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Short-term impact of the COVID-19 lockdown on the energy and economic performance of photovoltaics in the Spanish electricity sector

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ABSTRACT

The present work investigates how the COVID-19 related lockdown imposed in Spain in between March and June 2020 affected the national electricity sector and the share of photovoltaics in the energy mix. The analysis is conducted by comparing actual electricity demand, generation and price data with forecasts based on their pre-lockdown trends. The results show that the lockdown decreased the electricity demand by 11%, and affected even more severely the price of electricity, causing a total loss for the electricity sector of 6.1 million € per day. These losses were unevenly distributed among the different power technologies of the energy mix. The market share of photovoltaics raised by almost 1% because of the lockdown-related demand drop, even if it performed at capacity factors lower than expected. Overall, because of the lockdown and of the recently installed capacity, photovoltaic provided, for the first time, more than 9% of the national electricity consumed in June 2020, more than twice the maximum share achieved in the previous years.

1. Introduction

On March 11, 2020, the World Health Organization (WHO) declared the ongoing COVID-19 respiratory disease caused by the SARS-CoV-2 virus a pandemic (World Health Organization, 2020). In order to slow the spread of the virus, several governments put in place severe lockdown measures, limiting the people's freedom of movement, cancelling public events and suspending several commercial activities. These measures led to changes in the socioeconomic habits that affected also the electricity sector, with consequences on the consumption profiles of several countries. As a result of the restrictions on the industrial and commercial activities and of the "stay at home" policies, the residential electricity demands increased, while the industrial/commercial demands decreased (Madurai Elavarasan et al., 2020).

By March 13, 2020, Europe had become the epicenter of the pandemic (World Health Organization, 2020b). Spain, one of the top 5 energy consumers in Europe and of the top 20 worldwide (U.S. Energy Information Administration, n.d.), was one of the first European countries severely hit by COVID-19. The Spanish Government imposed, on March 14, 2020, a national lockdown that lasted until June 21, 2020 (Table 1). An even stricter halt on all non-essential activities was put in place around Easter (March 30 to April 9, 2020). A first analysis on the effects of the lockdown on the Spanish electricity sector found that, in between March 14 and April 30, 2020, the electricity demand fell by 13.5% compared to the

Abbreviations: a, Actual value; CAMS, Copernicus Atmosphere Monitoring Service; CF, Capacity Factor [%]; CP_{PS}, *changepoint_prior_scale*; CP_R, *changepoint_range*; d, Day; DNI, Direct Normal Irradiance [kWh/m^2/day]; FBP, Facebook Prophet; f, Forecasted value; GHI, Global Horizontal Irradiance [kWh/m^2/day]; MS, Market Share [%]; ME, Mean Error; OMIE, Operador del Mercado Ibérico de Energía (nominated electricity market operator); $PM_{2.5}$, Mass concentration of suspended fine particles (diameter $\leq$ 2.5 μm) [μg/m3]; PM_{10}, Mass concentration of suspended coarse particles (diameter $\leq$ 10 μm) [μg/m3]; PV, Photovoltaics; REE, *Red Eléctrica de España* (Spanish electricity grid operator); StD, Standard Deviation; WHO, World Health Organization.

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Table 1
Timeline of the State of Alarm in Spain in spring 2020 and summary of the main measures.

Date	Event	Main Measures
March 14	Declaration of State of Alarm for fifteen days (RD 463/2020), later extended multiple times.	• Movements only allowed for work or necessities. • Closure of restaurants and businesses, except of those that sell food or basic necessities. • Closure of schools, universities and other types of educational centers. • Promotion of remote working in most of the jobs.
March 30 to April 9	Non-Essential Work Ban (RD 10/2020)	• Closure of work places of companies and compulsory paid leave for all non-remote working employees who do not provide essential services.
May 4	Start of Phase 0 (SND/388/2020), postponed in some areas.	• Outdoor walks and non-contact sport practice allowed. • Opening of small businesses by appointment only. • Opening of restaurants for take-away.
May 11	Start of Phase 1 (TMA/400/2020), postponed in some areas.	• Movements inside provinces allowed. • Gatherings of up to 10 people of non-high-risk groups allowed. • Opening of bar terraces, religious centers, libraries, museums, and small business stores at limited capacities. • Partial opening of hotels and touristic accommodations. • Restart of cultural events with limited capacity. • Opening of gyms and health clubs' installations by appointment only.
May 25	Start of Phase 2 on mainland Spain, postponed in some areas.	• Gatherings of up to 15 people per group allowed. • Opening of indoor areas of restaurants, commercial establishments, beaches, cinemas, theatres and museums with capacity restrictions • Opening of driving schools and academies. • Wedding ceremonies allowed with limited capacity. • Non-professional sport training in groups allowed.
June 8	Start of Phase 3 on mainland Spain, postponed in some areas.	• Gatherings of up to 20 people per group allowed. • Increased capacity for restaurants, commercial establishments, museums. • Progressive return of non-essential workers to offices. Conferences and business meetings up to 80 people allowed. • Wedding ceremonies allowed, with up to 75 people indoors and 150 people outdoors.
June 22	End of State of Alarm. New Normality.	• Freedom of movement across the country. • Opening of borders to people from European Union and Schengen countries, with the exceptions of Denmark (27/06) and Portugal (01/07). From July 4, progressive opening of borders to countries from other continents. • From August 19, compulsory use of face mask for all people of age >6 on mainland Spain in public spaces.

previous five years, with the most severe drops on the weekdays (Santiago et al., 2021). A subsequent investigation found that the energy demand in Spain in between March and July 2020 lowered by 21% compared to the forecast, and that it returned to the baseline level only at the end of July (López Prol and O, 2020).

The loss in demand was not the only effect of the lockdown on the electricity sector. Indeed, most of the electricity in Spain, as well as in other European and worldwide countries, is subject to a daily market-based competition (Ciucci, 2020). This means that the price of electricity varies depending on the daily and hourly difference between supply and demand, and on the sources and costs of the available energy. Therefore, because of the lockdown effects on the electricity demand and on the energy mixes, even the prices of the electricity were reported to lower. For example, in between March and May 2020 the electricity price in Germany dropped by 20 €/MWh compared to the previous year (Halbrügge et al., 2021), pushed by the drop in consumption and the higher renewable contribution. Similarly, in March 2020, the electricity price in Italy decreased by 30% compared to the previous years, following a drop in consumption of 37% (Ghiani et al., 2020). So, in order to understand the full extent of the effects of the lockdown on the Spanish electricity sector, it is important to take also into account its impact on the electricity price trends.

An additional result of the drop in electricity demand was the increased share of renewables in the energy mix of several countries, at the expense of coal, oil and nuclear technologies (Werth et al., 2021). A similar increase in the share of renewables has been already reported for Spain (Santiago et al., 2021). However, it should be noted that the Spanish electricity market had been already experiencing a significant shift toward renewables. At the end of 2019, indeed, renewables accounted for 50.2% of the 110 GW of the national energy generation capacity, 3.4$\%_{abs}$ more than the year before (REE, 2020). Therefore, the analysis of the energy mix should also take into account these longer-term trends, and isolate them from the effects of the lockdown.

Photovoltaic (PV) has been the fastest growing technology in the Spanish energy mix since 2019. The cumulative PV capacity has doubled in just 18 months, from 4.7 GW in January 2019 to >9.5 GW in June 2020. PV systems convert the sunlight into electricity and, therefore, their energy generation strongly depends on the solar irradiance. Air quality improvements have been reported worldwide as consequences of the lockdown measures (Le Quéré et al., 2020) and, in a cleaner air context, an increase in irradiance could also be expected. For this reason, a lockdown-related raise in PV performance was anticipated as well, at least in severely polluted areas (Peters et al., 2020).

The present work aims to contribute to the analysis of the short-term impact of the spring 2020 lockdown on the Spanish electricity sector. This study takes into account that the Spanish electricity market was already experiencing lockdown-unrelated changes, such as the pre-existing shift toward renewables. A univariate-forecasting tool is used to differentiate the consequences of the lockdown from the effects of long-term and seasonal trends affecting the energy sector. The findings of the previous publications are here extended to include also a study on the electricity price and a discussion on photovoltaics, which was already expected to achieve record market shares in 2020, because of the significant new capacity installed in 2019. Overall, the three main objectives of this work are:

- Providing a first estimate of the revenue lost by the Spanish electricity sector in the first half of 2020 because of the

concurrent and related drops in electricity demand and price caused by the lockdown,
- Analyzing the capacity factors of each power generation technology in the energy mix, distinguishing between the long term effects of the growing renewable capacity and the shorter term effects of the lockdown,
- Investigating the performance of photovoltaics in a period in which it supplied a record 9% of the Spanish electricity consumption, separating the impact of the lockdown-related demand drop from the contribution of the recently installed capacity.

This work estimates the economic loss caused by each day of lockdown to the national electricity sector and analyzes the different behaviors of the various power technologies. These results can help policy makers and energy players to better understand and predict the impact of similar measures that might be put in place in the future. The findings can be considered representative for a number of countries whose economy, electricity market, green energy policies and COVID-related measures are similar to, if not even the same as, those of Spain. In addition, the implemented methodology can be easily re-applied to simulate the effects of a lockdown on different countries and for various conditions.

2. Materials and methods

The analysis implemented in this work follows the procedure described in Fig. 1. Electricity data from 2011 to February 2020 are used to generate forecasts, which are compared with the actual 2020 data to estimate the impact of the COVID-19 related measures. The market share and the capacity factor of PV are then analyzed in particular and discussed in light of irradiance and particle matter data.

2.1. Electricity data

The performance of each power technology in the electricity mix is quantified through the daily capacity factor, which expresses the ratio of the energy produced to the maximum possible energy output. The capacity factor *CF* of each *i*-technology on the day *d* is calculated as:

$$CF_i(d)[\%] = \frac{Daily\ National\ Generation_i\ (d)}{National\ Capacity_i(d)\cdot 24h}\cdot 100\% \qquad 1$$

Daily generation data are sourced from the data made available by the *Red Eléctrica de España* (REE), which operates the national electricity grid (REE, 2020). Data from 2011 to August 2020 are collected for ten electrical power technologies: coal, cogeneration, combined cycle, fuel & gas, hydro, nuclear, pumped storage, solar photovoltaic, thermal solar, and wind. The remaining technologies, including hydroeolian, renewable waste, geothermal and biomass, representing about 1% of the national capacity, are grouped and classified as “Other Renewables”. REE also provides daily demand data and the national installed capacity of each technology. Monthly capacities are made available for 2019 and 2020, while only the annual capacities are available for the previous years. The analysis presented in this work considers daily capacity values: these have been estimated through linear regression.

Since all the PV-generated energy is supplied to the consumers, the contribution (or “market share”) of the PV technology is calculated as:

$$MS_{PV}(d)[\%] = \frac{Daily\ National\ PV\ Generation(d)}{Daily\ National\ Demand(d)}\cdot 100\% \qquad 2$$

The turnover, or revenue, of the electricity sector in Spain is estimated as the sum of the daily product of electricity price and electricity demand. About 80% of the electrical energy in Spain in 2019 was managed by OMIE (*Operador del Mercado Ibérico de Energía*), the nominated electricity market operator, through one day-ahead and two intraday markets (OMIE, 2020a). The weighted average of the electricity prices of these three markets (*precio final medio demanda nacional*) was used to calculate the turnover of the electricity sector for the period in between January 2011 and August 2020 (OMIE, n.d.). It is important to note that this price contains the additional cost of the system, but does not include taxes and grid access fees.

2.2. Forecasts and uncertainty

In Spain, the electricity demand and the electricity price have seasonal trends, with typically lower values in spring. Fig. 2 shows that, for both the electricity demand and price, the drops recorded during the lockdown are visually more severe than any seasonal variation. These cannot be related to long-term patterns either, as the effects of the lockdown imposed in March 2020 are gone towards the end of the summer. In order to remove the effects of any long-term and seasonal trend from the analysis, this work compares the 2020 data with forecasts rather than with previous years' averages. The impact of the COVID-related measures on each variable was calculated as the deviation of the actual values (a) from the forecast values (f): $(a-f)/f$. In this form, the deviation is negative if the actual value is lower than the forecasted one. The mean monthly deviations were calculated as average of the daily deviations. Where shown, the mean error (ME) was calculated as mean of the daily deviations in January and February 2020 (the last months before the lockdown was put in place).

The forecasts presented in this study were produced using the Facebook Prophet (FBP) algorithm (Taylor and Letham, 2017). FPB generates univariate forecasts through the addition of three components that it extracts from the historical time series of each

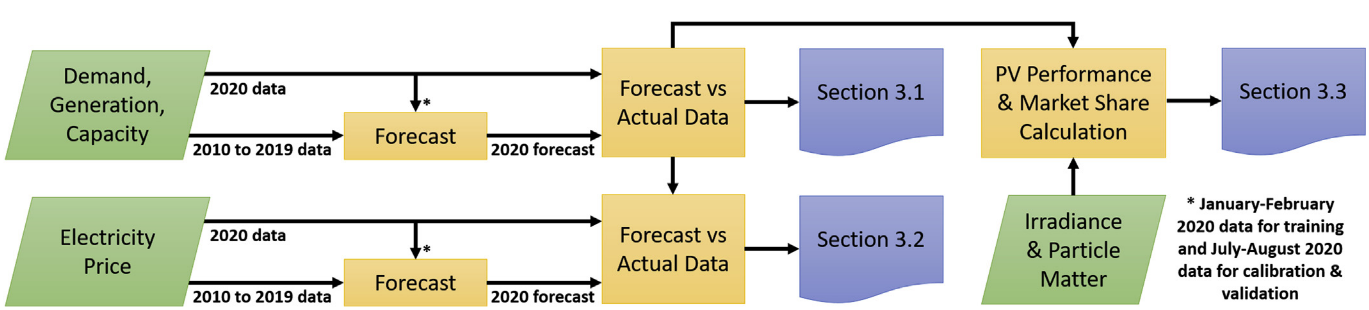

Fig. 1. Schematic of the procedures employed in this work and organization of the results.

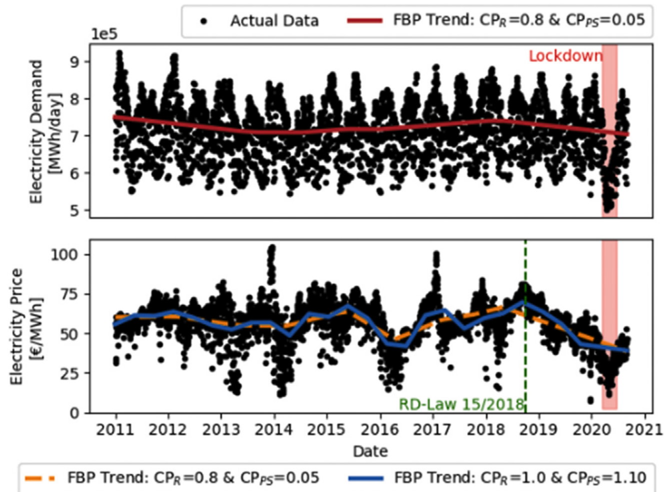

Fig. 2. Data and trends of daily energy demand (upper plot) and electricity price (lower plot). The red area highlights the lockdown period. The Facebook Prophet inputs are shown as CP_R (changepoint_range) and CP_{PS} (changepoint_prior_scale).

variable: trend (non-periodic changes), seasonality (periodic changes), and holidays (irregular schedules). In this work, the trends were modelled through the default piecewise linear regression, making use of automatically detected change points. A logistic growth trend model was also tested, but it did not lead to significant improvements in this case. Fourier series were used to model the seasonality. FBP was provided with the actual data up to the end of February 2020 and with the default set of parameters as inputs, and it was left to self-tune. By default, the algorithm looks for change points in the initial 80% of the time series (*changepoint_range* = 0.8). This limit is recommended so that FBP avoids overfitting variations toward the end of the time series. In this case, the default inputs worked well for the estimation of the electricity demand (upper plot of Fig. 2), as the average monthly forecasts met the actual values in July and August 2020, the two months immediately after the end of the lockdown (deviation $\leq$ 0.5%).

On the other hand, FBP would have not been able to catch the change in price trend occurred on October 5th, 2018, if provided with the default inputs (dashed orange line in lower plot of Fig. 2). On this date, indeed, a series of measures related to tax regulations were adopted (RD-Law 15/2018) and are considered to have contributed, along with a decrease in gas, coal and Brent prices (AleaSoft, 2019), to the drop in electricity price experienced since 2019. Therefore, it was decided to increase the *changepoint_range* and, in light of the high daily variability of the electricity price, to raise also the flexibility of the model, through the *changepoint_prior_scale* input parameter (default = 0.05). A calibration was conducted for various input values, assuming that the electricity price had restored by August 2020, similarly to the demand profile (López Prol and O, 2020). The *changepoint_range* parameter was varied between 0.80 and 1.00 at steps of 0.05 and the *changepoint_prior_scale* parameter was varied between 0.05 and 1.50 at steps of 0.05. The minimum deviation in the estimation of the price in August 2020 was returned for *changepoint_range* = 1.0 and *changepoint_prior_scale* = 1.1 (blue solid line in lower plot of Fig. 2).

The economic revenue (or turnover) forecast, in this work, was produced as product of the price and the demand forecasts.

The quality of the model implemented in this work can be seen in Table 2, where the mean errors between the actual and the modelled electricity demand, price and revenues are shown for the years in between 2015 and 2019. As it can be seen, the errors are minimal for the electricity demand, while range in between ±2% for price and revenues.

Table 2
Average mean error, in %, between the modelled and the actual daily data for three investigated variables, considering the years in between 2015 and 2019.

	Demand	Price	Revenues
2015	−0.39	−1.51	−2.01
2016	−0.09	1.93	1.74
2017	0.01	−1.35	−1.45
2018	0.03	1.22	1.06
2019	−0.37	−0.07	−0.63

The capacity factor of each power technology was independently analyzed, using the daily data from 2011 to the end of February 2020 (Fig. 3) and the default FBP's settings, as in the electricity demand model. Data for "Other Renewables" were only available since 2014. No reliable forecast could be produced for "Coal" and, so, it was excluded from the technology-specific analysis.

2.3. Irradiation and particle matter

In order to analyze the PV performance, the present work made use of the irradiation data sourced from CAMS (Copernicus Atmosphere Monitoring Service, n.d.). Daily time series were downloaded from 2010 to the end of August 2020 for 205 locations at a resolution of 0.5° latitude × 0.5° longitude (left plot of Fig. 4). Only data points on Spanish mainland were considered. CAMS makes available both actual weather and clear-sky data (Lefèvre et al., 2013; Qu et al., 2017). These latter represent the estimated irradiation in cloud-free conditions, and are generated using aerosol, ozone and water vapor data.

Also the aerosols can affect the PV performance. For this reason, the present work includes also an analysis of the particle matter, whose 2013 to 2020 daily concentrations were downloaded from (European Environment Agency, n.d.). The particle matter is generally expressed through the PM_{10} and $PM_{2.5}$ indexes, which measure the concentrations of airborne solid or liquid particles less than 10 μm and less than 2.5 μm in diameter, respectively. The database makes available PM_{10} and $PM_{2.5}$ data for respectively 513 and 261 locations in Spain. However, monitors that stopped taking measurements before July 2020 or that started measuring air quality after the end of 2014 were discarded. This way, only time series that covered the full lockdown period and had at least 5 years of prior data were considered. However, this limited the number of locations to 189 for PM_{10} and 68 for $PM_{2.5}$ (right plot of Fig. 4). This means that, unfortunately, at the time of the study, the 2020 data were not available for most of the monitors. It is acknowledged that the available monitors were unevenly distributed across the country and that some regions, such as the Northeast, were not or under-represented. Future works should extend this investigation as new data become available.

3. Results and discussion

3.1. Electricity demand and generation

The present analysis focuses on the period in between March 14 and June 22, 2020. In this period, the Spanish electricity consumption typically lowers, reaching the yearly minimum in between April and May. In the years in between 2011 and 2019, the energy demand in these months has been 85.5% and 88.2% of that in January, the month of maximum consumption. Percentages of

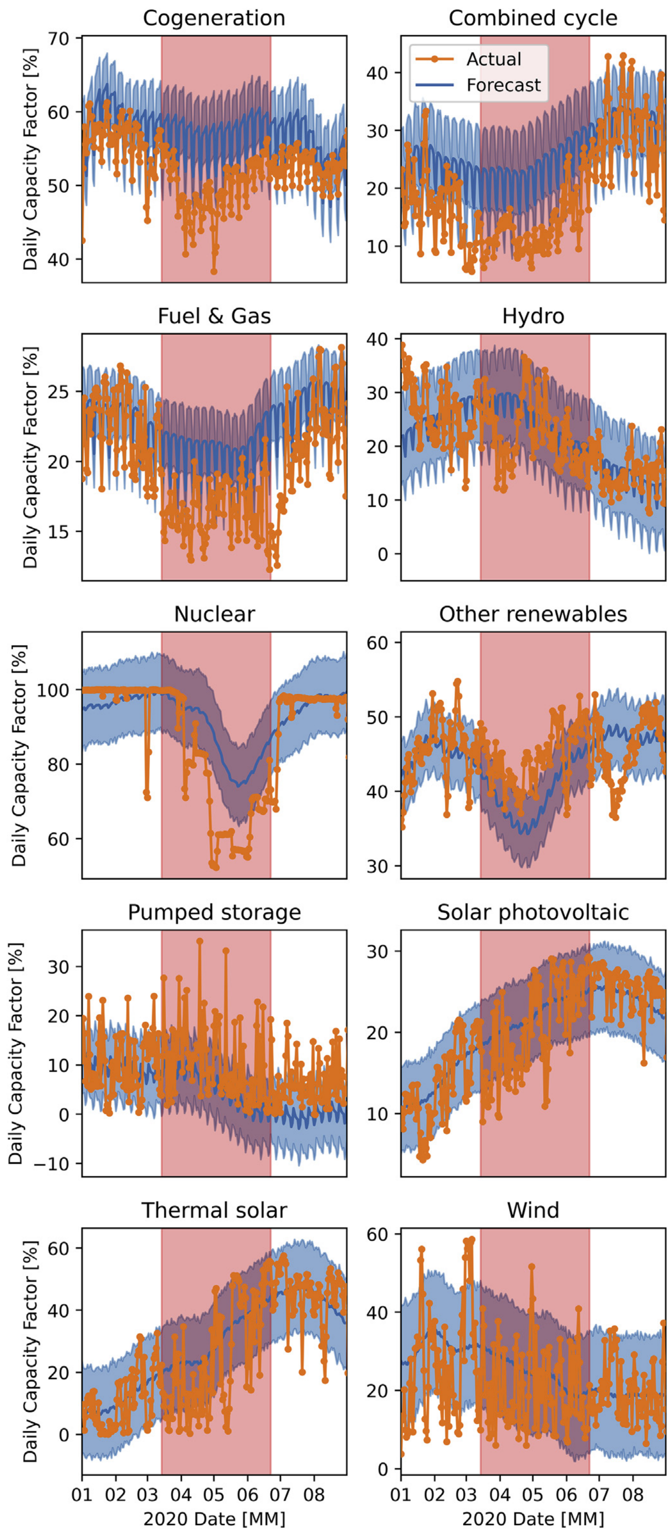

Fig. 3. Forecasted (blue) and Actual (orange) capacity factors of the different technologies in the Spanish energy mix. The blue area represents the forecast's uncertainty.

84.4% and 86.7% were forecasted for April and May 2020 by FBP. However, in reality, the electricity demands in April and May 2020 were only 71.5% and 76.8% of that in January 2020.

So, the lockdown worsened the seasonal low typically experienced in the spring months. Between March 14 and June 22, 2020, the energy demand was indeed averagely 11.0% lower than forecasted (Fig. 5), a drop significantly larger than the mean modelling error registered for January and February 2020 (−2.0%). It is worth highlighting that these losses are on top of the seasonal trends. The most severe losses occurred in April (−14.3%), with a peak of −20.0% per day in the week of April 6, toward the end of the non-essential work ban. After that period, the demand started to recover and reached its expected value at the end of the lockdown. Indeed, in July and August 2020, the deviation of the actual data from the forecast was ≤0.5%, smaller than the modelling error.

The deviation in demand compared to the forecast was more intense during the lockdown weekdays (12.1% ± 0.6%) than on the weekends (8.5% ± 0.9%). This gap became even more significant during the non-essential work-ban, with an average 14.4% ± 1.6% drop on weekdays and 8.4% ± 0.7% drop during the weekends. This was probably due to the suspension of commercial and industrial activities and to the closure of offices and schools, which, in normal conditions, are predominantly active during weekdays.

The lower electricity demand affected unevenly the various technologies of the Spanish energy mix (Fig. 6). Cogeneration, combined cycle, fuel & gas, and nuclear were the technologies whose underperformance exceeded the forecast uncertainty. These technologies combined represented the 38% of the national electrical capacity at the end of 2019. On the other hand, positive performances have been found only for the "Other Renewables" technology group, representing only ~1% of the national capacity. This is a cumulative result and does not necessarily mean that all the technologies in the group over-performed. The uncertainty bars in Fig. 6 have been conservatively calculated as difference between the sum of the maximum daily values and the sum of the minimum daily values in the forecast uncertainty range.

The negative results of cogeneration, combined cycle and fuel & gas are justified by the fact that these are the sources with the highest opportunity costs. This means that they typically stand at the top of the hourly supply curve of the electricity market. Therefore, in a lower-demand context, as that experienced during the COVID lockdown, it is not surprising to see their contributions to the energy mix drop. Renewables and nuclear energy covered respectively 96%, 99% and 97% of the day-ahead operations program in March, April and May 2020 (OMIE, 2020), compared to 94%, 93% and 87% in 2019. It should be noted that, even if not included in the day-ahead market, where most of the electricity is traded, cogeneration, combined cycle and fuel & gas energies were still sold through the intraday markets. On the other hand, nuclear energy is always at the base of the day-ahead supply curve, because of the high start and stop costs. However, due to the reduced energy demand and the low electricity prices experienced during the lockdown (discussed in the following section), they were also set to work at minimum performance (Monforte, 2020).

3.2. Electricity price and market revenues

The drop in electricity price during the lockdown was more severe than the energy drop (−15.8% compared to the forecast), with average decreases of 17.9% in April and 24.8% in May (Fig. 7) and substantial effects that prorogated at least one month after the end of the lockdown. In this case, the maximum drop (−43.6%) is found on the week of April 27, with a mean error in January and February of 5.0%.

The variation in electricity price during the lockdown period is found to be correlated to the change in electricity demand. Indeed, when the weekly averages are compared, a drop of 0.09 €/MWh is registered for every GWh of reduction in energy demand (R^2 of 70%). However, it should be noted that the demand is not the only factor affecting the electricity price. Indeed, also the type, the

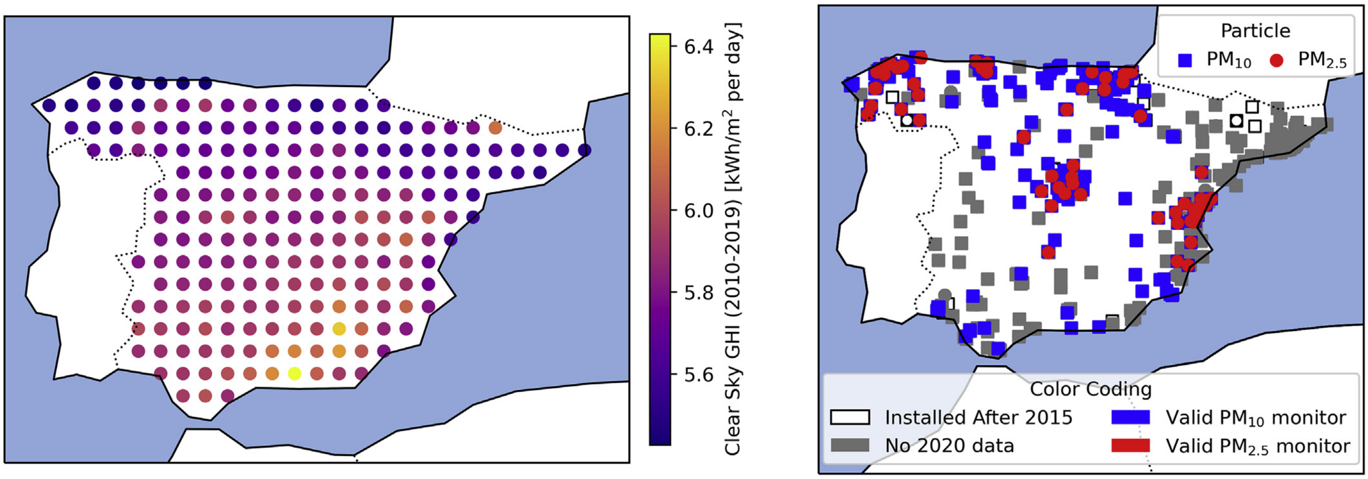

Fig. 4. Left: grid showing the irradiation data used in this study. The average daily clear sky Global Horizontal Irradiation (GHI) is shown, calculated for the years 2010–2019. Right: map of the particle matter monitors used in this study, and location of the discarded ones.

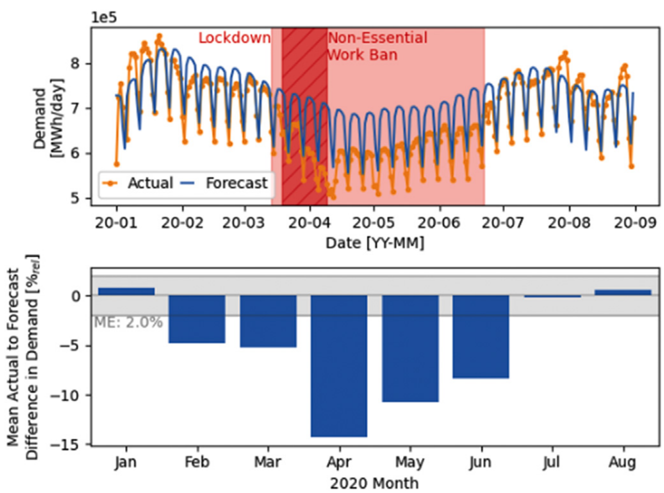

Fig. 5. Upper plot: Forecasted and actual daily energy demand in Spain in 2020. The light red area highlights the lockdown period, while the darker hatched red area marks the non-essential work ban period. Lower plot: Difference between monthly mean forecasted and actual demand. The grey area represents the estimated mean error (ME), calculated as the average of the difference between actual and forecast data in January and Februray.

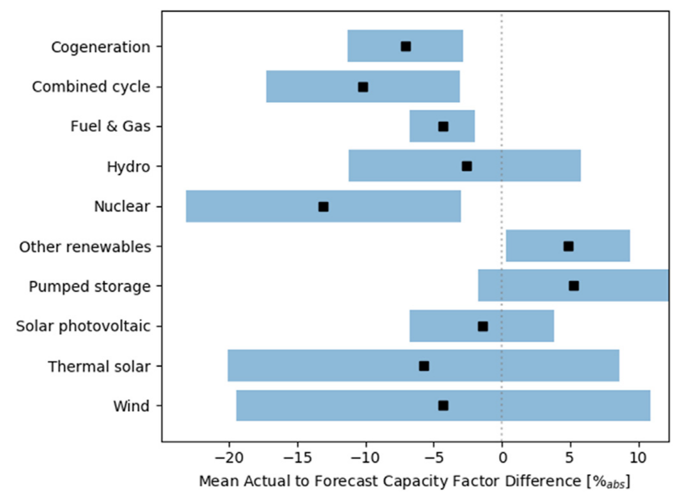

Fig. 6. Average difference, in absolute values, between the actual and the forecasted energy of each technology (black markers) during the lockdown. The blue areas mark the uncertainty ranges. A positive difference means that the actual values are higher than the forecasts.

performance and the availability of the sources in the energy mix affect the wholesale electricity price, along with the fuel costs. These factors are not necessarily independent of each other. For example, as mentioned earlier, the drop in demand changed the energy mix, favoring renewables and affecting the portion of demand covered by some of the conventional sources. Therefore, the amount of higher cost electricity in the mix was reduced. In addition, also the fuel cost lowered during the lockdown. In the recent years, gas has been preferred as fuel for electrical power plants, while the generation from coal has been severely reducing, penalized by the European CO_2 emission prices (MIBGAS, 2019). In April and May 2020, the gas prices fell substantially in several EU countries, including Spain (Market Observatory for Energy, 2020). The regulated gas sold on the Iberian market reached a minimum price of 4 €/MWh in May 2020 and returned to its pre-pandemic level (~10 €/MWh) only in August 2020 (MIBGAS, 2020).

As a result of the demand and of the subsequent electricity price drops, the turnover for the Spanish electricity sector was 620 million € lower than expected during the lockdown. This means that the 24.9% of the forecasted revenues for the period were lost, corresponding to an average loss of 6.1 million € per day. A maximum of 11.7 million € loss per day occurred on the week of April 27, the same period in which the maximum drop in price was registered. On average, the revenues in April and in May were ≥30% lower than forecasted. As shown in the lower plot of Fig. 8, most of the losses were a consequence of the price drop. The electricity price fall was indeed responsible for 55.5%, 69.8% and 60.9% of the turnover loss in April, May and June 2020.

3.3. Photovoltaic performance

Differently from the expectations (Peters et al., 2020), PV systems did not overperform in terms of capacity factor during the first half of 2020. Actually, when the capacity factor is compared with that of the previous years, PV is found to underperform, especially during the lockdown (top plot of Fig. 9). Indeed, in March and April 2020, the PV capacity factor at national level was more than 20% lower than in the previous years. In April in particular, the deviation

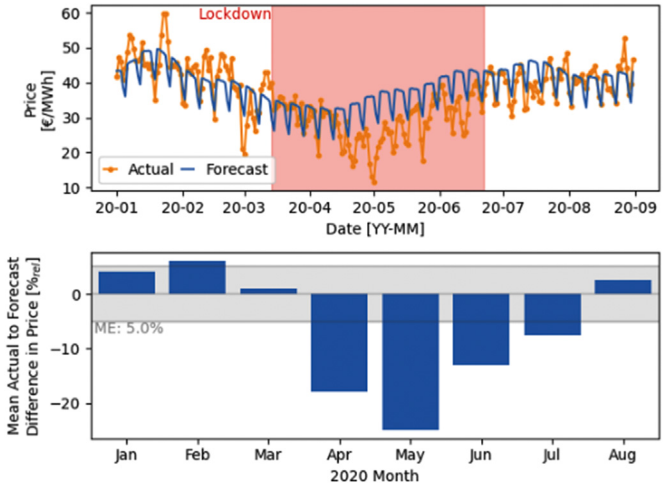

Fig. 7. Upper plot: daily electricity prices (orange line) and forecasted trend (blue line). The red area marks the start and the end of the lockdown. Lower plot: comparison of the average monthly electricity price in 2020 with the average values recorded in previous ten years. The grey area represents the estimated mean error, calculated as the average of the difference between actual and forecast data in January and Februray.

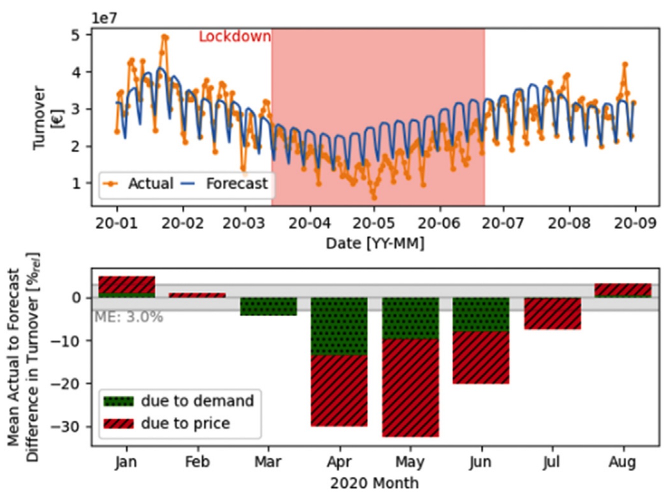

Fig. 8. Upper Plot: Forecasted vs. Actual turnover for the national electricity sector in Spain. The red area highlights the lockdown period. Lower Plot: Differences between actual and forecasted turnover in each month. A positive difference means that the actual values are higher than the forecasts. Price and demand contributions to the turnover losses are represented by red hatched and green dotted bars, respectively. The grey area represents the estimated uncertainty, calculated as the mean error (ME) of the difference between actual and forecasted data in January and Februray.

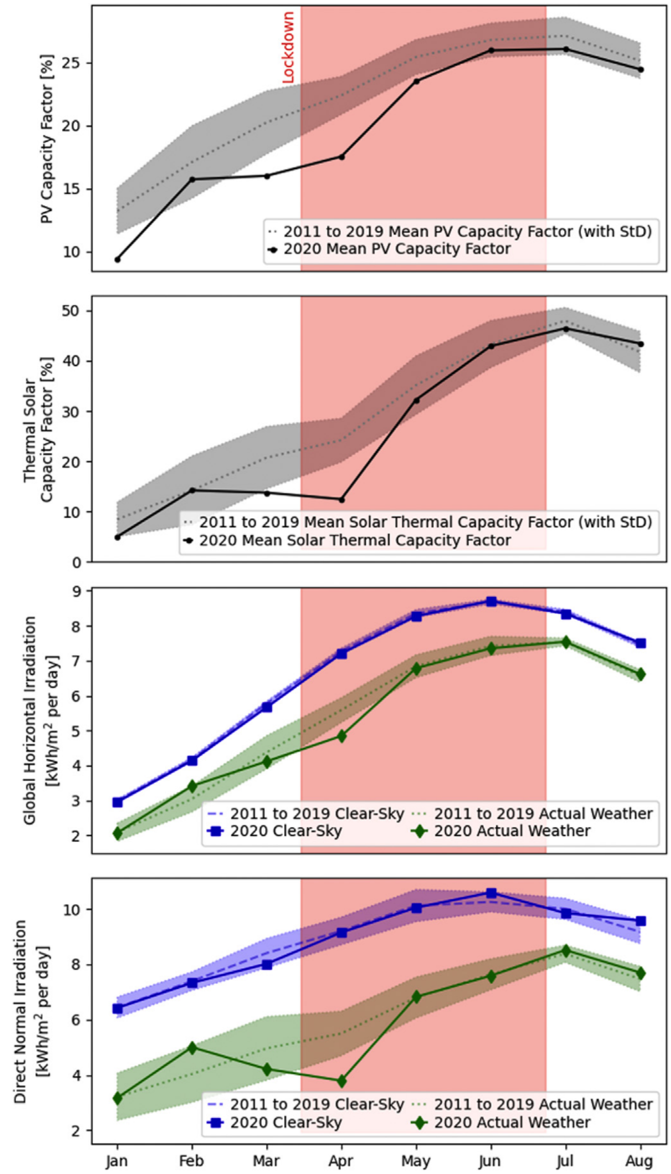

Fig. 9. Upper plots: 2020 monthly mean capacity factor compared to previous-year averages and standard deviation for photovoltaics and thermal solar. Lower plots: 2020 monthly mean clear-sky and actual-weather global horizontal irradiation and direct normal irradiation compared to previous-year averages and standard deviation.

from the average was three times larger than the standard deviation of the previous years.

The results are not surprising if compared with the irradiation profiles (Fig. 9). Indeed, despite the expectations, profiles similar to those of PV capacity factor can be seen for the actual-weather global and direct irradiation values. In fact, the global and direct irradiations in April 2020 were respectively 13% and 31% lower than the previous ten-year average. The difference is more than twice the value of the standard deviation. This means that the PV underperformance can be at least partially attributed to the exceptionally cloudy weather conditions, which led to low irradiation values and that drastically counteracted any potential lockdown-related improvement. The low irradiation in March and April 2020 was also confirmed by the ground-measurements of the 20+ irradiance stations of the Spanish State Meteorological Agency's network (Agencia Estatal de Metereología, 2020a, 2020b). This finding is also supported by the capacity factor of the thermal solar plants, shown also in Fig. 9. Even in this case, the capacity factors dropped by 14% and 30% in March and April 2020 compared to the previous years. As PV, thermal solar power plants convert irradiance into electricity and were therefore possibly affected by the adverse weather conditions that lowered the PV performance in spring 2020. Thermal solar systems make use of the direct component of the irradiance and, for this reason, the correlation between their capacity factor and the direct irradiance is particularly clear. On the other hand, PV modules convert the global irradiance and their performance can change depending on plant-specific factors such as tracking configuration and tilt angle. Additional studies should be conducted, in future, on the causes of this PV capacity factor drop, taking into account also the uneven distribution of the PV installations over the national territory.

In addition, it should be also noted that the clear sky irradiation does not deviate from the previous-year average for values larger than the standard deviation. This suggests that the air quality improvement had no or limited effect on the PV potential in Spain, at least at continental level. This is probably related to the fact that no clear reduction in particle matter concentration was recorded. This can be seen in Fig. 10, which shows the difference between the particle matter concentrations in 2020 and the previous year averages for each month. No significant and consistent drop in particle matter concentration is found during the lockdown months compared to the previous years. This result is in line with the findings of an investigation conducted in between March and April 2020, where lockdown-related PM_{10} reductions were detected only in three of the 11 investigated Spanish cities (Briz-Redón et al., 2021). A study of the Spanish Ministry for the Ecological Transition and the Demographic Challenge attributed the lack of improvements in PM_{10} during the lockdown to the influence of frequent natural events affecting Spain (Ministerio para la Transicion Ecologica y el Reto Demografico, 2020a). Indeed, according to the data shown in a provisional report (Ministerio para la Transicion Ecologica y el Reto Demografico, 2020c) the Spanish mainland experienced Saharan dust intrusion events for 88 days in between January 1 and June 30, 2020. This is the second highest number since 2013 and is about 36% higher than the previous-year average (Ministerio para la Transicion Ecologica y el Reto Demografico, 2020b). The exceptional number of natural events in 2020 also explains the high particle matter values recorded in January and February. These are indeed also the results of the high number of days in which dust Saharan intrusions occurred in 2020. In January 2020, the number of days was the highest since 2013, twice than the previous maximum and more than three times the previous-year average.

Despite the previous findings, PV reached its maximum share in the Spanish electricity mix during 2020, with peaks of 8.9% in May and 9.3% in June (Fig. 11). These values are about twice the typical previous yearly maximums, which generally ranged in between 3% and 5% and occurred in between June and September. It is possible to estimate the contribution of the lockdown-driven electricity demand drop to the PV share increase by comparing the actual value with that calculated from the forecasted demand. This way, it is found that the PV share increase was also partly due to the lockdown, even if it was most significantly driven by the PV capacity installed in 2019. Indeed, the PV share was on average $0.8\%_{abs}$ lower if calculated with the energy demand forecast ($12.7\%_{rel}$). This represents the contribution of the lockdown-related demand drop to the PV share increase. The largest deviation between actual and forecasted share was recorded in April ($1.0\%_{abs}$ and $17.1\%_{rel}$), also the month with the strongest decrease in electricity demand. The

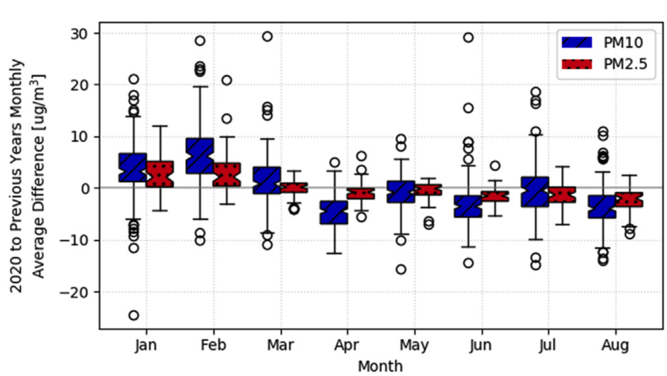

Fig. 10. Difference between average particle matter concentrations in 2020 and average particle matter concentrations in between 2013 and 2019. A positive difference means that the 2020 value was higher than before.

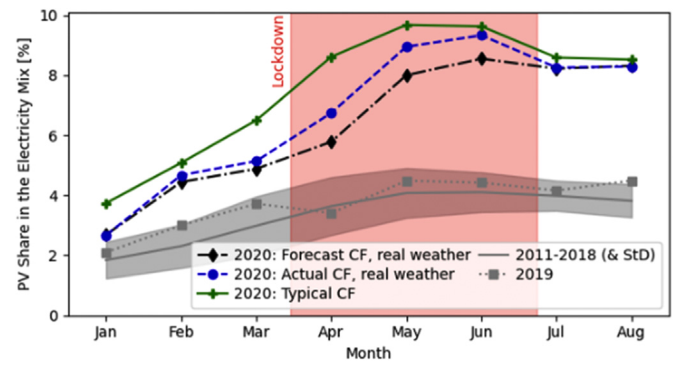

Fig. 11. PV share (i.e. PV contribution to the total electricity demand) in Spain in 2020, 2019 and previous years (blue solid line with round markers, dark grey dotted line with squared markers and light grey dotted line without markers respectively). In addition, the forecasted 2020 PV share is shown to highlight the effect of the COVID-19 related energy demand drop (black dash-dotted line with diamond markers). A potential PV market share is also calculated taking into account the previous years' average PV capacity factors ("typical", green dashed line with crossed markers).

same absolute deviation is found in May ($1.0\%_{abs}$ and $12.2\%_{rel}$), while it slightly decreased in June ($0.8\%_{abs}$) and continued lowering until the actual share met the expected profile in July ($<0.1\%_{abs}$ difference).

Despite the record share in the mix, it was already mentioned that PV suffered of a drop in capacity factor compared to the previous years. If PV had performed at the same capacity factors as before (top plot of Fig. 9), it would have reached even higher market shares during the lockdown months: 6.5% in March ($+1.4\%_{abs}$ compared to actual value), 8.6% in April ($+1.9\%_{abs}$), 9.7% in May ($+0.7\%_{abs}$) and 9.6% in June ($+0.3\%_{abs}$).

3.4. Discussion

The COVID-19 crisis hit the Spanish electricity sector in a time in which it was already experiencing some significant changes. In the last five years, indeed, the average coal generation had lowered from 144 GWh/day in 2015 to 102 GWh/day in 2018 and to 35 GWh/day in 2019, partially replaced by gas-powered plants. In the same period, renewables had significantly grown and represented at the end of 2019 slightly more than half of the national electrical capacity already.

In order to take into account these long-term terms and differentiate them from the effects of the COVID-related lockdown, this work made use of a univariate forecasting tool. However, some of the investigated variables, as the electricity price, are the results of a number of external factors, which could introduce a degree of uncertainty in the estimations. In this case, as described in 2.2, the electricity price forecast was corrected by assuming that the effects of the lockdown had gone by August 2020, similarly to what occurred to the electricity demand (López Prol and O, 2020). It was already mentioned that the wholesale electricity price in Spain has been decreasing since October 2018. In addition, during calibration, a last change point was identified in the second half of October 2019 (lower plot of Fig. 2), in which the rate at which the electricity price decreased went from −0.097 €/MWh/day to −0.013 €/MWh/day. Modelling a different electricity derate trend would have led to different results. For this reason, a sensitivity analysis was conducted to quantify the correlation between the modelled electricity derate and the estimated impact of the lockdown. The results are shown in Fig. 12 and confirms that the identified electricity derate is the one returning (i) the minimum mean modelling error in January and February 2020, and (ii) also the minimum deviation from the actual data in August 2020, at the end of the lockdown. The figure also shows that the more severe the derate, the higher the error and the deviation, and the lower the estimated economic impact of the lockdown. Similarly, the less severe the expected daily price derate, the higher the estimated impact of the lockdown on the electricity price.

Assuming a different daily variation in price would have changed also the estimated turnover. In particular, a linear relation is found between the economic impact of the lockdown and the modelled daily variation in price (right y-axis of Fig. 12). The mean daily loss caused by the lockdown indeed lowers by €1.3 M per each 0.01 €/MWh/day variation in electricity price derate. This means that the estimated economic impact of the lockdown would be double (12.3 M € per day on average) if the electricity price were expected to increase by 0.033 €/MWh/day. On the other hand, the lockdown would have had no economic impact if the electricity price were modelled to decrease by −0.058 €/MWh/day. In both cases, however, the deviation between the modelled and the actual electricity price in August 2020 would have been significant. As mentioned, the present investigation assumed expected electricity price derate in 2020 of −0.013 €/MWh/day, because it returned the minimum modelling errors and minimized the deviation from the actual data in August 2020. Nonetheless, future studies should validate and refine the forecasts and the findings of this work using different approaches and a larger variety of inputs.

The analysis also showed that the combination of increased PV capacity and drop in electricity demand led the renewables' share to 43.9% of the total energy consumption in the first 8 months of 2020. This is 21.8%$_{rel}$ (7.9% $_{abs}$) higher than the contribution in the same period of the previous year. During the lockdown days only, the renewables share raised to 48.0%, mostly due to wind and with a significant contribution from PV. These two variable renewable sources combined represented one quarter of the national energy generation. Their share could have been higher if PV had performed at its typical capacity factor. Through the analysis of the PV generation, the irradiance data and the available information on the installed capacity, the present work found that adverse weather conditions affected the PV performance.

The drops in irradiance and in PV performance shown in this work were calculated as averages of the data available for the Spanish mainland. However, it should be noted that individual systems and areas might have experienced different conditions. So, future works should evaluate the performance of PV at regional or even individual site level. Similar analysis should be conducted on the particle matter, investigating how it varied in different environments. Indeed, the lockdown measures can be expected to have affected dissimilarly urban, industrial and rural areas. The effects of the lockdown on pollutants other than the particle matter should also be investigated as these could have affected the spectral performance of PV. In addition, if the concentration of suspended particles was reduced because of the lockdown measures, a reduction in the amount of particles deposited on the PV module surfaces could also be expected. The deposition of dust and particles is a phenomenon known as soiling and negatively affects the PV performance. In Spain, it is particularly intense in summer and especially in the southernmost regions. So, the potential effect of the lockdown on PV soiling should be also investigated in future.

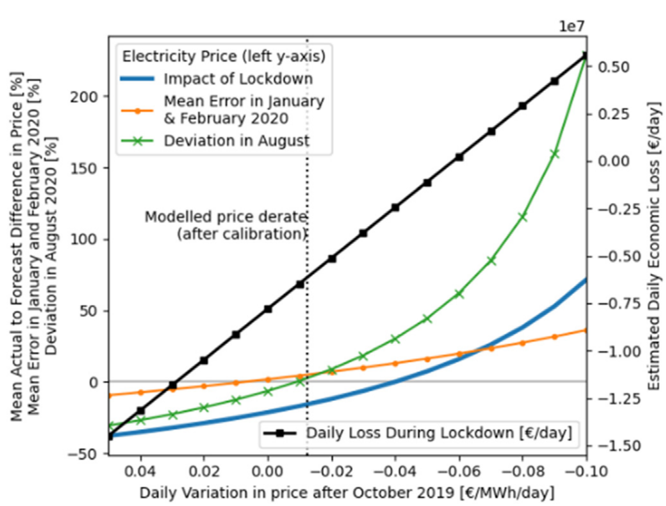

Fig. 12. Sensitivity analysis. Left y-axis: how price modelling changes depending on the estimate daily price variation in 2020. Right y-axis: estimated impact of the lockdown, in average €/day, as function of the modelled electricity derate.

The analysis of this paper is conducted on the immediate effects that the spring 2020 lockdown had on the electricity sector because of the "stay-at-home" recommendations and of the stop to the commercial and industrial activities. However, the ongoing COVID-19 crisis might leave some longer-term effects on the consumers' habits and behaviors that will continue to affect the electricity sectors. Activities such as online classes and remote working might last, at least partially, even after the lift of the lockdown and can change the typical electrical load profile. These longer-term effects are currently more difficult to characterize, as restraining measures are still in place in most countries, but should be evaluated in future studies.

4. Conclusions

This work presents a techno-economic analysis of the short-term effects that the spring 2020 lockdown had on the Spanish electricity sector and on its energy mix. This study assesses the energy and economic losses in the first half of 2020 and evaluates the performance of photovoltaics, the fastest growing technology in the country, in its record-year so far. The analysis is conducted by comparing the actual electricity demand, price and generation with forecasts generated by taking into account pre-existing long-term and seasonal trends.

The results show that, on average, 6.1 million € were lost on each day of lockdown, with a maximum loss of 11.7 million € per day at the end of April. These losses were due to an unprecedented drop in energy demand and to a subsequent reduction in electricity price. The most affected technologies were cogeneration, combined cycle, fuel & gas and nuclear. On the other hand, photovoltaics reached a record 9% share in the Spanish energy mix in June 2020, doubling its previous year maximum. Overall, the lockdown increased the PV share by 0.8%$_{abs}$ compared to the expectation. However, the PV generation, as well as the thermal solar generation, was negatively affected, at least partially, by the exceptional and unrelated reduced irradiation recorded during part of the lockdown.

All the forecasts produced and employed in this work were validated using data from August 2020. Because of its extreme variability, the analysis of the electricity price required the most careful calibration. The model estimated a long-term and lockdown-unrelated decrease in electricity price of 0.013 €/MWh/day. A sensitivity analysis shows how the economic loss estimation would have changed if different electricity price derates were modelled.

This investigation provides policy makers, energy operators and researchers with an estimate of the daily economic loss caused by the COVID-19 related lockdown. The methodology employed in this work can be used in future to assess in advance the potential impact of similar measures. Also, this work offers a detailed analysis of the performance of photovoltaics in the first half of 2020, which can help understanding the future role of this expanding technology in one of the most appealing markets for PV investors in Europe.

The COVID-19 crisis is still ongoing at the time this paper is written, and lockdowns are still in place in several countries, even if in various and different forms. Therefore, the findings of the current study should be extended in future to investigate the effects of the various COVID-19 related measures put in place in Spain and worldwide after August 2020. In addition, future works should investigate the longer-term effects of the COVID-19 related measures on the electricity sectors, analyzing which changes to the consumers' habits and behaviors will last even after the end of the current crisis.

CRediT authorship contribution statement

Leonardo Micheli: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration. **Álvaro F. Solas:** Data curation, Writing – original draft, Writing – review & editing. **Alberto Soria-Moya:** Methodology, Validation, Writing – review & editing. **Florencia Almonacid:** Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition. **Eduardo F. Fernández:** Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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