Technology Determinants of Renewables Curtailment: The Case of Spain

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Abstract

With the increasing share of renewables, increasing volumes of scheduled generation in the electricity markets should be curtailed by system operators to ensure system security and meet network constraints. We study these curtaiments and their drivers in Spain (2024), a country where RES represents 56% of the annual production. Finally we also provide some policy recommendations to reduce curtailments.

Keywords: Energy-only market; day-ahead markets; renewables; decarbonization; ancillary services; redispatching

JEL Classification: D47, L10, L22, L50, L94

1. Introduction

With the decarbonization of power systems, higher volumes of renewable energy sources (RES) are scheduled in the electricity markets. Grid regulations require system operators to always follow specific network operation and system security standards. To achieve this, system operators should, through congestion management services, modify the market schedule by curtailing or dispatching specific units to manage the energy flows.[1]

Activating congestion management services impacts on several dimensions of social welfare. First, curtailed units cannot deliver their production, which might affect their profits if they are not financially compensated. Second, activated units must be financially compensated. Third, CO_2 emissions might increase if conventional thermal generators replace scheduled RES. Finally, customers bear these costs in their electricity tariffs, which impact on customer surplus and economic competitiveness (Davi-Arderius et al., 2023a, 2024).

In Europe, the volumes of curtailed RES have increased and amounted to 58 TWh in 2023, representing less than 1% of total European RES production, and 3% of total electricity demand (ACER, 2024). Between 2019 and 2023, these costs more than doubled in Germany and the United Kingdom, more than fourfold in the Netherlands and almost nine times in Spain (IEA, 2025; REE, 2025). During the covid lock down, cost of curtailments peaked since system operators had to dispatch more non-scheduled thermal plants to ensure system security (Graf et al., 2021; Davi-Arderius et al., 2023a).[2] In 2024, the total energy curtailed by the Spanish system operator was 15 TWh, representing 6% of total electricity demand. Some studies estimate that the annual volumes in Europe might reach more than 800 TWh by 2040 (Thomassen et al., 2024).

We analyze the curtailed and activated units with the congestion management services, namely redispatching processes, in the Spanish power system. We also describe the main operational drivers behind the redispatches. Finally, we provide some regulatory recommendations to reduce their welfare impacts.

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2. Renewable Curtailments in Spain

In 2024, nearly 56% of the electricity generated in Spain was from RES (REE, 2025). Table 1 shows the annual scheduled energy from each technology in the day-ahead markets, as well as the curtailed activated energy for each technology. It is noteworthy that 10% and 21% of all scheduled wind and thermosolar were curtailed. At the same time, system operators activated 15.0 TWh of combined cycle and 2.1 TWh coal power. The cost of these actions amounted to 2.5 b€. These actions produced 7 million tn of CO_2, which accounted for a quarter of total emissions in the Spanish power sector in 2024.[3]

These volumes are used to ensure the security criteria for safe grid operation, in particular (Davi-Arderius et al., 2025):

- **Thermal limits**: Networks have a maximum capacity for energy flows, known as maximum congestion level.
- **Grid redundancy**: Relates to the (back up) redundant network in case of disconnection of a line or transformer and ensures continuity of electricity supply.
- **Voltage limits**: Each network has an operating voltage range.
- **Adequacy reserves**: Minimum upward and downward dispatchable scheduled generation able to cover unforeseen changes in the generation or demand in real-time.

Figure 1 shows the drivers behind the curtailments and activations. Interventions to manage network constraints

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Table 1: Total scheduled energy in the day-ahead markets and sum of the curtailed and the activated volumes from each technology in 2024 (in TWh). Positive values imply volumes of activated energy are higher than curtailed and negative values imply the opposite

	Comb. Cycle	Coal	CHP	Hydrop.	Pumping Generat.	Photov.	Thermosolar	Wind
Scheduled	6.7	0.4	23.7	37.3	4.2	47.8	6.5	68.1
(Net)Volumes of actions	+15.0	+2.1	−1.5	−1.5	−1.3	−2.4	−1.4	−6.8
%	**225%**	**483%**	−6%	−4%	−32%	−5%	−21%	−10%

Source: own calculations based on REE (2025).
Note: Scheduled generation corresponds to the energy scheduled in the day-ahead market, while (net) volumes of actions correspond to the curtailed and dispatched units after day-ahead markets, after intraday-markets and in real-time.

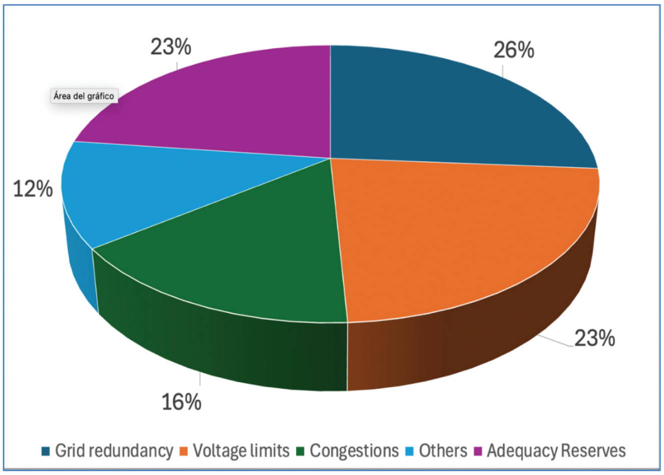

Figure 1: Operational and security needs behind of activated volumes in 2024.
Source: own elaboration based on REE (2025).

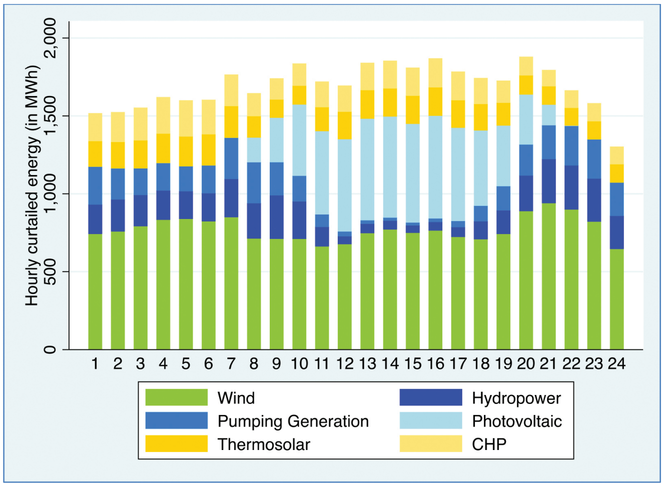

Figure 2: Volumes of curtailed energy by technology and hour (horizontal axis) in 2024.
Source: own elaboration based on REE (2025).

(congestion and grid redundancy) amount to 42% of the total energy. However, the need to ensure operational limits (voltage issues) and minimum dispatchable generation (adequacy reserves) account for 23% of the energy. This shows that operating a highly decarbonized power system requires addressing operational constraints beyond grid bottlenecks. Accordingly, decarbonized power systems require technical solutions that go beyond simply increasing the network capacity.

Volumes for solving voltage issues and ensuring minimum adequacy reserves are explained by lower scheduled production from rotating dispatchable thermal plants, i.e. combined cycles or coal plants, due to higher scheduled RES. Controlling voltage with RES, namely inverter-based resources (IBR), imply that they must meet costly technical requirements such as replaced rotating thermal plants. A combination of different mechanisms can be established for this purpose: (i) grid operators invest in specific assets (capacitors, reactances or static synchronous compensators); (ii) new RES includes specific costly IBR with corresponding impact on their business plans[4]; (iii) customers bear the additional costs for RES through new Ancillary Services paid in their bills (Davi-Arderius et al., 2023c). Increasing adequacy reserves, i.e. increasing dispatchable generation with the capacity to ramp up and down in real-time, implies replacing scheduled RES with dispatchable thermal plants. In the future, hybridization of storage and RES might offer a solution (Frew et al., 2021).

Figure 2 shows the disaggregated average hourly curtailed energy by technology. Between 1.5 and 2 GWh of scheduled energy was curtailed every hour. When analyzing patterns, scheduled wind production is curtailed in all hours of the day, while photovoltaics peak between 12h and 16h. Some of these volumes are "indirect curtailments" related to the need for balancing the demand and generation after activating specific units. Figure 3 shows that activated units are made up of only thermal conventional plants, i.e. combined cycle and coal.

Davi-Arderius et al. (2025) report a detailed empirical analysis of redispatching actions in Spain (2019-2023) and identify main patterns in the scheduled generation technologies, electricity demand and security criteria for safe grid operation. First, volumes to solve voltage issues increase as the electricity demand decreases or increases the scheduled production from RES in the day-ahead markets. Conversely, these volumes decrease when scheduled generation from thermal rotating technologies increases, i.e. combined cycles or CHP. Second, energy volumes for solving grid bottlenecks or congestions increase when demand increases or production from the following technologies increases: combined cycle, CHP or Nuclear. Third, volumes for solving grid reliability issues

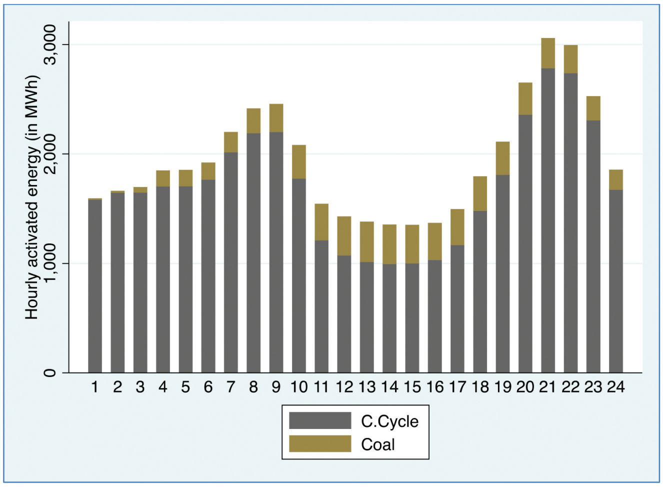

Figure 3: Volumes of activated energy by technology and hour (horizontal axis) in 2024.

Source: own elaboration based on REE (2025).

(N-1) increase when increases the scheduled production from thermosolar, CHP, wind or photovoltaics. Finally, volumes for solving deficit of adequacy reserves increase with the scheduled generation from RES, pumping generation or CHP.

Assessing how these volumes could evolve in the future, Davi-Arderius et al. (2024) find that connecting additional 10 GW of photovoltaics and wind in Spain would increase annual volumes of conventional thermal plants in redispatching processes on 0.8 and 1 TWh, respectively. These volumes imply curtailing equivalent volumes of RES to ensure system balance between generation and consumption. Moreover, implementing energy efficiency programs – reducing 10% of energy consumption each hour – would increase these volumes up to 4.9 TWh. These figures show that operating highly decarbonized power systems increasingly requires solving different operational needs. These actions result in higher costs for customers since they bear the economic compensations for the curtailed or activated units.

3. Policy recommendations

The relevance of interventions is described in the previous section. The key question is how to reduce the rescheduled volumes, costs and emissions. The first set of recommendations relates to operational efficiency of networks. Many studies conclude that reducing congestions requires more locational economic signals, which includes several regulatory instruments:

- Moving from zonal (bidding) prices to nodal prices (Eicke et al., 2022).
- Splitting the current bidding zones (Fraunholz et al., 2021).
- Introducing locational incentives on RES auctions (Davi-Arderius et al., 2023b).
- Introducing regional or dynamic network charges (Wang et al., 2023b).

However, we find that some rescheduled volumes are not related to congestions, but to voltage issues or adequacy reserves. In such cases, complementary regulatory recommendations would be needed (Denholm et al., 2021):

- Optimizing operating rules currently used by system operators to decide under which conditions some generators or customers are curtailed or activated (Mishra et al., 2017).
- Improving grid planning processes currently used by grid operators to optimize when building or reinforcing network (Caputo et al., 2023).
- Implementing stricter technical specifications for IBR, i.e. new wind and photovoltaic plants (Davi-Arderius et al., 2023c).
- Creating new ancillary services to make generators or customers operating under specific conditions to solve voltage issues or ensure volumes of adequacy reserves (Rancilio et al., 2022).
- Implementing hourly time of use tariffs to increase or reduce the consumption and make the system operate under more optimal conditions (Wang et al., 2023a).

Another discussion relates to who (customers or generators) should pay the costs of these actions. In Spain, customers pay these variable hourly costs applied to their hourly energy consumed. Alternatively, these costs could be recovered through fixed network charges, which would require making a prediction in advance of the costs to be recovered during the year. An alternative is to assign some of these costs to generators, especially if their generation patterns cause congestion or voltage issues. However, implementing a fair and transparent assignment of costs requires detailed studies to avoid impacts on the efficiency of electricity markets. In any case, customers will pay these costs through their electricity bills.

4. Conclusions

In this article we discussed the volumes of curtailed and activated generators in a highly decarbonized power system. Most of the curtailed units are made of RES, while the activated units are conventional thermal technologies. It is noteworthy that non-grid bottlenecks represent volumes of curtailed and activated energy. In terms of economic welfare, these processes result in additional costs for customers and CO_2 emissions. This highlights that it is essential to deep dive in forecasts of how these figures could evolve in the future to ensure a reliable, sustainable and affordable energy transition.

As described in the above, there is no single and perfect regulatory recommendation to reduce the volumes since they have very different drivers: congestions, voltage issues and adequacy reserves. Countries need to implement a panel of solutions aimed at providing locational incentives. They can also implement additional solutions to create ancillary services or improve how these operational constraints are made or solved. Otherwise, welfare impacts will become significant, and some expected benefits of decarbonizing power systems might not be achieved.

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Footnotes

[1] Congestion management services include mechanisms such as redispatching processes, flexible connection agreements or local flexibility services.

[2] Due to the lower demand, less thermal capacity was scheduled in the day-ahead markets.

[3] The CO2 emission factors considered are 0.95 tn CO2/MWh for coal, 0.37 tn CO2/MWh for combined cycle, 0.38 tn CO2/MWh for CHP and 0.24 tn CO2/MWh for biomass plants. Source: REE (2021). Annual CO2 emissions in 2024 were 27 million tn of CO2 (REE, 2025).

[4] This includes the Levelized Cost of Energy (LCOE), which considers the investment and operational costs over lifetime of RES (Shen et al., 2020)