DECARBONISING THE POWER SYSTEM IN SPAIN. AN ANALYSIS WITH HIGH SPATIO-TEMPORAL RESOLUTION

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RESUMEN

La descarbonización del sistema eléctrico requerirá un despliegue masivo de generación solar fotovoltaica y eólica, ambas caracterizadas por una importante variabilidad espacio-temporal. La modelización del sistema energético permite identificar combinaciones costo-efectivas de los elementos de un sistema eléctrico que garanticen la seguridad del suministro y unas bajas emisiones de CO2. Este estudio investiga la relación entre el objetivo de reducción de emisiones de CO2 considerado para el sector eléctrico y la configuración óptima del parque de generación renovable y almacenamiento para el caso de España. Para ello se emplea PyPSA-Spain, un modelo de código abierto basado en el modelo europeo PyPSA-Eur. Los resultados muestran una fuerte correlación entre la capacidad fotovoltaica necesaria y el objetivo de reducción de CO2 considerado, una mayor idoneidad de la energía eólica para el balance espacial con países vecinos y el papel de las interconexiones para moderar las necesidades de nueva potencia renovable. Además, la alta resolución espacio-temporal del modelo permite obtener las necesidades de capacidad renovable a nivel NUTS 3 (provincias), lo que proporciona información valiosa para responsables políticos, autoridades locales y otros agentes sociales.

Palabras clave: modelado del sistema eléctrico, descarbonización, energías renovables, reanálisis atmosférico, economía de la energía, optimización.

ABSTRACT

Future decarbonised power systems will be based on large-scale deployment of solar and wind generation, both of which are characterised by significant spatio-temporal variability. Energy modelling plays a key role in identifying cost-effective generation mixes that ensure security of supply and low CO2 emissions. This study investigates the impact of the CO2 reduction target on the optimal configuration of renewable generation and storage for Spain. It uses PyPSA-Spain, an open-source model of the Spanish energy system based on the European model PyPSA-Eur. The results show a strong correlation between the required PV capacity and the CO2 reduction target, a higher suitability of wind energy for spatial balancing with neighbouring countries, and the role of interconnections in reducing the required renewable generation

capacity. In addition, the high spatio-temporal resolution of the model allows detailed capacity requirements at the NUTS 3 level (provinces), providing valuable insights for policy makers, local authorities and other societal actors.

Key words: power system modelling, decarbonisation, renewable energy, atmospheric reanalysis, energy economics, optimisation.

1. INTRODUCTION

One of the most cost-effective actions to mitigate climate change in the short-term is the large-scale deployment of wind and solar PV capacity (IPCC, 2023). However, achieving high shares of renewable generation in a power system, where generation and consumption must be balanced at all times, poses new challenges for both system operation and system planning. The main reason for that is the variability of wind speed and solar radiation at different spatio-temporal scales. Several strategies are usually considered to balance variable renewable generation, the most important of which are: massive deployment of storage technologies (temporal balance), expansion of the transmission network capacity and interconnections with neighbouring countries (spatial balance), back-up generation (*e.g.* hydropower or combined cycle gas turbines, CCGT), demand-side management, and oversizing of renewable capacity. The above strategies are highly interconnected in the sense that increased investment in one of them can reduce the need for investment in the others. In this context, energy system models make it possible to analyse the interplay between the aforementioned elements, and to provide national policy-makers, local authorities and other societal actors with insights into cost-optimal configurations of a decarbonised and reliable power system. The implementation of such models requires skills and inputs from a range of disciplines, including meteorology, power system modelling, renewable generation technologies, energy economics and optimisation.

For the specific case of Spain, time-resolved analyses of the power system have been carried out in the past (Galbete, 2013), (Linares, 2017), (Greenpeace, 2018), (Victoria, 2019), (Gallego-Castillo, 2021), (Bonilla, 2022). At the governmental level, at least two relevant analyses have been performed: the one included in the Experts Commission on Energy Transition report commissioned by the Spanish government in 2017 (CETE, 2018) and the Spanish National Energy and Climate Plan (PNIEC by its Spanish acronym) (MITERD, 2024). All these studies are characterised by the adoption of the single-node hypothesis, which neglects the relevance of spatial resolution by assuming infinite capacity of the transmission network. According to the literature, this assumption has several limitations, such as overlooking the conflict between locating wind and PV plants in high resource areas or in areas that minimise the need for transmission grid expansion (Hörsch, 2017).

This work analyses the decarbonisation of the power system in Spain considering high spatio-temporal resolution. The impact of the CO2 reduction target on the optimal mix is studied to provide insights into the role of each technology and their interaction for different stages of the decarbonisation process. In addition, two opposing scenarios are considered: one assumes an isolated power system, and the other includes interconnections with the European power system optimised according to the decarbonisation targets set for 2030.

2. METHODS

The open-source model PyPSA-Spain (see reference in Supplementary Materials) has been used to obtain the optimal generation and storage capacity mixes for peninsular Spain under different decarbonisation scenarios. PyPSA-Spain is an extension of the European model PyPSA-Eur (Hörsch, 2018) that includes a number of specific functionalities to improve the representation of the Spanish power system.

The basic aspects of the power system model implemented in PyPSA-Eur are as follows: the model allows to obtain a clustered version of the high voltage transmission network for a predefined number of nodes. Several elements can be associated with each network node, where energy balance is imposed for every hour during a one year period: conventional and renewable generation capacity, storage capacity, electricity demand and transmission capacity with neighbouring nodes. A Voronoi cell is also associated with each node of the clustered network. It represents the spatial region closest to the node, and is used to estimate the renewable resource. In particular, hourly capacity factors for different renewable technologies (wind and solar PV) are estimated at each Voronoi cell, based on reanalysis data. Land availability in each Vononoi cell is obtained for specific CORINE land cover uses compatible with the deployment of renewable generation capacity, excluding Natura 2000 areas. The electricity demand associated with each node of the network is proportional to the national demand, according to the estimated population and GDP of the associated Voronoi cell. Based on techno-economic assumptions, an optimisation problem with constraints is defined to minimise the total annualised cost of the power system, including investment and operating costs of all elements (generation, storage and transmission grid). Long-term equilibrium is assumed, *i.e.* every investment cost is recovered over the lifetime of the associated asset. The constraints include, among others, security of supply (electricity demand is met every hour in every node) and a predefined CO2 limit. The results of the optimisation comprise the optimal capacity for each technology at each node, and the optimal dispatch, see Supplementary note S15 in (Victoria, 2022) for a mathematical description of the objective functions and constraints.

The main functionalities implemented in PyPSA-Spain to improve the representation of the Spanish power system are: (i) an improved estimation of hourly renewable capacity factors based on a statistical correction (quantile-to-quantile) calibrated with historical data; (ii) the use of real time series of aggregated electricity demand at NUTS 3 level; (iii) the possibility to consider isolated system or with interconnections with Portugal and France. In the latter case, electricity exchanges are determined during the optimisation through price arbitrage. For this purpose, electricity prices for Portugal and France need to be provided as additional inputs.

In this work, the number of clusters was set at 100, which is considered to be high enough to represent the main aspects of the real high-voltage transmission network topology. Figure 1 shows the real (left) and the clustered (right) networks, together with the corresponding Voronoi cells (onshore and offshore within the EEZ area). The meteorological data are taken from ERA 5 reanalysis (horizontal resolution of 0.25º, temporal resolution of 1 hour). Figure 2 shows the spatial distribution of the annual mean irradiance (left) and annual mean wind speed at 100 m (right).

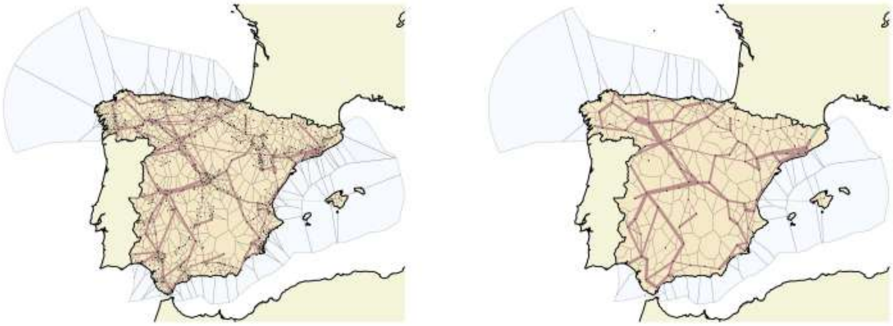

Fig. 1: Real high-voltage transmission network (left) and clustered network with 100 nodes (right), together with the corresponding Voronoi cells. Source: own elaboration.

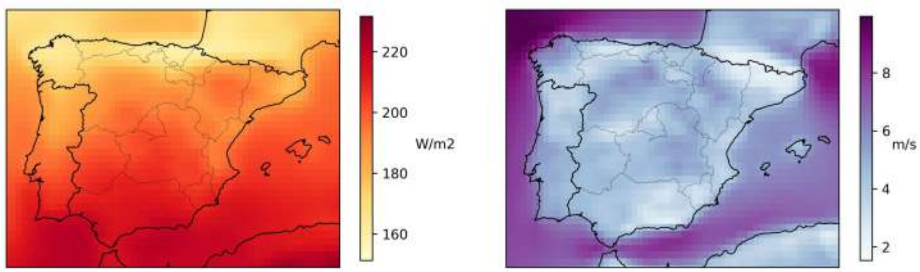

Fig. 2: Annual mean irradiance (left) and annual mean wind speed at 100 m (right). Source: own elaboration from ERA 5 reanalysis data.

The wind turbine models considered are Vestas V112 of 3 MW for onshore and the NREL Reference Turbine 2020ATB of 7 MW for floating offshore. For solar PV panels, a slope of 35º was considered. Storage technologies included in the model comprise batteries, electrolysers, fuel cells and underground H2 storage. Conventional generation technologies included in the model comprise nuclear (3,112 MW, according to the Spanish nuclear decommission pathway for 2030), hydropower (14,965 GW with storage, 8,870 GW with pumped-storage and 277 MW run-of-river) and CCGT (capacity determined during the optimisation stage). The electricity demand for peninsular Spain was set at 344 TWh/year, in line with the 2030 scenario considered in the PNIEC. It is important to note that this scenario assumes a strong electrification, with 50 TWh added to conventional electricity demand due to electric vehicles deployment and green H2 production. Hourly profiles for electricity demand correspond to real data from 2022 provided by Datadis, a platform created by the Spanish electricity distribution companies. To compute the annualised cost of the power system, a discount rate of 7% was assumed. As a conservative approach, the lifetime for wind turbines and solar PV panels was assumed to be of 20 years. Hourly electricity prices in Portugal and France were pre-calculated with PyPSA-Eur for a decarbonisation target of -70% in Europe, in line with the 2030 targets stated in the Fit for 55 package. Table 1 gathers the main investment cost assumptions.

Solar PV	440.0 EUR/kWe
Onshore wind power	1,095.8 EUR/kWe
Floating offshore wind power	2,350.0 EUR/kWe
Battery inverter	169.3 EUR/kWe
Battery storage	150.3 EUR/kWh
Electrolyser	1,500.0 EUR/kWe
Fuell cell	1,164.0 EUR/kWe
H2 underground storage	2.1 EUR/kWh

Table 1: Main investment cost assumptions. Source: https://github.com/pypsa/technology-data

3. RESULTS

The optimal generation and storage mix for peninsular Spain has been obtained for the isolated and interconnected with Portugal and France cases, and for different CO2 emission reduction targets for the power system between 50% to 98% with respect to 1990. To provide context, in 2023 the CO2 emission reduction of the power system was of approximately 62%, and the recently updated version of the Spanish National Energy and Climate Plan (PNIEC) sets a CO2 emission reduction of 82% with respect to 1990 by 2030.

3.1. Global results

Figure 3 shows, on the left, the optimal capacities for the isolated case (no interconnections with Portugal and France) for different CO2 reduction targets. On the right, results for the case considering interconnections with France and Portugal are illustrated.

For the isolated case, the optimal mix shows consistently increasing needs of solar PV capacity for higher CO2 reduction targets, while onshore wind capacity stabilises beyond a 65% of CO2 reduction. Beyond this limit, the deployment of wind capacity occurs mainly for floating offshore wind. This suggests a certain degree of competition between onshore and offshore wind, with capacity being deployed in an order determined by assumed costs, but not between solar and wind. The optimal capacity for batteries run in parallel with solar PV capacity. The optimal CCGT capacity decreases linearly with the CO2 target, well below the actual capacity of approximately 25 GW.

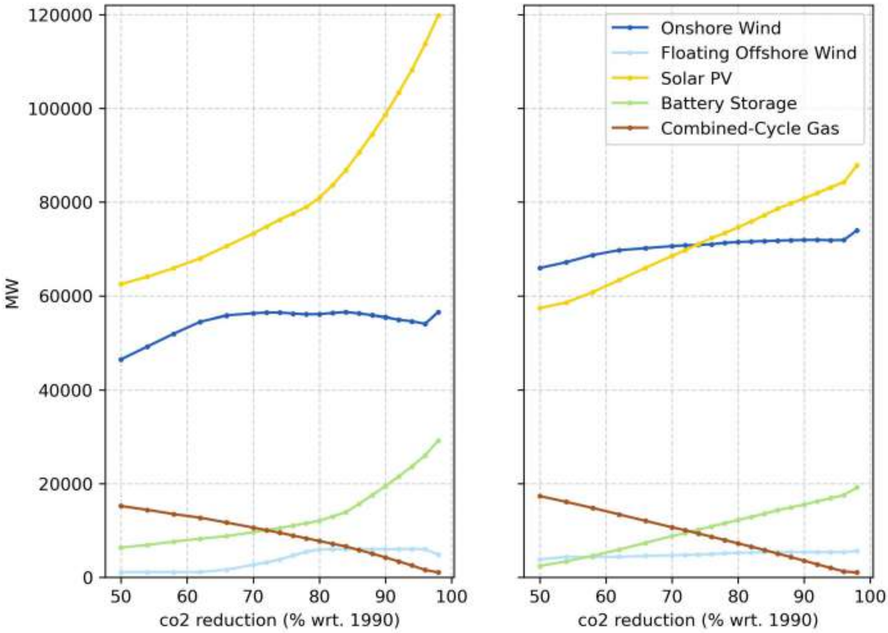

Fig. 3: Optimal capacity for different technologies and CO2 reduction targets. Left: isolated power system. Right: Power system interconnected with France and Portugal. Source: own elaboration.

For the interconnected case, the main difference with respect to the isolated case is that a higher capacity is observed for onshore wind, and a more moderate increase is in solar PV capacity is observed for high CO2 targets. This suggests that wind energy is more likely to be balanced across countries than solar PV, which seems reasonable due to the lower spatial correlation of wind speed compared to solar irradiance. It is also observed that the total renewable capacity (solar PV and wind power) is lower in the interconnected case for high CO2 targets than in the isolated case, highlighting the role of interconnections in reducing the required renewable generation capacity for the same CO2 target.

Finally, it is worth noting that H2 storage is not part of the optimal mix in any of the cases analysed, probably due to the low efficiency of the round-trip electricity-H2-

electricity conversion process. This would probably not be the case if a H2 demand were considered together with the electricity demand.

3.2. Spatial distribution of renewable capacity

Figure 4 shows the spatial distribution of the optimal capacities for onshore wind (top left), floating offshore wind (top right), solar PV (bottom left) and batteries (bottom right), for a CO2 reduction target of 82% (as in the PNIEC) and for the interconnected case. This figure is obtained by aggregating the optimal capacities obtained for the 100 Voronoi cells at NUTS 3 level (provinces).

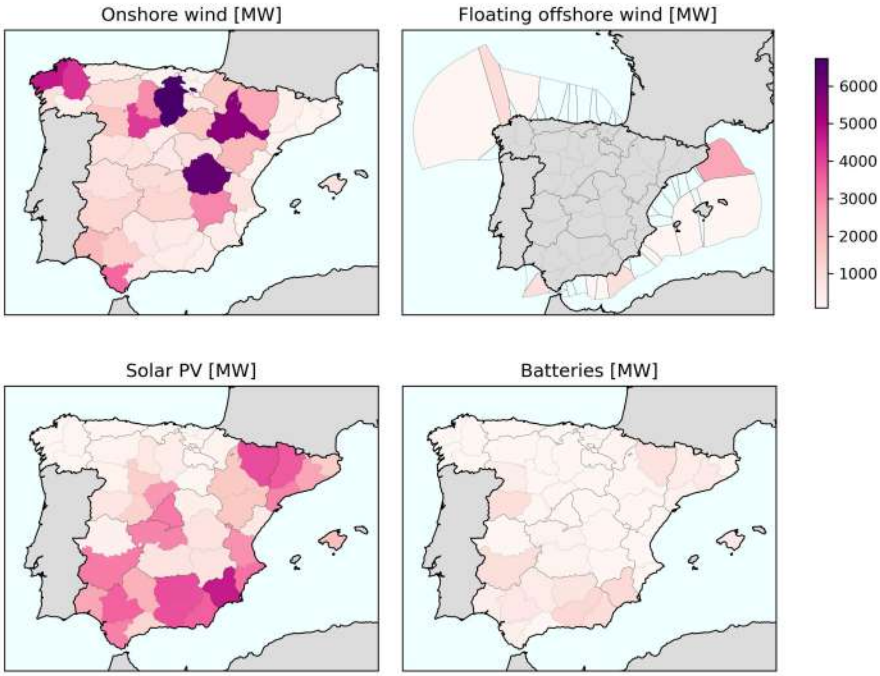

Fig. 4: Optimal capacity aggregated at NUTS 3 level (provinces), CO2 target of 82% wrt. 1990, interconnected case. Source: own elaboration.

It can be seen that onshore wind is the technology that tends to be more concentrated in certain regions, while solar PV capacity is generally more evenly distributed in southern regions. Interestingly, regions with high electricity demand, such as Madrid and Barcelona, or poorly interconnected (as the central part of the Pirenees, see figure 1) also have high solar capacity. Batteries are usually located together with solar PV capacity in order to use the surplus of solar generation during the day to meet electricity demand at night. Concerning floating offshore, specific optimal locations are identified in the map.

4. DISCUSSION

This work provides insights into the renewable and storage capacity requirements to meet different CO2 reduction targets for the electricity sector. In general, the results obtained are in good agreement with the Spanish National Energy and Climate Plan (PNIEC), which foresees the need for a large-scale deployment of renewable generation in order to meet the climate targets. In particular, in order to maintain the actual 62% CO2 reduction in the power sector by 2030 compared to 1990, the results obtained here for the interconnected case show that onshore wind capacity would need to increase from 31 GW to 70 GW and solar PV from 29 GW to 63 GW, while around 4 GW and 6 GW of new capacity would be needed for floating offshore wind and batteries respectively. This would be a consequence of the large increase in electricity demand due to electrification, which would reduce emissions in other sectors such as transport and industry. Increasing the CO2 reduction target from the current 62% to the 82% envisaged in the PNIEC would require an additional 1.5 GW of onshore wind and 13 GW of solar PV, together with 1 GW of floating offshore and 6 GW of batteries. However, it is expected that extending the model with a coupled sector approach (particularly with electric vehicles) would reduce the required capacity for batteries.

The spatial resolution considered in PyPSA-Spain makes it possible to determine the shares of renewable energy and storage capacity required in the different regions of Spain. In this context, the notion of "optimal" is based solely on minimising the total system cost, but does not take into account issues related to public acceptance. Local resistance to the massive deployment of renewable energy is emerging as a potential problem in the energy transition process. The results obtained here could be used as a starting point for the discussion between global needs to decarbonise the Spanish power system, local impacts in specific regions, and required actions to minimise these impacts. Further developments of PyPSA-Spain will aim at analysing the impacts of a more even deployment of renewable capacity across the country.

Finally, in order to place the results obtained in context, the main limitations of this study are detailed: (i) electricity demand time series for 2030 are a re-scaled version of real data from 2022 to meet the assumed annual demand; however, the hourly profile between 2022 and 2030 is likely to change due to emerging electricity uses like the deployment of electric vehicles and green H2 generation; (ii) No grid capacity expansion was considered; according to the literature, grid capacity expansion allows reducing grid bottlenecks, which usually leads to a better utilisation of high wind resources concentrated in specific areas; this could lead to a modified spatial layout of renewable capacity with respect to the obtained here; (iii) the optimisation process assumes perfect forecasting (the electricity demand and generation time series are known in advance for every hour of the year); therefore, the results obtained here represent the best scenario, especially in terms of optimal dispatch.

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SUPPLEMENTARY MATERIALS

The code of PyPSA-Spain is available at: https://github.com/cristobal-GC/pypsa-spain, and related documentation can be found at: https://pypsa-spain.readthedocs.io/en/ latest/. The figures in this paper were generated with pypsa-Xplore, an open set of Jupyter notebooks for exploring the objects generated with PyPSA-Spain and PyPSA-Eur, available at: https://github.com/cristobal-GC/pypsa-Xplore.

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