Short-Term Impact of the COVID-19 Lockdown on the Energy and Economic Performance of Photovoltaics in the Spanish Electricity Sector

Micheli, Leonardo and Solas, Álvaro F. and Soria-Moya, Alberto and Almonacid, Florencia and Fernandez, Eduardo F.

Advances in Photovoltaic Technology (AdPVTech), CEACTEMA, University of Jaén, Jaén, Spain, Advances in Photovoltaic Technology (AdPVTech), CEACTEMA, University of Jaén, Jaén, Spain, Solar Energy Training Centre (Censolar), Sevilla, Spain, Advances in Photovoltaic Technology (AdPVTech), CEACTEMA, University of Jaén, Jaén, Spain, Advances in Photovoltaic Technology (AdPVTech), CEACTEMA, University of Jaén, Jaén, Spain

16 April 2021

Preprint: L. Micheli *et al.*, "Short-Term Impact of the COVID-19 Lockdown on the Energy and Economic Performance of Photovoltaics in the Spanish Electricity Sector," J. Clean. Prod. (2021) 127045.
DOI: 10.1016/j.jclepro.2021.127045

Short-Term Impact of the COVID-19 Lockdown on the Energy and Economic Performance of Photovoltaics in the Spanish Electricity Sector

Leonardo Micheli [,1], Álvaro F. Solas [1], Alberto Soria-Moya [2], Florencia Almonacid [1], Eduardo F. Fernández [1]*
[1] CEAC Tierra, Energía y Medio Ambiente (CEACTEMA), Universidad de Jaén, Jaén, Spain
[2] Solar Energy Training Centre (Censolar), Sevilla, Spain

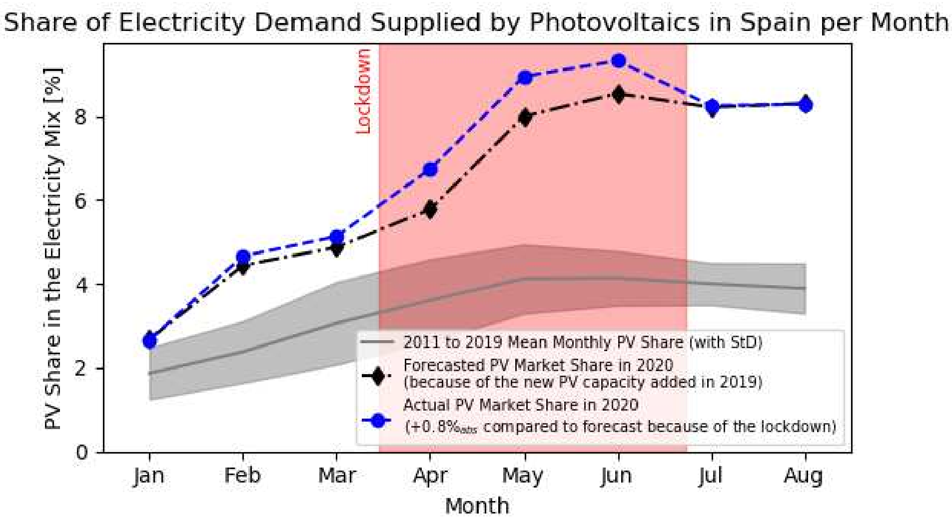
Abstract: In response to the COVID-19 outbreak, the Spanish government declared a State of Alarm that lasted from the 14th of March 2020 to the 21st of June 2020. The main measure put in place was a lockdown that suspended most of the activities and the movements in the entire country. The present work investigates the effects of this anti COVID-19 measure on the national electrical energy sector. The lockdown is found to have caused an average decrease in electricity demand of 11%, followed by a more severe drop in electricity prices of 0.09 €/MWh per each GWh of missed daily demand. These led to an average turnover reduction of 6.1 million € per day for the electricity sector. The losses are found to be unevenly distributed across the different power technologies of the energy mix. In particular, the performance of photovoltaics, the fastest growing technology in the country, is investigated in-depth. During the lockdown, for the first time, photovoltaics provided more than 9% of the national electricity, more than double than the previous annual maximum. However, despite the expectations related to the improved air quality, the average capacity factor of photovoltaic systems is found to be lower than in the previous years. The reasons behind this are investigated through the analysis of the behaviors of the environmental factors affecting this technology's performance.

Keywords: power generation mix; photovoltaics; lockdown; COVID-19; Spain; irradiation

Highlights:

- The Spanish electricity sector lost 6.1 million € per day during the lockdown
- The electricity demand dropped by 11.0%, with a peak of 14.3% in April
- The electricity price lowered by 0.09 €/MWh per each GWh of missed daily demand
- Photovoltaics supplied > 9% of the national electricity consumption in June 2020
- The lockdown-related demand drop increased the share of photovoltaics by $0.8\%_{abs}$

Graphical Abstract



* *Corresponding author: lmicheli@ujaen.es*

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). At that time, the virus had spread across 114 countries, with 118,000 cases reported worldwide (World Health Organization, 2020).

The first 44 cases of disease were reported in China in between December 31, 2019, and January 3, 2020 (World Health Organization, n.d.). The global number of cases had grown to 132,000 by March 13, 2020, when Europe had become the epicenter of the pandemic (World Health Organization, n.d.), with Italy and Spain being the most affected countries (Guirao, 2020). The following day, in order to limit the spread of COVID-19, the Spanish Government imposed a national lockdown that lasted until June 21, 2020. Restrictions were put in place on the people's freedom of movement, public events were canceled and several commercial activities were suspended. An even stricter halt on all non-essential activities was established between March 30 and April 9, 2020.

All these measures led to changes in socioeconomic habits that also included a variation in the electricity demand and a transformation in the electricity consumption profiles (Abu-Rayash and Dincer, 2020; Santiago et al., 2021; Zhang et al., 2020). A first analysis on the impact of the lockdown on the Spanish energy demand was presented by Santiago et al. (Santiago et al., 2021) and covered the period between March 14 and April 30, 2020. The authors found a drop in energy demand of 13.5% compared to the previous five years, most severe during weekdays. This drop changed also the energy mix, with a larger share from renewables and a subsequent reduction in CO_2 emissions. A more recent analysis made use of dynamic harmonic regression to compare expected and actual electricity consumption data from March to July 2020 in Spain, other EU countries and the USA (López Prol and O, 2020). The authors found, for Spain, an energy demand during the lockdown 21% lower than forecasted, which reached the baseline levels by the end of July. An investigation conducted on the profitability of natural gas combined cycles power plants in Spain found margins, measured in terms of Clean Spark Spread (CSS), lower than expected during the first six months of 2020 (Abadie, 2020). In particular, the most severe restrictions put in place in April led the CSS down by 11.3 €/MWh, turning profits into an average loss of 4.15 €/MWh.

The present study extends the findings of previous works (Abadie, 2020; López Prol and O, 2020; Santiago et al., 2021) by adding to the energy demand also an analysis of the trend the electricity price, which in Spain is subject to a daily market-based competition (Ciucci, 2020). This makes it possible to get a first estimate of the revenue lost by the Spanish electricity sector during the lockdown. In addition, the performance of each power generation technology of the mix is also individually investigated, with a particular focus on photovoltaics (PV). This is indeed the fastest growing power technology in the country and was expected to benefit from the lockdown-driven air quality improvements (Peters et al., 2020).

A univariate forecasting tool is used in this work to generate expected electricity demand, production and price time series based only on historical data. These estimations are then compared with the actual data to calculate the effects of the lockdown on each variable. For more reliable results, the forecasts are validated against the actual post-lockdown values (August 2020). Comparing actual data with forecasts rather than with bare previous years data is essential for a market that is experiencing a shift toward renewables and that is subject to long-term and seasonal trends that would otherwise bias the analysis.

Spain, which is among the top 5 energy consumers in Europe and among the top 20 worldwide (U.S. Energy Information Administration, n.d.), can be considered representative of a large number of countries. Indeed, similar lockdowns were put in place in the same period in several

European and worldwide nations. Moreover, the methodologies employed in this work can be of use for additional studies in different regions and, more importantly, to predict the effects of similar measures that might be put in place in future.

The paper is structured as follows. A literature review on the impact of COVID-19 related measures on energy and environment is reported in 2, which includes also an overview on the Spanish lockdown and a description of the national electricity sector. The methodologies used in this work and the data sources are listed in 3. The energy and economic impact of the lockdown on the Spanish electricity sector is reported in 4. Last, the performance of photovoltaics during the lockdown is assessed in 5.

2. Background

2.1. COVID-19 impact on international energy markets

Lockdown measures were put in place in several countries in 2020 to slow the spread of COVID-19 and have been reported to hit considerably national electricity sectors worldwide (Madurai Elavarasan et al., 2020). A 10% peak reduction in electricity consumption was reported in April and May for the U.S. (Ruan et al., 2020). In Italy, the electricity consumption dropped by 37% in March compared to the previous year, causing also a 30% decrease in electricity price (Ghiani et al., 2020). Similar electricity consumption trends were reported also for other European countries (Bahmanyar et al., 2020), China (Norouzi et al., 2020), India (Aruga et al., 2020) and Brazil (Carvalho et al., 2020). As a result of the electricity demand drop, the share of renewables in energy mix of several countries increased substantially at the expense of coal, oil and nuclear technologies (Werth et al., 2021).

An analysis conducted on countries representing 85% of the world population and 97% of global CO_2 emissions estimated that the daily global CO_2 emissions lowered by 17% compared to 2019 (Le Quéré et al., 2020). In addition, several publications have been showing how the COVID-19 related lockdown measures led to an improved air quality worldwide (Baldasano, 2020; Chen et al., 2021; Gillingham et al., 2020; Menut et al., 2020; Sharma et al., 2020). In a cleaner air context, an increase in irradiance can be expected. The energy generated by photovoltaic (PV) systems strongly depends on the solar irradiance and, therefore, a raise in PV generation could also be expected because of the lockdown, at least in severely polluted areas (Peters et al., 2020).

2.2. The Lockdown in Spain

Spain was in state of alarm from March 14, 2020 to June 21, 2020. Some important dates are reported in Table 1. The restraining measures led to a severe drop in mobility (Dirección General de Tráfico, 2020). The urban traffic was reduced by more than 60% in April compared to the previous years, with daily peaks up to 90%, and slowly recovered until the end of June. The limited activities led to an reduction of the NO_2 levels in major cities (Briz-Redón et al., 2021; Ministerio para la Transición Ecológica y el Reto Demográfico, 2020a); just in March 2020, drops in NO_2 of 62% and 50% were estimated for Madrid and Barcelona (Baldasano, 2020). Conflicting results have been reported, instead, for other pollutants. The authors of (Briz-Redón et al., 2021) found improvements in CO, SO_2, and PM_{10} only in some cities after 4 weeks of lockdown. On the other hand, a study of the Spanish Ministry for the Ecological Transition and the Demographic Challenge concluded that clear improvement in PM_{10} could not be identified because of the influence of frequent natural events, such as Saharan dust intrusions (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020a).

Table 1. Timeline of the State of Alarm in Spain in spring 2020. A summary of the main measures is reported.

DOI: 10.1016/j.jclepro.2021.127045

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 29 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 2	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 are allowed and with limited capacity. • Non-professional sport training in groups is 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 6	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.

2.3. Energy Market and PV Capacity in Spain

At the end of 2019, the energy generation capacity in Spain was 110 GW, with almost half of it represented by combined cycle systems (23.8%) and wind (23.4%) (Fig. 1a) (REE, 2020). Ten major technologies covered 98.9% of the electricity capacity: coal, cogeneration, combined cycle, fuel & gas, hydro, nuclear, pumped storage, solar photovoltaic, thermal solar, and wind. The remaining portion was made of a group of technologies, such as geothermal and biomass, classified as “Other Renewables”. In this work, hydroeolian and renewable waste are also included in the “Other Renewables” group. Since 2010, the daily electricity generation in Spain has represented on average the 101.3% of the electricity demand (± 5.4% in standard deviation). Surpluses and deficits between electricity generation and demand are balanced through cross-border exchanges with neighbor countries.

Since the start of 2019, the PV capacity in Spain has significantly grown (Fig. 1b), mainly as a result of a renewable energy generation capacity auctions held by the Spanish government in 2017 (Bellini, 2017; Unión Española Fotovoltaica, 2020). In these auctions, up to 3,909 MW were awarded to photovoltaics, of which 3,728 MW were installed in 2019 (95% of the total). In addition, the repeal of the so-called "Sun Tax" on October 5 2018 (RD-Law 15/2018) encouraged the installation of 459 MW self-consumption PV systems. Last, around 247 MW were installed in purely private initiatives in 2019, frequently under Power Purchase Agreements umbrella (Asociación Nacional de Productores de Energía Fotovoltaica, 2020; Unión Española Fotovoltaica, 2020). At the end of 2019, renewables (hydro, wind, solar photovoltaic, thermal solar and other renewables) represented 50.2% of the national capacity, 3.4%$_{abs}$ more than the year before.

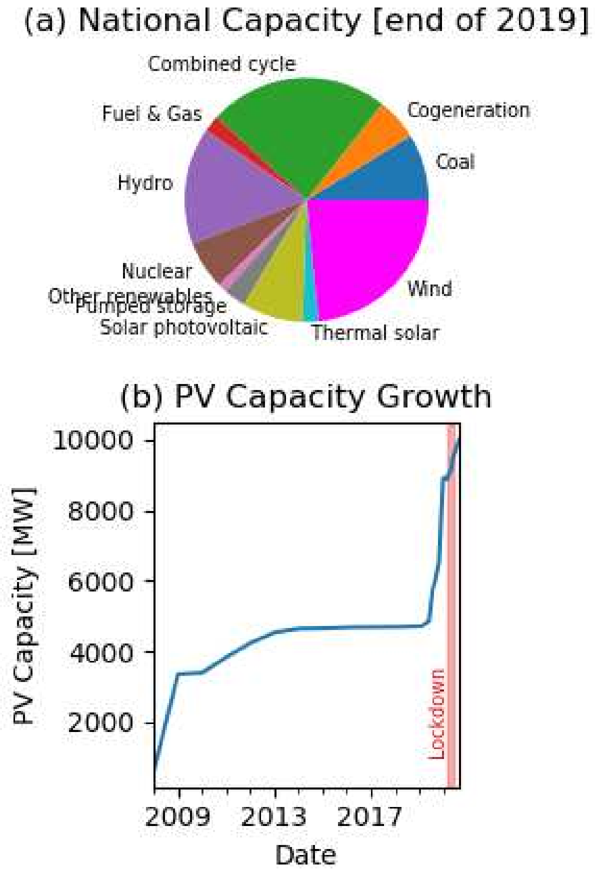


Fig. 1. (a) Distribution of Power Capacity per Technology at the end of 2019. (b) Evolution of PV capacity in Spain. Data Sourced from (REE, 2020).

The electricity market in Spain was born in 1997, following the liberalization of the electrical sector (Jefatura del Estado, 1997). Ten years later, its fusion with the Portuguese electricity market led to the foundation of the Iberian Electricity Market (MIBEL in Spanish), which is nowadays coupled to the rest of electricity markets of central and northern Europe. The operator in charge of managing the MIBEL wholesale market is called OMIE (www.omie.es). About 80% of the electrical energy demanded in Spain in 2019 was managed by OMIE (OMIE, 2020a).

In Spain, the price of electricity varies over time, depending on the difference between supply and demand, and on the type and costs of the energy available. Most of the energy is sold through the so-called day-ahead market: every day, OMIE handles the electricity price offers that sellers and buyers present for each hour of the following day. The offers are ordered by price to configure the market supply curve: purchase offers are put in ascending order to obtain the demand curve, whereas suppliers' offers are descending-sorted to create the supply curve. The final electricity market price is set by the intersection of the curves as it can be seen in the example of Fig. 2. All the offers "to the left" of the final price (i.e. at prices lower than the final price) are accepted.

The offers at the bottom of the supply curve belong to nuclear and baseline hydroelectric power plants, whose price is set to 0 €/MWh due to the high start and stop costs. The following offers are those of wind and photovoltaic energies, which depend on the meteorological conditions and have low variable costs. The offers of coal power plants and thermal power stations are placed at the top of the supply curve because of their high opportunity costs. The fraction of energy supply provided by these last technologies, known as "thermal gap" (Fig. 2), depends on the demand and on the production of nuclear and renewable energy plants. Typically, the larger the thermal gap, the higher the electricity price, because of the impact of fossil fuel and carbon emissions prices on the production costs of the thermal plants.

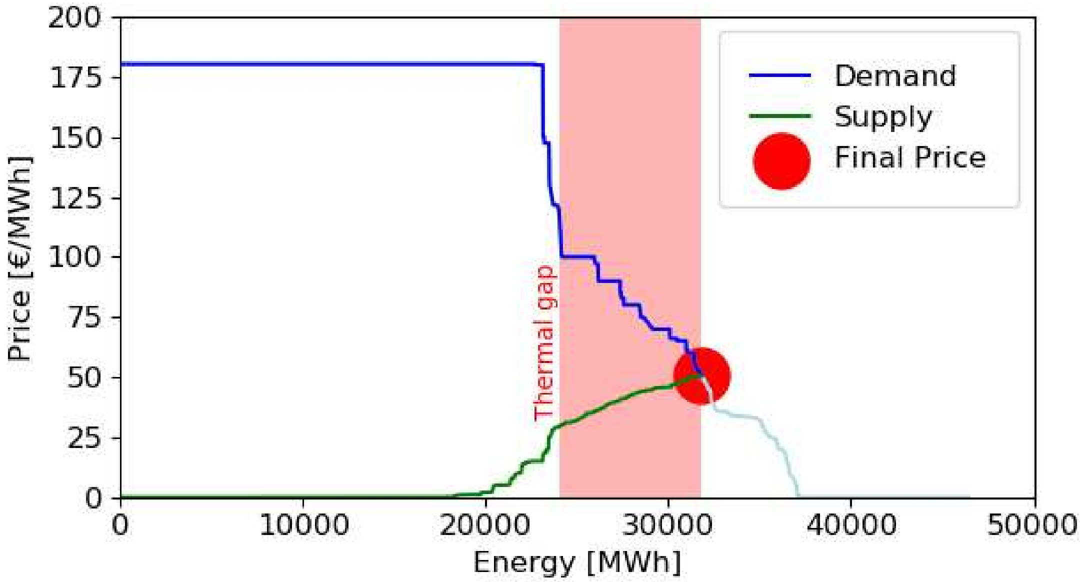


Fig. 2. Market supply curve for 1PM on 25/11/2020. The red area highlights the thermal gap. Data sourced from OMIE (OMIE, n.d.).

Nowadays, a progressive reduction of the thermal gap is expected because of the deployment of renewable sources, including the aforementioned record PV capacity installed in 2019. Indeed, after hitting an yearly mean value of 57.3€/MWh in 2018, the average electricity day-ahead market price in Spain in 2019 already lowered by 16.8% compared to the previous year (OMIE, 2020b). A series of measures related to tax regulations adopted on October 5, 2018 (RD-Law 15/2018) also contributed to this drop, along with a decrease in gas, coal and Brent prices (AleaSoft, 2019).

OMIE also manages the so-called intraday and continuous intraday markets, whose main purpose is to give sellers and buyers the chance of submitting near real-time offers to adjust possible mismatches between the day-ahead predictions of electricity demand and generation and the actual demand and generation values. The intraday market is structured in six daily sessions, which cover different time frames. It follows the same pricing process of the daily market and handles possible electricity exchanges between Spain and neighbor countries. On the other hand, the singularity of the continuous intraday market is that allows offers' submissions up to one hour before the electricity consumption. Of the total electrical energy managed by OMIE in 2019, 84% was negotiated on the daily-ahead market, 15% on the intraday market and the remaining on the continuous intraday market (OMIE, 2020a).

DOI: 10.1016/j.jclepro.2021.127045

3. Experimental Procedures

3.1. 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 for the power generation technologies 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 used. 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 are estimated through linear regression.

Since all the PV-generated energy is supplied to the consumers, the contribution (or "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. Since OMIE handles most of the electricity in the market, this work makes use of the weighted average of the electricity prices of the three markets managed by OMIE to calculate the turnover of the electricity sector. The average daily electricity prices (*precio final medio demanda nacional*) values are downloaded from OMIE for the period in between January 2011 and August 2020 (OMIE, n.d.). It is important to note that this average final price also contains the additional cost of the system, but does not include taxes and grid access fees.

3.2. Forecasts and Uncertainty

In Spain, the energy demand and the electricity price have seasonal trends, with typically lower values in spring. Fig. 3 shows that, for both the electricity demand and price, the drops recorded during the lockdown are visually more severe than any seasonal variation and cannot be related to long-term patterns either, as the effects of the lockdown are gone towards the end of the summer. Comparing the 2020 actual data with a forecast rather than with the average values of the previous years is therefore necessary as it makes it possible to eliminate the effects of long-term and seasonal trends from the analysis.

The forecasts presented in this study are based only on the historical trends of each variable and are produced using the Facebook Prophet (FBP) algorithm (Taylor and Letham, 2017), through long and seasonal trend decompositions. The univariate forecasts are generated using the actual data up to the end of February 2020. The algorithm employs a linear model and automatically produces also the forecast uncertainties, by taking into account uncertainty in the trend, uncertainty in the seasonality estimates, and the observation noise.

The impact of the COVID-related measures on each variable is calculated from the difference of the forecasted and actual data. For each variable, the deviation of the actual values (*a*) from the forecast values (*f*) is calculated as $(a - f)/f$. Therefore, the deviation is negative if the actual value is lower than the forecasted one. The mean monthly deviations are calculated as average of the daily deviations. Where shown, the mean error is calculated as mean of the daily deviations in January and February 2020.

Facebook Prophet was provided with the default set of 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 Prophet 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, as the average monthly forecasts met the actual values in July and August, the two months immediately after the end of the lockdown (deviation ≤ 0.5%).

On the other hand, Prophet would have not been able to catch the change in price trend occurred after October 5th, 2018 if provided with the default inputs (dashed orange line in lower plot of Fig. 3). So, 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 would have restored by August 2020 (as in the initial forecast). 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. 3).

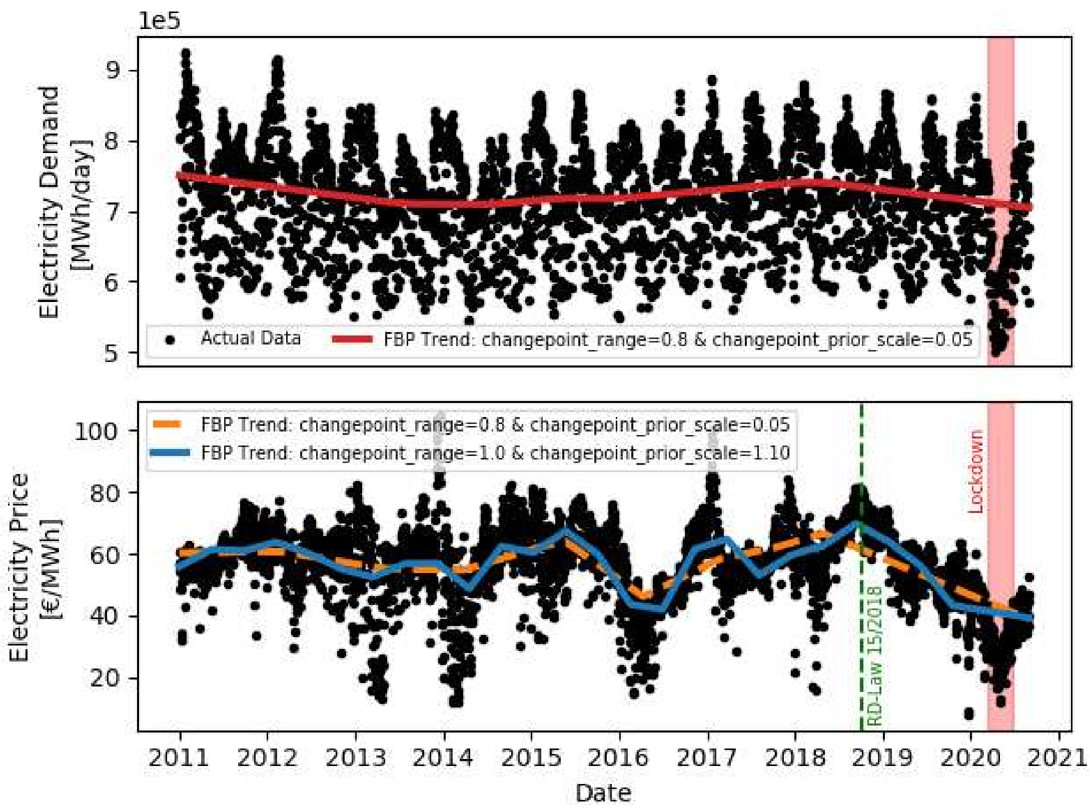


Fig. 3. Data and trends of daily energy demand (upper plot) and electricity price (lower plot). The red area highlights the lockdown period. The blue line represents the trend extracted from the historical data and the red line represents the forecasted trend.

Similarly, the capacity factor of each power technology is independently analyzed, using the daily data from 2011 to the end of February 2020 (Fig. 4) and the default Prophet's settings. Data for "Other Renewables" are only available since 2014. No reliable forecast could be produced for "Coal" and, so, it is excluded from the technology-specific analysis.

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

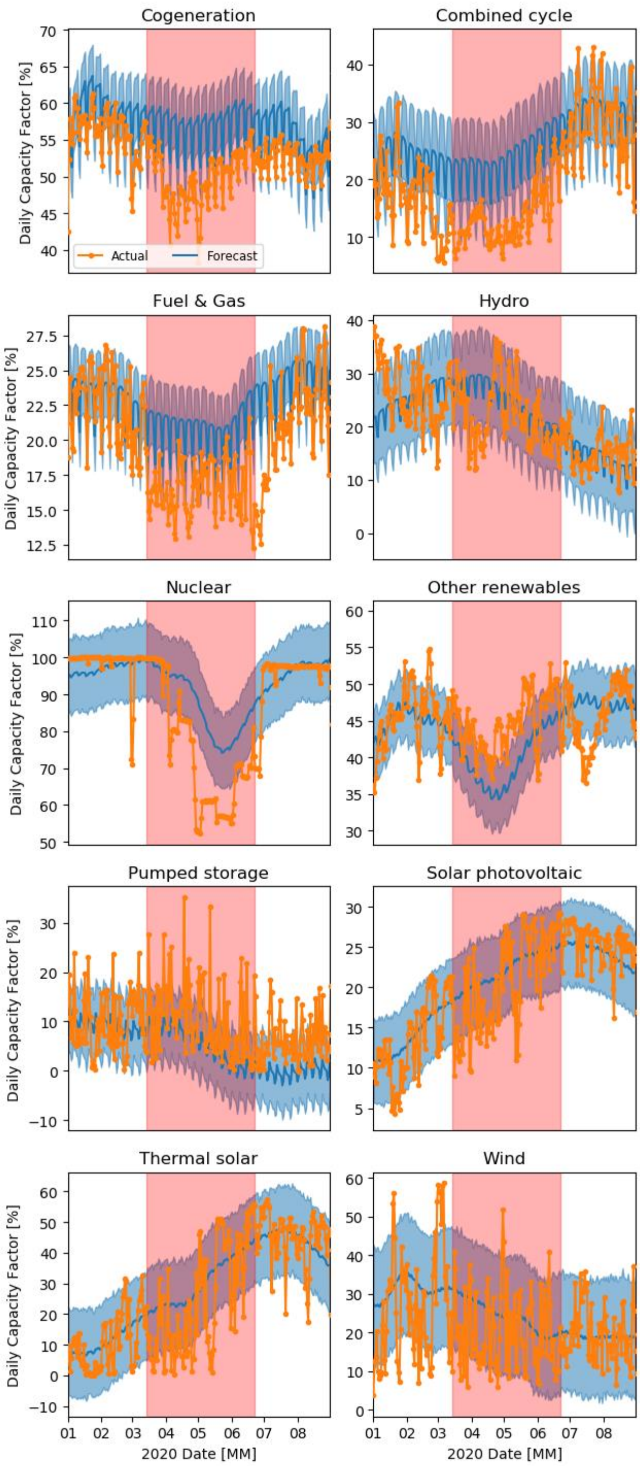


Fig. 4. Forecast (blue) and Actual (yellow) capacity factors of the different technologies in the Spanish Energy mix. The blue area represents the forecast's uncertainty.

3.3. Irradiation and Particulate Matter Data

Photovoltaic system converts the sunlight into electricity. Irradiation data for this analysis are sourced from the Copernicus Atmosphere Monitoring Service radiation service (Copernicus Atmosphere Monitoring Service, n.d.). Daily time series are 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. 5). Only data points on Spanish mainland are considered. The provider 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 using data on aerosol, ozone and water vapor.

The daily particulate matter concentrations from 2013 to 2020 are downloaded from the European Environment Agency's DiscoMap (European Environment Agency, n.d.). Particulate 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 microns and less than 2.5 microns in diameter, respectively. Daily PM_{10} and $PM_{2.5}$ data are available for 513 and 261 locations respectively 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. 5), meaning 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 are unevenly distributed across the country and that some regions, such as the Northeast, are not or under-represented. Future works should extend this investigation as new data become available.

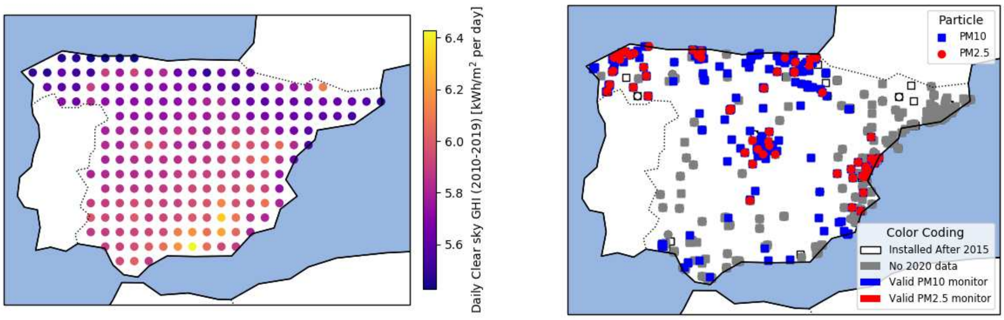


Fig. 5. Left: Data grid used for the irradiation analysis study. The average daily clear sky Global Horizontal Irradiation (GHI) is shown, calculated for the years 2010 to 2019. Right plot: Map of the PM monitors used in this study, and location of the discarded ones.

4. National Energy Sector

4.1. Energy Impact

During the lockdown, the energy demand was averagely 11.0% lower than forecasted (Fig. 6), with a mean error in January and February of -2.0%. 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 drop started to recover until the end of the lockdown, when the actual demand reached the expected value. Indeed, in July and August the deviation of the actual data from the forecast was ≤ 0.5%.

The deviation in demand compared to the forecast during the lockdown was more intense during the weekdays (12.1% ± 0.6%) than on the weekends (8.5% ± 0.9%). The 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% during the weekends.

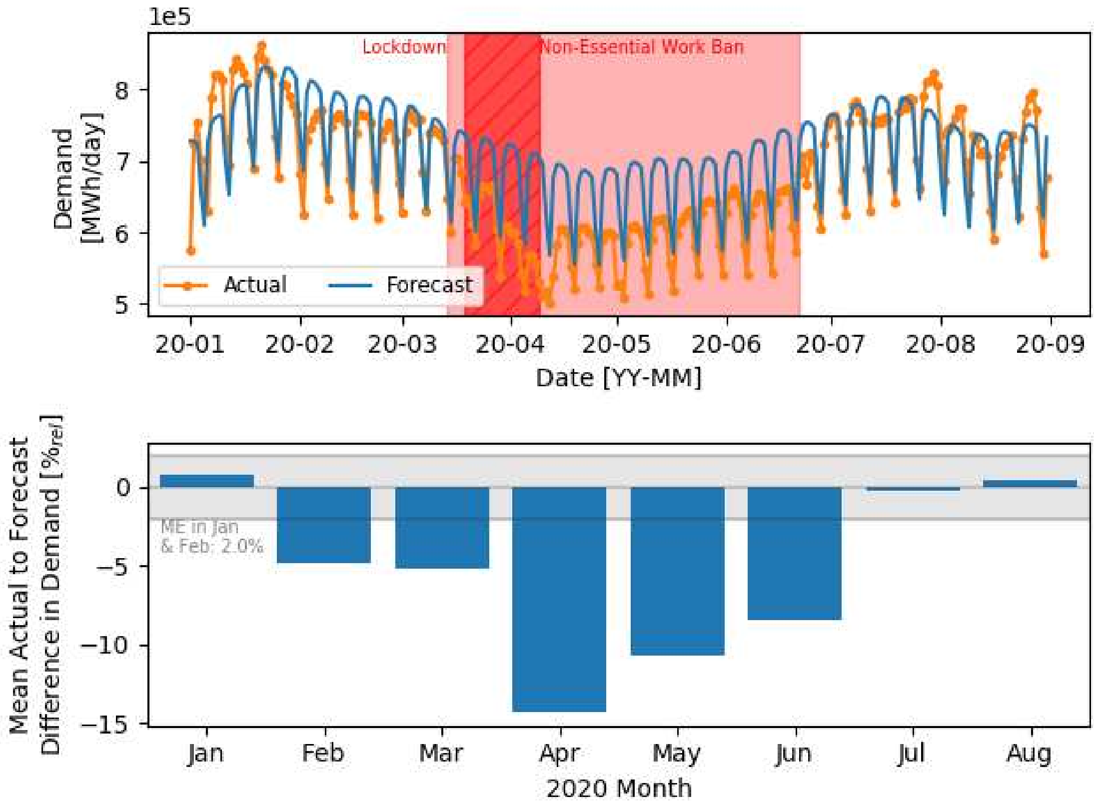


Fig. 6. Upper plot: Forecasted and actual daily energy demand in Spain in 2020. The light red area highlights the lockdown period, while the darker hatched red area marks the non-essential work ban period. Lower plot: Difference between monthly mean forecasted and actual demand. The grey area represents the estimated mean error, calculated as the average of the difference between actual and forecast data in January and Februray.

The lower energy demand affected unevenly the various technologies of the Spanish electricity mix (Fig. 4). Cogeneration, Combined Cycle, Fuel and Gas, and Nuclear were the technologies whose underperformance exceeded the forecast uncertainty (Fig. 7). 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. 7 have been conservatively calculated as difference between the sum of the maximum daily forecast uncertainty and of the sum of the minimum daily forecast uncertainty.

The combination of the 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 year before. During the lockdown days only, the renewables share raised to 48.0%.

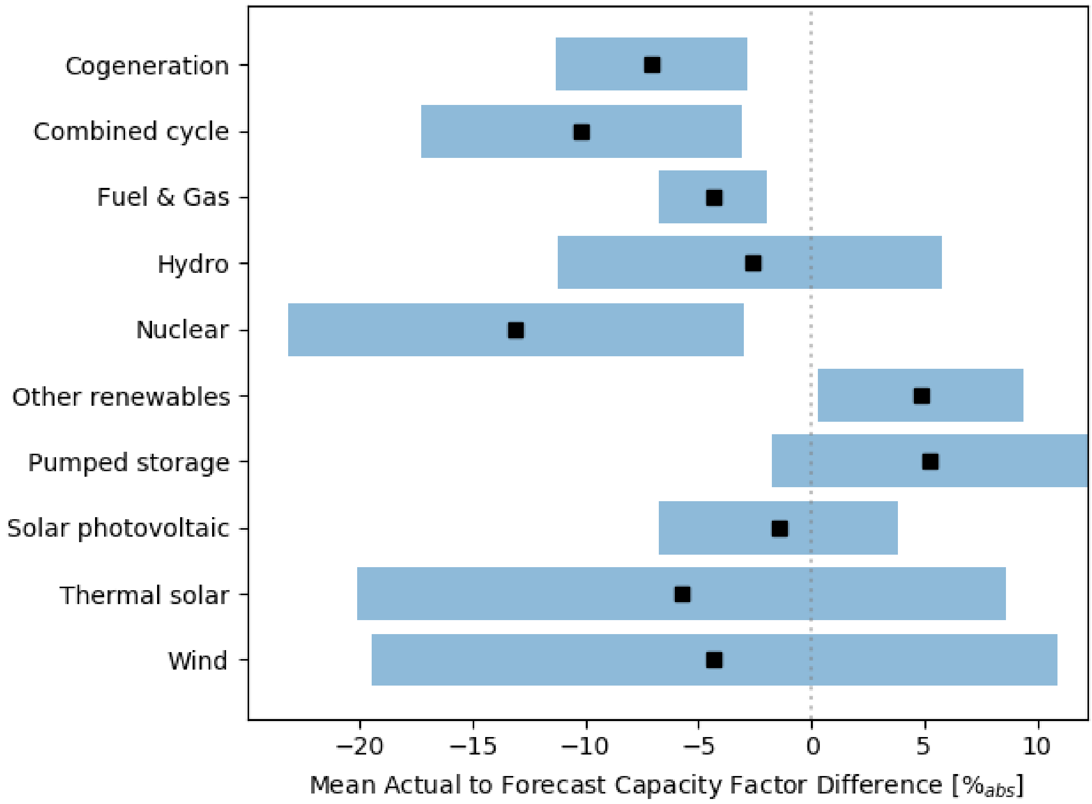


Fig. 7. Average difference, in absolute values, between the actual and the forecasted energy of each technology (black markers) during the lockdown. The blue areas mark the uncertainty ranges. A positive difference means that the actual values are higher than the forecasts.

4.2. Economic Impact

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. 8) 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 and the mean error in January and February is 5.0%. The variation in electricity price in the lockdown period is found to be mainly a consequence itself of 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%).

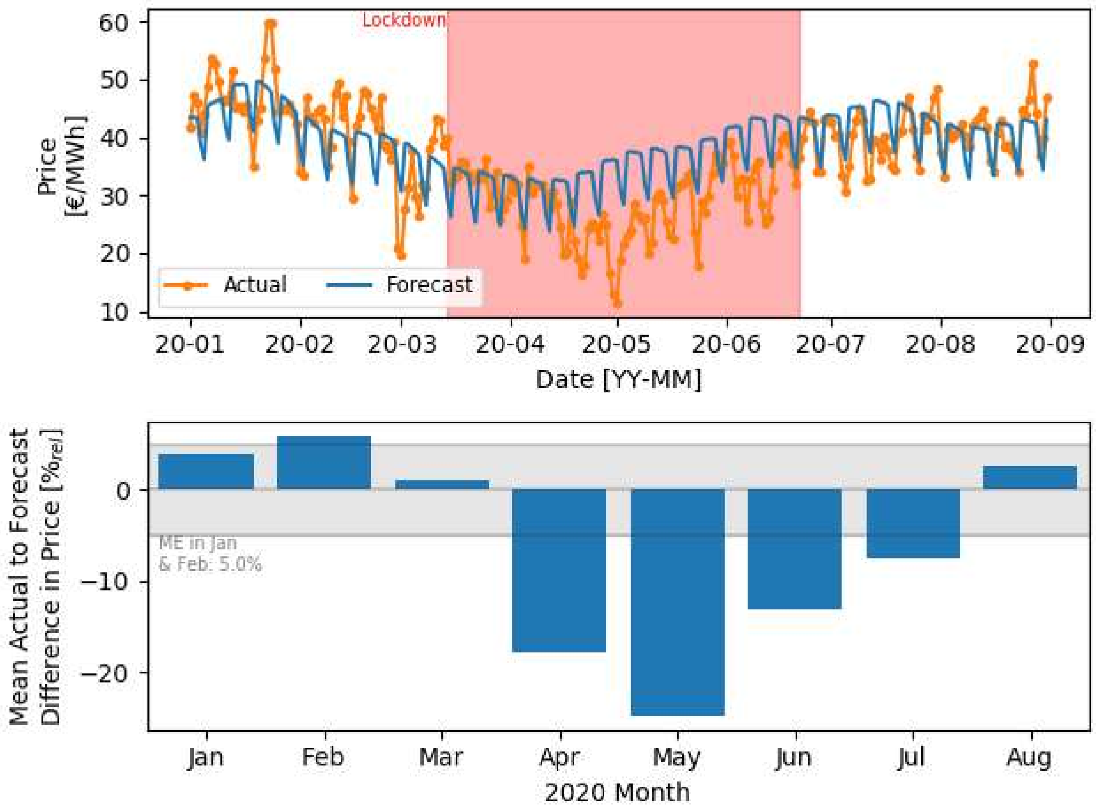


Fig. 8. Upper Plot: daily electricity prices (black markers) and extrapolated trend (blue line). The red area marks the start and the end of the lockdown. Lower plot: comparison of the average monthly electricity price in 2020 with the average values recorded in previous ten years. The grey area represents the estimated mean error, calculated as the average of the difference between actual and forecast data in January and Februray.

As result of the combination 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 represents the 24.9% of the forecasted revenues for the period and corresponds to an average loss of 6.1 million € per day. A maximum of 11.7 million € loss per day was found 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. 9, most of the losses are a consequence of the price drop. The price drop was indeed responsible for 55.5%, 69.8% and 60.9% of the turnover loss in April, May and June 2020.

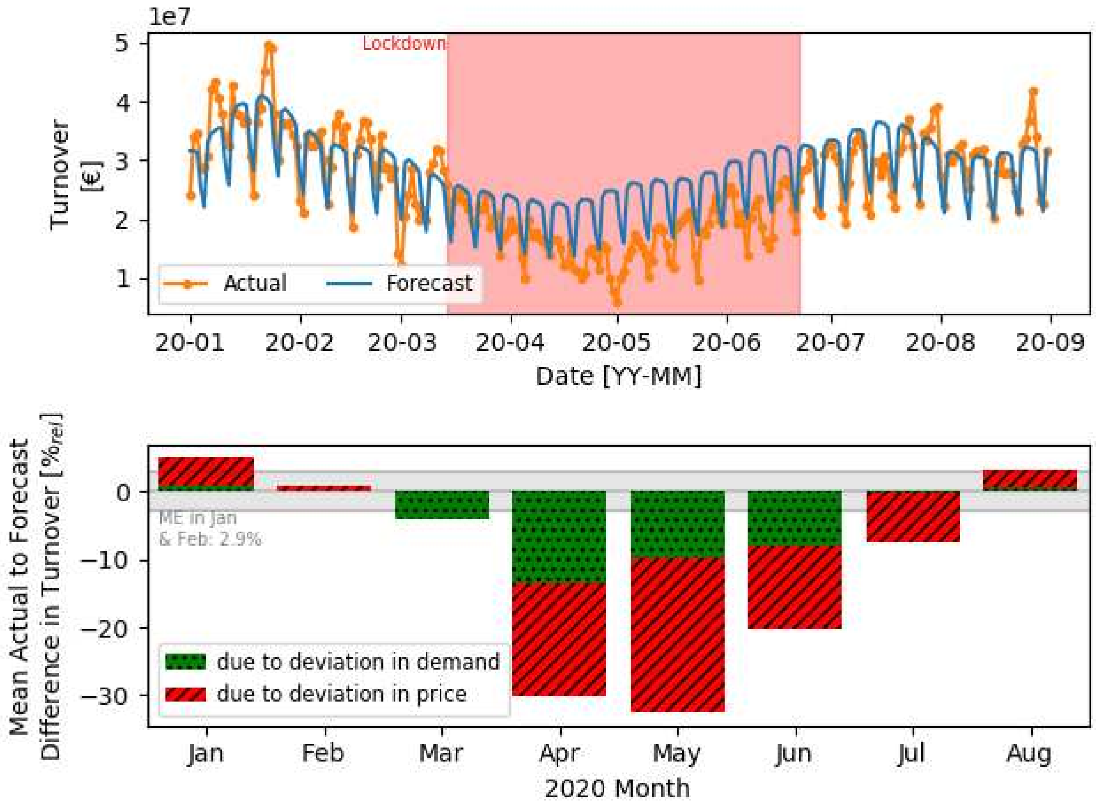


Fig. 9. Upper Plot: Forecasted vs. Actual turnover for the national electricity sector in Spain. The red area highlights the lockdown period. Lower Plot: Differences between actual and forecasted turnover in each month. A positive difference means that the actual values are higher than the forecasts. 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 of the difference between actual and forecast data in January and Februray.

5. Photovoltaic Sector

5.1. Performance

Differently from the expectations (Peters et al., 2020), PV systems are not found to overperform in terms of capacity factor during the first half of 2020. Actually, if the capacity factor of the PV systems is compared with that measured the previous years, PV is found to underperform, especially during the lockdown (top plot of Fig. 10). Indeed, in March and April 2020, the PV capacity factor at national level is more than 20% lower than in the previous years. In April, the deviation from the average is three times larger than the standard deviation of the previous years.

The results are not surprising if compared with the irradiation profiles (Fig. 10). Indeed, despite the expectations, drops similar to those of PV capacity factor can be seen for the actual-weather global and direct irradiation values at least for April. Indeed, in April 2020, global and direct irradiations were respectively 13% and 30% 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 were 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). Additional studies should be conducted, in future, to investigate the cause of this capacity factor drop, taking into account also the uneven distribution of PV installations and PV capacity over the national territory.

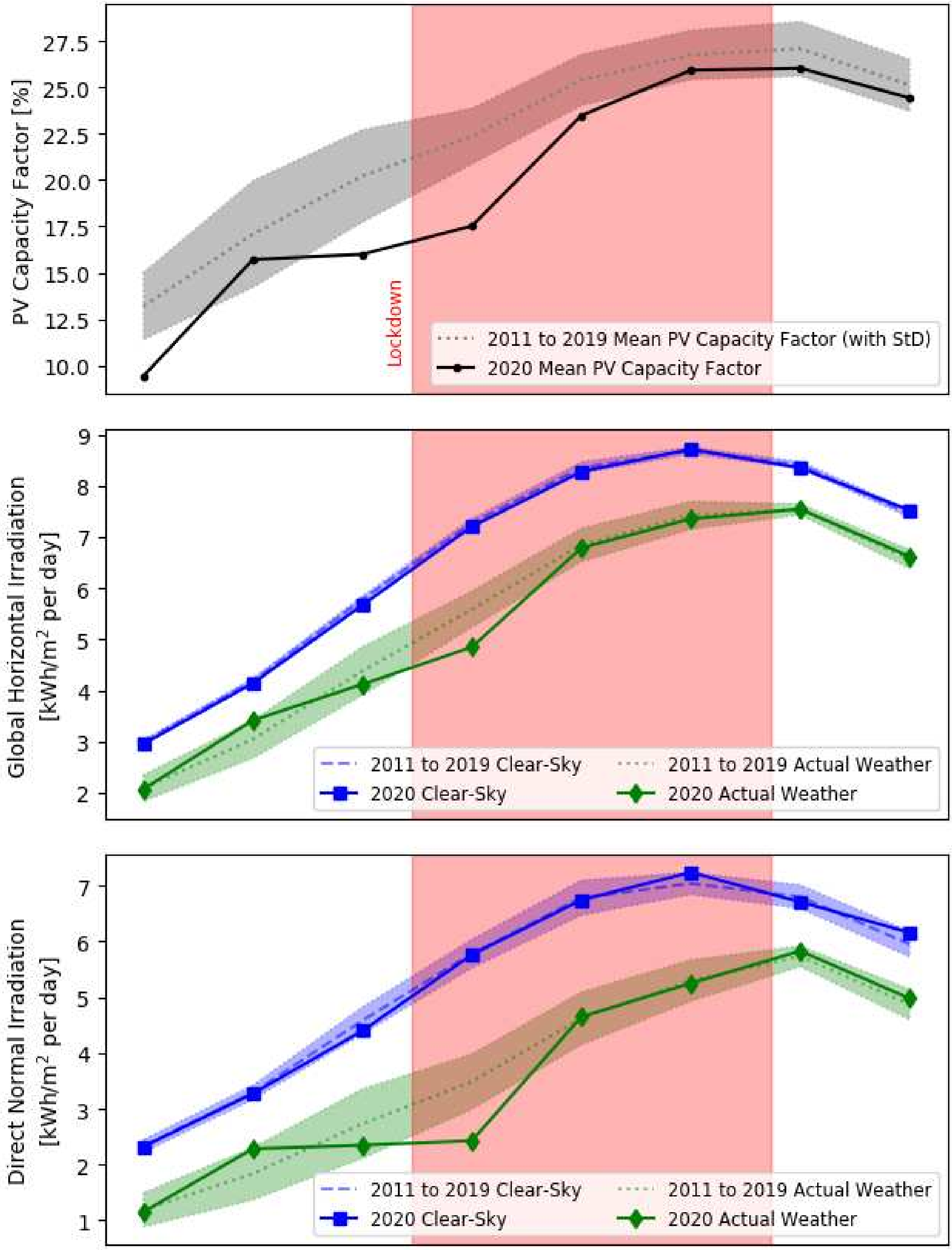


Fig. 10. Upper plot: 2020 monthly mean PV capacity factor compared to previous-year averages and standard deviation. Lower plots: 2020 monthly mean clear-sky and actual-weather global horizontal irradiation (GHI) and direct normal irradiation (DNI) compared to previous-year averages and standard deviation.

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 potentials in Spain, at least at national level. This is probably related to the fact that no clear reduction in particulate matter concentration was recorded, compared to the previous years, during the lockdown (Fig. 11). The data take into account all the particulate monitors available, but future studies should consider that the results might vary depending on the area type (e.g. urban, rural, industrial…) in which each monitor is installed.

According to a provisional report of the Spanish Ministry for the Ecological Transition and the Demographic Challenge (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020b), 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 Transición Ecológica y el Reto Demográfico, n.d.). The exceptional number of natural events in 2020 also explains the high particulate matter values recorded in January and February. These are indeed also the results of the unusually high number of days in which a dust Saharan intrusion 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.

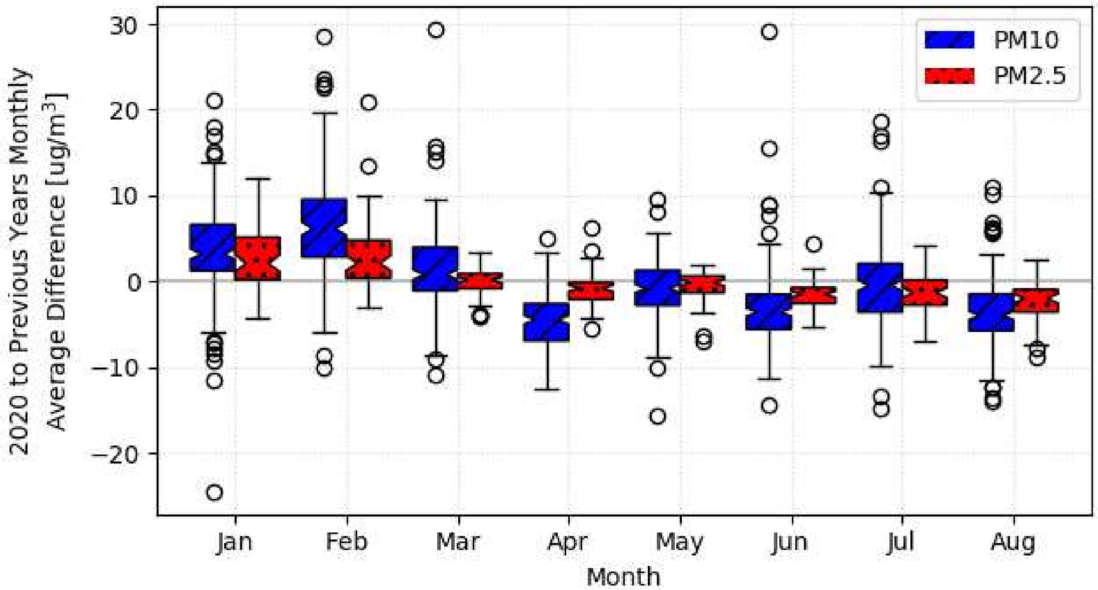


Fig. 11. Difference between average PM concentration in 2020 and average PM concentration in between 2013 and 2019. A positive difference means that the 2020 value was higher than before.

5.2. Share in the Electricity Mix

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. 12). These values are about twice the typical previous yearly maximums, which ranged in between 3% and 5% and generally occurred in between June and September.

It is possible to estimate the contribution of the electricity demand drop to the PV share increase, by comparing the value calculated with the actual demand and the value calculated with the forecasted demand. It is found that the PV share increased compared to the previous years is also partly due to the lockdown, even if it is most significantly driven by the PV capacity installed in 2019. Indeed, the PV share is on average 0.8%$_{abs}$ lower if calculated with the energy demand forecast (12.7%$_{rel}$). The largest deviation between actual and forecasted share is recorded in April (1.0%$_{abs}$ and 17.1%$_{rel}$), also the month with the strongest energy demand drop. The same absolute deviation is found is in May (1.0%$_{abs}$ and 12.2%$_{rel}$), while its value slightly decreases June (0.8%$_{abs}$) and continues lowering until the actual share meets 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 would have performed following the same capacity factor profile as previously (top plot of Fig. 10), 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%$_{abs}$).

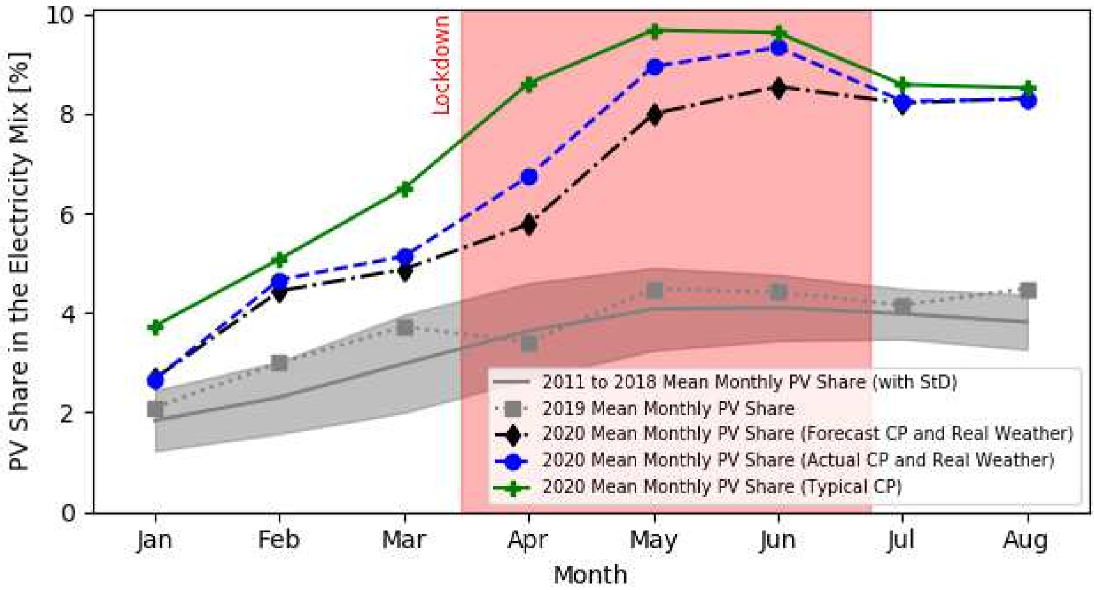


Fig. 12. PV share (i.e. PV contribution to the total electricity demand) in Spain in 2020, 2019 and previous years (blue solid line with round markers, dark grey dotted line with squared markers and light grey dotted line without markers respectively). In addition, the forecasted 2020 PV share is shown 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).

6. Conclusions and Future Works

This work presents a techno-economic analysis of the lockdown impact on the Spanish national electricity sector in the first half of 2020. On average, 6.1 million € per day were lost during the lockdown, with a maximum loss of 11.7 million € per day at the end of April.

These revenue losses are the results of two factors: (i) an unprecedented drop in energy demand and (ii) a subsequent reduction in electricity price. Most of the losses were due to the electricity price drop, which decreased, on top of any seasonal variation, by 0.09 €/MWh per each GWh of demand lost. Of the technologies in the Spanish energy mix, Cogeneration, Combined Cycle, Fuel and Gas and Nuclear were those that underperformed most seriously compared to the expectations from an energy perspective.

At national level, the PV technology was also found to underperform during the lockdown, in terms of capacity factors, with drops as high as 20% compared to the previous years. This was the at least partial result of the unrelated reduced irradiation recorded during those weeks (-13% global irradiation in April compared to the previous years). In addition, the lockdown did not significantly impact the particulate matter concentration at national level, as this was substantially affected by the large number of natural events occurred in the first half of 2020. This contributed to the missed PV performance improvements.

Despite that, PV reached its maximum share in the Spanish energy mix in 2020, doubling its previous year value. PV energy provided more than 9% of the electricity consumed nationally in June 2020, mainly thanks to the record PV capacity installed toward the end of 2019. Overall, the lockdown related energy demand drop increased the absolute value of the PV share by

0.8%$_{abs}$ in average compared to the expectation. This share could have been even higher if the capacity factor was similar to the previous years, with a potential peak of 9.7% in May.

Assumptions and limitations of the current work and potential future research directions have been detailed throughout the paper. In particular, this work made use of a univariate forecasting tool to predict the trends of various variables. However, some of these, as the electricity price, could have been affected by a number of external factors, which could introduce a degree of uncertainty in the estimations. While in this case the electricity price forecast has been corrected by assuming its value to be restored after the lockdown, future studies should validate and refine the findings of this work using different forecasting approaches and a larger variety of inputs. In addition, future works should be conducted to investigate the performance of PV and the particulate matter variation at regional or even individual site level. These should also study the effects of the lockdown on other pollutants. Indeed, these could have affected the spectral performance of PV and of the various PV technologies. Last, the effects of the lockdown on photovoltaic soiling (i.e. deposition of dust and contaminants on the PV surface), which is typically more intense in summer, should be investigated.

Acknowledgments

This work was conceived and funded as part of the European Union's Horizon 2020 research and innovation programme under the NoSoilPV project (Marie Skłodowska-Curie grant agreement No. 793120).

Álvaro F. Solas is supported by the Spanish Ministry of Science, Innovation and Universities under the program "Ayudas para la formación de profesorado universitario (FPU), 2018 (Ref. FPU18/01460).

Author Contribution

Leonardo Micheli: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Software, Visualization, Writing - original draft, Writing - review & editing, Funding acquisition, Project administration. Alvaro 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. Fernandez: Methodology, Validation, Writing - review & editing, Supervision, Funding acquisition.

References

Abadie, L.M., 2020. Current expectations and actual values for the clean spark spread: The case of Spain in the Covid-19 crisis. J. Clean. Prod. 124842. https://doi.org/10.1016/j.jclepro.2020.124842

Abu-Rayash, A., Dincer, I., 2020. Analysis of the electricity demand trends amidst the COVID-19 coronavirus pandemic. Energy Res. Soc. Sci. 68, 101682. https://doi.org/10.1016/j.erss.2020.101682

Agencia Estatal de Metereología, 2020a. Resumen mensual de la radiación solar (Marzo 2020).

Agencia Estatal de Metereología, 2020b. Resumen mensual de la radiación solar (Abril 2020).

AleaSoft, 2019. Third period of the spanish electricity market (2015 2019): current stage [WWW Document]. pv-magazine. URL https://www.pv-magazine.com/press-releases/third-period-of-the-spanish-electricity-market-2015-2019-current-stage/ (accessed 11.11.20).

Aruga, K., Islam, M.M., Jannat, A., 2020. Effects of COVID-19 on Indian energy consumption. Sustain. 12, 1–16. https://doi.org/10.3390/su12145616

Asociación Nacional de Productores de Energía Fotovoltaica, 2020. Anuario Fotovoltaico 2020.

Bahmanyar, A., Estebsari, A., Ernst, D., 2020. The impact of different COVID-19 containment measures on electricity consumption in Europe. Energy Res. Soc. Sci. 68, 101683. https://doi.org/10.1016/j.erss.2020.101683

Baldasano, J.M., 2020. COVID-19 lockdown effects on air quality by NO2 in the cities of Barcelona and Madrid (Spain). Sci. Total Environ. 741. https://doi.org/10.1016/j.scitotenv.2020.140353

Bellini, E., 2017. Spanish government provides auction's official numbers: allocated solar capacity reaches 3.9 GW [WWW Document]. pv-magazine. URL https://www.pv-magazine.com/2017/07/27/spanish-government-provides-auctions-official-numbers-allocated-solar-capacity-reaches-3-9-gw/

Briz-Redón, Á., Belenguer-Sapiña, C., Serrano-Aroca, Á., 2021. Changes in air pollution during COVID-19 lockdown in Spain: A multi-city study. J. Environ. Sci. (China) 101, 16–26. https://doi.org/10.1016/j.jes.2020.07.029

Carvalho, M., de Delgado, D.B., de Lima, K.M., de Cancela, M., dos Siqueira, C.A., de Souza, D.L.B., 2020. Effects of the COVID-19 pandemic on the Brazilian electricity consumption patterns. Int. J. Energy Res. 1–7. https://doi.org/10.1002/er.5877

Chen, Z., Hao, X., Zhang, X., Chen, F., 2021. Have traffic restrictions improved air quality? A shock from COVID-19. J. Clean. Prod. 279, 123622. https://doi.org/10.1016/j.jclepro.2020.123622

Ciucci, M., 2020. Internal energy market [WWW Document]. Fact Sheets Eur. Union. URL https://www.europarl.europa.eu/factsheets/en/sheet/45/internal-energy-market (accessed 7.3.20).

Copernicus Atmosphere Monitoring Service, n.d. CAMS solar radiation time-series [WWW Document]. URL https://ads.atmosphere.copernicus.eu/ (accessed 11.9.20).

Dirección General de Tráfico, 2020. EVOLUCIÓN DEL TRÁFICO POR EL EFECTO DE COVID-19 (22-06-2020).

European Environment Agency, n.d. DiscoMap [WWW Document]. URL https://discomap.eea.europa.eu/Index/Index.aspx (accessed 10.29.20).

Ghiani, E., Galici, M., Mureddu, M., Pilo, F., 2020. Impact on electricity consumption and market pricing of energy and ancillary services during pandemic of COVID-19 in Italy. Energies 13. https://doi.org/10.3390/en13133357

Gillingham, K.T., Knittel, C.R., Li, J., Ovaere, M., Reguant, M., 2020. The Short-run and Long-run Effects of Covid-19 on Energy and the Environment. Joule 4, 1337–1341. https://doi.org/10.1016/j.joule.2020.06.010

Guirao, A., 2020. The Covid-19 outbreak in Spain. A simple dynamics model, some lessons, and a theoretical framework for control response. Infect. Dis. Model. 5, 652–669. https://doi.org/10.1016/j.idm.2020.08.010

Jefatura del Estado, 1997. Ley 54/1997, de 27 de noviembre, del sector eléctrico. Spain.

Le Quéré, C., Jackson, R.B., Jones, M.W., Smith, A.J.P., Abernethy, S., Andrew, R.M., De-Gol, A.J., Willis, D.R., Shan, Y., Canadell, J.G., Friedlingstein, P., Creutzig, F., Peters, G.P., 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Chang. 10, 647–653. https://doi.org/10.1038/s41558-020-0797-x

Lefèvre, M., Oumbe, A., Blanc, P., Espinar, B., Gschwind, B., Qu, Z., Wald, L., Schroedter-Homscheidt, M., Hoyer-Klick, C., Arola, A., Benedetti, A., Kaiser, J.W., Morcrette, J.J., 2013. McClear: A new model estimating downwelling solar radiation at ground level in clear-sky conditions. Atmos. Meas. Tech. 6, 2403–2418. https://doi.org/10.5194/amt-6-2403-2013

López Prol, J., O, S., 2020. Impact of COVID-19 Measures on Short-Term Electricity Consumption in the Most Affected EU Countries and USA States. iScience 23.

https://doi.org/10.1016/j.isci.2020.101639

Madurai Elavarasan, R., Shafiullah, G.M., Raju, K., Mudgal, V., Arif, M.T., Jamal, T., Subramanian, S., Sriraja Balaguru, V.S., Reddy, K.S., Subramaniam, U., 2020. COVID-19: Impact analysis and recommendations for power sector operation. Appl. Energy 279, 115739. https://doi.org/10.1016/j.apenergy.2020.115739

Menut, L., Bessagnet, B., Siour, G., Mailler, S., Pennel, R., Cholakian, A., 2020. Impact of lockdown measures to combat Covid-19 on air quality over western Europe. Sci. Total Environ. 741, 140426. https://doi.org/10.1016/j.scitotenv.2020.140426

Ministerio para la Transición Ecológica y el Reto Demográfico, 2020a. Informe de Indicadores de Calidad del Aire durante el estado de alarma debido al COVID-19.

Ministerio para la Transición Ecológica y el Reto Demográfico, 2020b. Resumen de episodios 2020.

Ministerio para la Transición Ecológica y el Reto Demográfico, n.d. Predicción de episodios de intrusiones saharianas 2020 [WWW Document]. URL https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/atmosfera-y-calidad-del-aire/calidad-del-aire/evaluacion-datos/fuentes-naturales/Prediccion_episodios_2020.aspx (accessed 11.3.20).

Norouzi, N., Zarazua de Rubens, G., Choubanpishehzafar, S., Enevoldsen, P., 2020. When pandemics impact economies and climate change: Exploring the impacts of COVID-19 on oil and electricity demand in China. Energy Res. Soc. Sci. 68, 101654. https://doi.org/10.1016/j.erss.2020.101654

OMIE, 2020a. Evolucion del mercado de electricidad - Informe anual 2019.

OMIE, 2020b. Informes anuales [WWW Document]. URL https://www.omie.es/es/publicaciones/informe-anual (accessed 5.18.20).

OMIE, n.d. Curvas agregadas de oferta y demanda [WWW Document]. URL https://www.omie.es/es/market-results/daily/daily-market/aggragate-suply-curves?scope=daily&date=2020-04-03 (accessed 11.30.20a).

OMIE, n.d. Mínimo, medio y máximo precio mercado diario [WWW Document]. URL www.omie.es

Peters, I.M., Brabec, C., Buonassisi, T., Hauch, J., Nobre, A.M., 2020. The Impact of COVID-19-Related Measures on the Solar Resource in Areas with High Levels of Air Pollution. Joule 4, 1681–1687. https://doi.org/10.1016/j.joule.2020.06.009

Qu, Z., Oumbe, A., Blanc, P., Espinar, B., Gesell, G., Gschwind, B., Klüser, L., Lefèvre, M., Saboret, L., Schroedter-Homscheidt, M., Wald, L., 2017. Fast radiative transfer parameterisation for assessing the surface solar irradiance: The Heliosat-4 method. Meteorol. Zeitschrift 26, 33–57. https://doi.org/10.1127/metz/2016/0781

REE, 2020. National statistical series [WWW Document]. URL https://www.ree.es/en/datos/publications/national-statistical-series (accessed 7.28.20).

Ruan, G., Wu, D., Zheng, X., Zhong, H., Kang, C., Dahleh, M.A., Sivaranjani, S., Xie, L., 2020. A Cross-Domain Approach to Analyzing the Short-Run Impact of COVID-19 on the US Electricity Sector. Joule 1–16. https://doi.org/10.1016/j.joule.2020.08.017

Santiago, I., Moreno-Munoz, A., Quintero-Jiménez, P., Garcia-Torres, F., Gonzalez-Redondo, M.J., 2021. Electricity demand during pandemic times: The case of the COVID-19 in Spain. Energy Policy 148. https://doi.org/10.1016/j.enpol.2020.111964

Sharma, S., Zhang, M., Anshika, Gao, J., Zhang, H., Kota, S.H., 2020. Effect of restricted emissions during COVID-19 on air quality in India. Sci. Total Environ. 728, 138878. https://doi.org/10.1016/j.scitotenv.2020.138878

Taylor, S.J., Letham, B., 2017. Forecasting at Scale. PeerJ Prepr.

https://doi.org/10.7287/peerj.preprints.3190v2

U.S. Energy Information Administration, n.d. Rankings about energy in the World - Total energy consumption [WWW Document]. URL https://www.eia.gov/international/data/world (accessed 11.2.20).

Unión Española Fotovoltaica, 2020. El sector fotovoltaico. Informe anual UNEF 2020. Unef.Es 138.

Werth, A., Gravino, P., Prevedello, G., 2021. Impact analysis of COVID-19 responses on energy grid dynamics in Europe. Appl. Energy 281, 116045. https://doi.org/10.1016/j.apenergy.2020.116045

World Health Organization, 2020. WHO Director-General's opening remarks at the media briefing on COVID-19 - 11 March 2020 [WWW Document].

World Health Organization, n.d. Novel Coronavirus (2019-nCoV) - Situation Report -1 (21 January 2020). https://doi.org/10.13070/mm.en.10.2867

World Health Organization, n.d. WHO Director-General's opening remarks at the media briefing on COVID-19 - 13 March 2020 [WWW Document]. 2020. URL https://www.who.int/dg/speeches/detail/who-director-general-s-opening-remarks-at-the-mission-briefing-on-covid-19---13-march-2020 (accessed 11.18.20b).

Zhang, X., Pellegrino, F., Shen, J., Copertaro, B., Huang, P., Kumar Saini, P., Lovati, M., 2020. A preliminary simulation study about the impact of COVID-19 crisis on energy demand of a building mix at a district in Sweden. Appl. Energy 280, 115954. https://doi.org/10.1016/j.apenergy.2020.115954