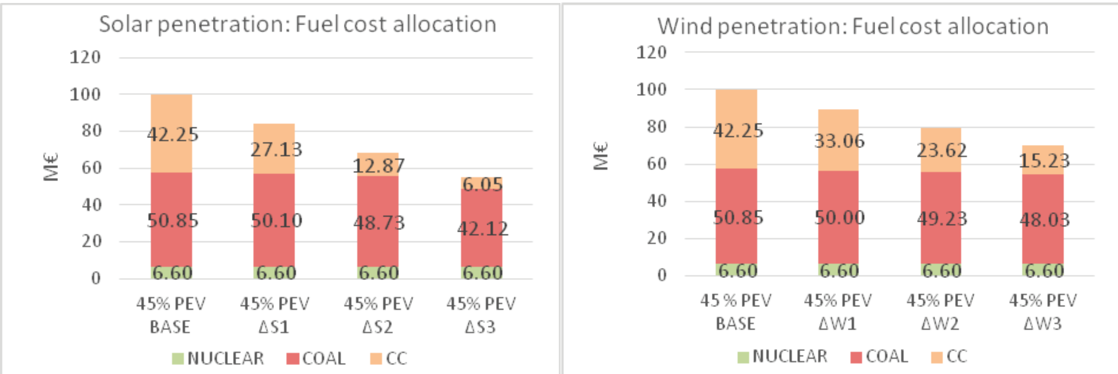


Fig. 8: Fuel cost allocation for a) solar and b) wind scenarios

Nuclear plants are always producing at maximum capacity so their productions and their costs remain constant for all scenarios, as expected. Coal plants are also producing at almost their maximum capacity due to the PEVs large consumption. However, as renewable energy increases, coal plants production decreases and, as mentioned, this decrement is larger for solar penetration due to its hourly production profile. In addition, even if CC production is much lower than coal one, its impact on the cost is larger due to their higher variable cost. For example, from Fig. 4, coal production in scenario ΔS3 is 65.7% of the total thermal production. From Fig. 8, coal impact on the total cost is almost 77% for the same scenario. On the contrary CC production is about 6.3% while its impact on the cost is around 11%. It is also possible to appreciate a significant decrement of 17% of coal costs with respect to the base scenario, while this reduction is only around 5.5% for scenario ΔW3. Again, large penetration of installed capacity of solar generation seems to be more profitable for the system operation than the same capacity increment of wind generation. It will be shown however, than the larger investments cost of solar technology makes the solar investments less profitable than wind ones.

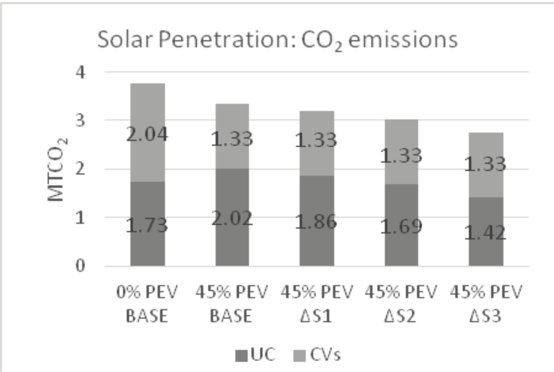
CO_2 emission cost

CVs emissions data are shown in Table 3, where the total kilometers driven by the vehicles of the 21 fleets in [2] for the first week of May are used, distinguishing between gasoline and diesel vehicles whose average CO_2 emissions are slightly different.

Table 3. Basic data of CVs

Fuel	%	Consumption [l/100 km]	Price [€/l]	CO_2 Emissions [TCO2 / km]	CO_2 Emissions Cost [€/TCO2]
Gasoline	46.10	18693.51	1.47	166.15	9.99
Diesel	53.90	4168.60	1.39	126.7	9.99

Fig. 9 shows the CO_2 emissions of the power system and CVs, and Fig. 10 their cost allocation over the thermal technologies. The replacement of CVs with PEVs causes an important decrement of CO_2 emissions (see CVs emissions in light grey for cases 0% PEV and 45%). However, the reduction of CO_2 emissions due to new installed renewable generation is not very large. Indeed, due to the PEVs extra demand, coal plants are producing at maximum capacity and CC plants are needed to supply the demand, so the reduction of the thermal gap reduces only this additional CC production. Since CC emissions are almost negligible, new renewable generation has a final low impact on the total system emissions. Again this reduction is higher for solar penetration due to its hourly generation profile.



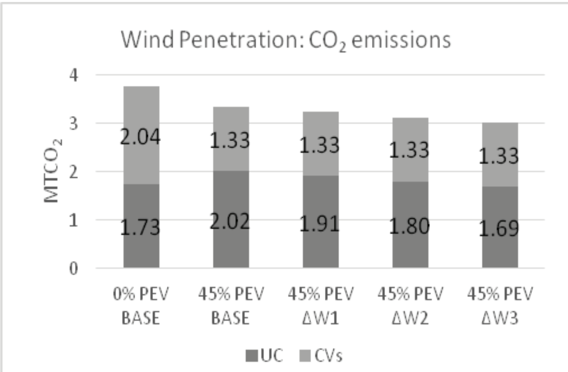


Fig. 9: CO2 emissions for a) solar and b) wind scenarios

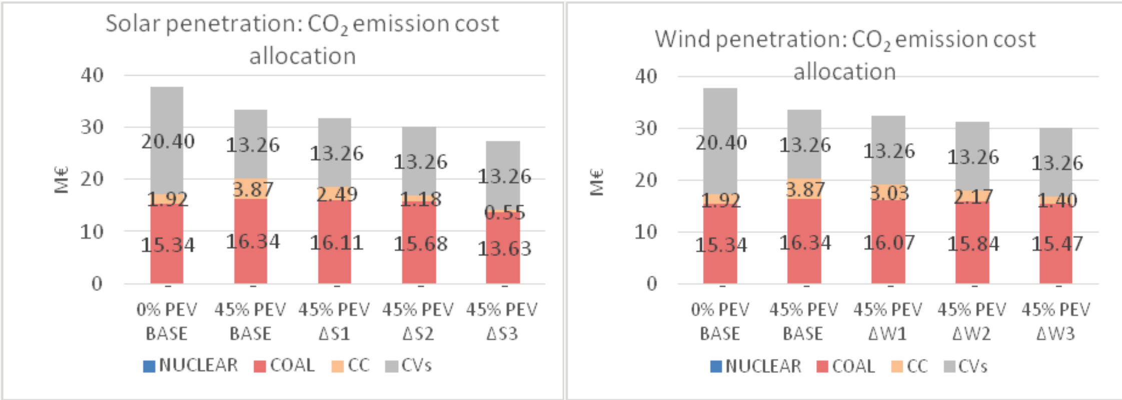


Fig. 10: CO_2 emissions costs allocation for a) solar and b) wind scenarios

Coal plants emissions are much larger, since it is the technology that produces more energy and has larger CO_2 emissions, as shown in Table 2. This implies that the emissions costs of electricity generation are almost hundred percent due to coal plants (Fig. 10), being the impact of CC plants negligible. Since the production of coal plants do not change significantly over the different scenarios (they are supplying at almost maximum capacity), CO_2 costs variations depend mainly on the fluctuations of CC production. Since CC plants have much lower emissions, total CO_2 emissions remain almost constant for most scenarios. Only scenario ΔS3 with a larger reduction of coal production shows a more significant CO_2 emissions reduction. Fig. 11 shows the total variable costs for the simulated week. The impact of CO2 emissions cost on the total cost is almost negligible.

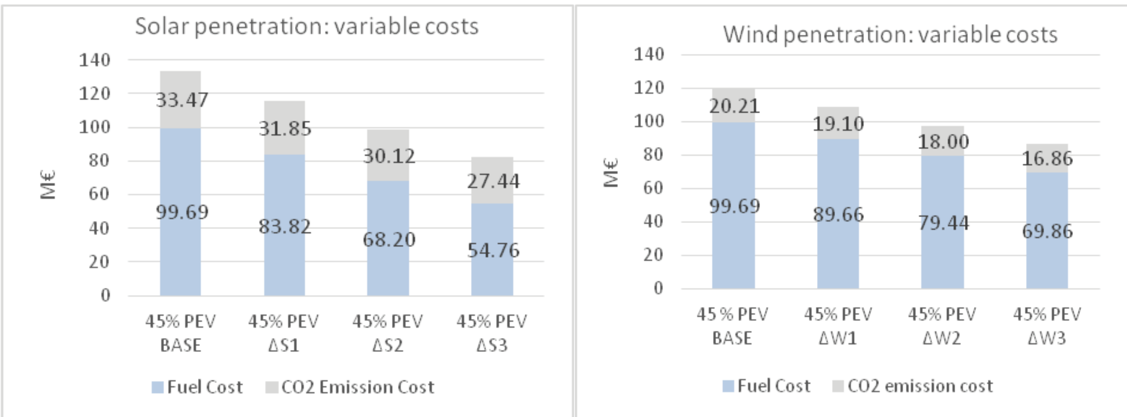


Fig. 11: Fuel costs vs CO2 costs for a) solar and b) wind penetration scenarios

3.5. Electricity price and energy cost

If the electricity price is set as the dual variable of the energy balance constraint (system marginal cost), Fig. 12 shows the resulting prices for scenarios ΔS3 and ΔW3 of solar and wind penetration, for a selected day.

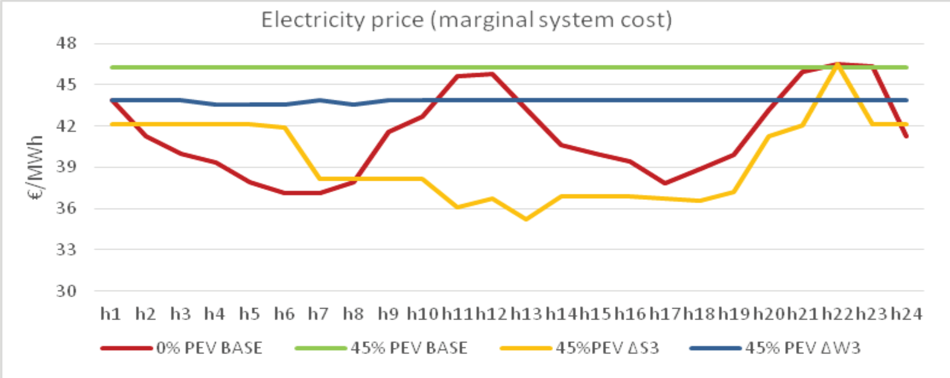


Fig. 12: Electricity prices for scenarios ΔW3 and ΔS3

The first thing to note is how the large PEVs penetration increases demand but smooth electricity prices making them almost constant. This implies a much better behavior of thermal plants, reducing ramps dramatically, and as a consequence their maintenance costs. In addition, as it can be seen in the previous figure, prices for the solar penetration scenario are lower, but show more variability than wind scenario prices. Prices for the solar scenario become up to 6 €/MWh lower than the base case (with 45% PEV but no additional renewable installed), while prices for the wind scenario are only about 2 €/MWh lower than those of the base case. It is also interesting to remark that, at dusk, when solar decreases almost to zero but demand is still high, there are a few hours where solar scenario prices become larger than wind ones, because CC plants are needed to supply the high net demand at these hours.

Fig. 13 shows the average cost of the energy (sum of the energy consumed at each hour times the price at this hour divided by the total energy consumed), which corresponds to the average payment for the consumed energy at the wholesale market (ignoring taxes and additional charges impact, beyond the scope of this research).

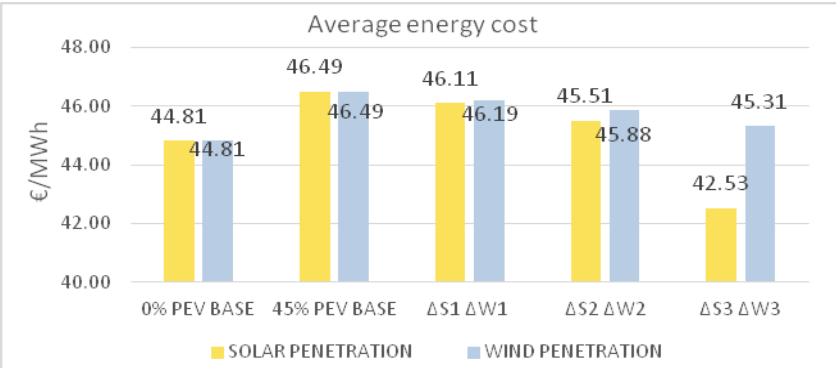


Fig. 13: Average energy costs for solar and wind penetration scenarios

As can be seen, the average costs for the simulated week are very similar for both solar and wind penetrations, although they are lower for the solar scenarios since its generation tends to be located at peak demand hours, so most expensive thermal units are replaced by solar generation. This effect is particularly relevant for scenarios ΔW3 and ΔS3, where the average cost of the solar scenario energy is around 3 €/MWh lower than the wind one. These results are logically coherent with the prices patterns shown in Fig. 12.

3.6. Total costs analysis

For a 45% PEVs penetration, Table 4 summarizes all the costs for all scenarios analyzed for the week under study (RES denoting the particular renewable penetration scenario).

Table 4. Total costs for solar and wind scenarios

RES	Wind/Solar Investment Cost (M€)	Startup and Shutdown Cost (M€)	Fuel Cost (M€)	CO2 Emission Cost (M€)	Total Production Cost (M€)	Total Cost (M€)	Wind/Solar Investment Cost (M€)
BASE	-	3.65	99.69	20.21	123.55	123.55	156.97
ΔW_1	11.5	3.55	89.66	19.10	112.31	123.81	150.83
ΔW_2	23.1	3.55	79.44	18.00	101.00	124.1	132.49
ΔW_3	34.6	3.39	69.86	16.86	90.11	124.71	120.25
ΔS_1	19.2	3.45	83.82	18.59	105.87	125.07	138.27
ΔS_2	38.5	3.35	68.20	16.86	88.41	126.91	119.24
ΔS_3	57.7	3.26	54.76	14.18	72.21	129.91	95.78

For the same PEVs penetration, Table 5 shows the cost increments between each scenario with additional renewable capacity, and the base case with no additional renewable capacity.

Table 5. Total costs variations for solar and wind scenarios

RES	Wind/Solar Investment Cost (M€)	Production Cost Variation (M€)	Energy Cost Variation (M€)
ΔW1	11.5	-11.23	-6.14
ΔW2	23.1	-22.55	-24.48
ΔW3	34.6	-33.43	-36.72
ΔS1	19.2	-17.68	-18.70
ΔS2	38.5	-35.14	-37.73
ΔS3	57.7	-51.34	-61.19

As the previous table shows, given the hypothesis of this paper, investment costs for both solar and wind penetration scenarios are not totally compensated by the production cost reduction. In addition, even if solar generation fits better the demand, with a larger reduction of production costs, its larger investments costs make more profitable wind generation investments. Anyway, the differences between the total cost (investment plus production costs) of increasing solar or increasing wind generation are not very significant. Renewable investments decrease the marginal price (Fig. 12) and so all the technologies' profit, and in particular, thermal plants profits. However, this does not mean that, under a market framework, the total benefit obtained for a particular agent investing in renewable and selling the energy at the marginal price could not be positive (indeed this might be currently happening in Spain with the elimination of the subsidies for renewable generation).

4. Conclusions

This paper presents a detailed analysis of the behavior of the power system when 45% of PEV penetration is combined with different solar and wind penetration amounts. Thermal dispatch, reserve allocation, prices, emissions, emission costs, and total system cost including investments are reviewed. Although this analysis is a simplified approach and considers only a particular week, several relevant conclusions can be drawn from the results:

- The first thing to note is that PEV penetration increases electricity demand. However, if PEVs charge is optimally allocated, thermal plants production is significantly smoothed and prices become almost constant. The optimal allocation of PEVs consumption has a beneficial impact on the final production costs, leading to an almost flat net demand (total demand minus renewable generation).
- Even if solar and wind generation have very similar capacity factors, solar penetration leads to larger prices variability. However, since its production concentrates on peak hours, the resulting production cost is lower than for wind penetration.
- Since current solar investment costs are larger than wind ones, wind penetration is more profitable in terms of total system costs. Neither solar nor wind penetrations are totally profitable for the system from a centralized point of view under the hypothesis of the case studies, due to its investment costs that does not totally compensate the corresponding production cost decrement. However, grid parity is almost reached if no additional costs (such as those for additional reserve requirements or unbalances) are assigned to these technologies.
- The impact of the renewable generation on CO_2 emissions is not very significant under the costs scenarios analyzed. Indeed, large PEVs penetration increases the net demand so much that coal plants are at their maximum capacity and CC are needed to supply the demand. Since renewable penetration is almost only able to reduce CC production, whose emissions are not very significant, final CO_2 emissions do not decrease significantly.

Future ongoing research is oriented to extend this analysis to a whole year simulation, to confirm that conclusions for only one week can reasonably be extrapolated to longer periods. A comparison of this extension with respect to other previous analysis will be also carried out as a future line of research.

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