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# Impact analysis of COVID-19 responses on energy grid dynamics in Europe

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A B S T R A C T

When COVID-19 pandemic spread in Europe, governments imposed unprecedented confinement measures with mostly unknown repercussions on contemporary societies. In some cases, a considerable drop in energy consumption was observed, anticipating a scenario of sizable low-cost energy generation, from renewable sources, expected only for years later. In this paper, the impact of governmental restrictions on electrical load, generation and transmission was investigated in 16 European countries. Using the indices provided by the Oxford COVID-19 Government Response Tracker, precise restriction types were found to correlate with the load drop. Then the European grid was analysed to assess how the load drop was balanced by the change in generation and transmission patterns. The same restriction period from 2020 was compared to previous years, accounting for yearly variability with ad hoc statistical technique. As a result, generation was found to be heavily impacted in most countries with significant load drop. Overall, generation from nuclear, and fossil coal and gas sources was reduced, in favour of renewables and, in some countries, fossil gas. Moreover, intermittent renewables generation increased in most countries without indicating an exceptional amount of curtailments. Finally, the European grid helped balance those changes with an increase in both energy exports and imports, with some net exporting countries becoming net importers, notably Germany, and vice versa. Together, these findings show the far reaching implications of the COVID-19 crisis, and contribute to the understanding and planning of higher renewables share scenarios, which will become more prevalent in the battle against climate change.

## 1. Introduction

The COVID-19 emergency established an unprecedented challenge for modern societies. Governments had to face a novel disease with exponential spread and considerable death rate. While intensive care cases were overwhelming healthcare systems, scientific experts tried to determine new behavioural models with little scientific knowledge, due to the substantial novelty of the situation. Despite the economic and political interconnections between European countries, the countermeasures against the epidemic were diverse in severity and temporal implementation. The efficacy of these interventions and their economic impact on industries [1], stock markets [2], environment [3,4] and energy markets are still unclear. As governments try relaunching economies and softening restrictions, it is crucial to understand the short and long term consequences of the adopted measures, not only to be better prepared for future crises, but also to unveil potential opportunities [4], in particular for sustainability research on electricity [5,6]. With the analysis of electricity data, available at almost real time, it was possible to provide a fine-grained view on the economic and environmental impact of COVID-19. Indeed, as Fezzi and colleagues [7] demonstrated for the case of Italy, high frequency electricity data could be used to estimate the effect of COVID-19 on the national GDP.

Previous studies reported that national lockdown had a strong influence on the electricity consumption in many countries heavily affected by the epidemic [4,8,9]. Norouzi and colleagues [10] used an artificial neural network model to evaluate the elasticity of oil and electricity demand in China, based on parameters including number of infections and gross domestic product without actual electricity data in input. Ruiz and colleagues [1] found that electricity consumption in China increased due to large quarantine and health service demand. Other studies ascribed the decrease in energy consumption to governmental interventions in the USA and Canada [9,11–13], in Brazil [14] and in Europe [7,15–17].

The present work aims at understanding the impact that restrictions, associated to COVID-19, had on the electrical energy consumption in Europe, and the downstream consequences to generation and international exchange of electricity. Leveraging the work from [18], the types of intervention whose severity correlated with consumption loss were identified, and their time of implementation was determined.

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Following this data driven approach, such period of active restrictions in 2020 was analysed comparing it to the same time interval from past years, using the Percent Deviation statistic, and accounting for yearly variability with ad hoc statistical procedures. With this methodology, energy load, generation and international transmission were studied for 16 European countries, for which data were available, to understand how Europe's electric grid was affected by the epidemic.

## 2. Methodology and data

### 2.1. Electricity data

The data were obtained from the Transparency Platform of the European Network of Transmission System Operators for Electricity (ENTSOE [19]). The available data consist of time-series with a 15, 30 or 60 min resolution depending on the country. The following time series for 16 European countries from 1/1/2015 to 30/6/2020 were used:

- Load data [MW]
- Generation data for each type of source
- Generation capacities for each type of source (annually)
- Cross-country power flows for neighbouring countries (imports and exports)

Because of inconsistencies or omissions in the data, the following were removed:

- Netherlands generation data, since they disagreed with load data, particularly for the years before 2019;
- Italy and Switzerland 2015 generation data, because largely incomplete.

All other non-substantial missing data points were imputed by linear interpolation.

### 2.2. Governments responses quantification and comparison with energy load

In the evolving scenario of COVID-19 emergency, quantifying in a comparable way governments responses is a very complex task. Several attempts have been done to systematize institutional intervention data [18,20]. The Oxford COVID-19 Government Response Tracker [18] (OxCGRT in the following) provides a systematic cross-national, cross-temporal measure to understand how governmental responses have evolved during the epidemic. This reference was identified as most suitable to compare the intensity of interventions in the COVID-19 emergency with different nations' electricity load. The OxCGRT includes 18 indices sorted into 3 main categories: "Containment and closure", "Economic response", "Health systems". Each indicator quantifies, on a daily basis, the intensity of a governmental restriction executed from a country included in their dataset.

For the present analysis, all the indices of the "Containment and closure" were used, that most obviously have a more direct relation with the energy load. "Economic response" indices were instead excluded for the lack of a direct relation with the electric load and also for the timescale of their action. Economic responses, in fact, do have consequences on a longer time scale while the present study takes into account only the first 6 months of 2020. "Health systems" indices were also excluded because of their negligible impact on the energy load, with the exception of the "Public info campaigns", which, in principle, could affect people behaviours and thus energy consumption on a large scale. The list of the 9 indices taken in consideration can be found in Table 1.

For each of these 9 indices, the time of action was determined for each country. The time of action was defined as the days when the relative index is greater than zero. Summing an index over its time of action provided the cumulative extent of severity for the governmental actions associated with it, in that country, for the first 6 months of 2020. This quantity was named *Cumulative Index*. In order to study the relation between intervention intensity and load variations, also the cumulative energy load was calculated in the time of action of each index in each country. The mean of the cumulative load of the five previous years was then used as a forecast reference for 2020 cumulative load, and the *Cumulative Forecast Excess* (CFE) was calculated as

**Table 1**
The list of the OxCGRT indices selected for the present study. For each index, the correlation of the Cumulative Index and the Cumulative Forecast Excess of different countries are reported. In bold, the indices with a meaningful correlation ($P$-value $< 0.05$).

| Intervention index | Correlation | $P$-value |
|---|---|---|
| **School closing** | **0.577** | **0.019** |
| **Workplace closing** | **0.521** | **0.039** |
| Cancel public events | 0.423 | 0.103 |
| Restrictions on gatherings | 0.418 | 0.121 |
| Close public transport | 0.067 | 0.855 |
| **Stay at home requirements** | **0.640** | **0.014** |
| **Restrictions on internal movement** | **0.575** | **0.020** |
| International travel controls | −0.113 | 0.676 |
| Public information campaigns | 0.431 | 0.096 |

$$CFE = \frac{\sum_{i=2015}^{2019} CL_i/5 - CL_{2020}}{CL_{2020}}. \quad (1)$$

where $CL_y$ is the cumulative load in the time of action of a given index for the year $y$. E.g. $CL_{2018}$ is the cumulative load observed in 2018 in the same days corresponding to the time of action in 2020 of the given index. From this procedure, two values were obtained for each combination of one OxCGRT index and one country:

- the *Cumulative Index*, representing the cumulative severity of the intervention;
- the *Cumulative Forecast Excess* of the load, representing the total decrease in the load in the observed period compared to the same period in previous years.

### 2.3. Comparison methodology and extreme values detection

To understand and measure the impact of governmental restrictions on the electrical power system, at a country level, it is necessary to assess the data recorded during COVID-19 emergency against a counterfactual scenario where the epidemic did not occur. Therefore, defined the real number $X_y$ as the total energy transmitted, generated or consumed, over a fixed time period of year $y$ (for $y \in \{2015, \ldots, 2020\}$), the fluctuation of $X_y$ was estimated by the Percent Deviation from years before 2020, namely

$$S_y = \frac{X_y - \sum_{i=2015}^{2019} X_i/5}{\sum_{i=2015}^{2019} X_i/5}. \quad (2)$$

This formula scales the data from different countries and years into the same support. In particular, $S_{2020}$ effectively measures the impact of COVID-19 restrictions as the deviation of $X_{2020}$ from the average of previous years, which estimates year 2020 without epidemic.

To quantify how largely $S_{2020}$ deviated from past years, taking yearly variability into account, the number of years that were more extreme than 2020 were compared against the others averaged, using the value

$$r = \#\{y < 2020 : P_y \geq S_{2020}\}, \quad (3)$$

with $P_y = (X_y - \sum_{i\neq y} X_i/5)/|(\sum_{i\neq y} X_i/5)|$, $|z|$ being the absolute value of $z$, and $\#A$ being the number of elements in a set $A$. This approach follows the same rationale as a test for statistical significance by permutations [21] assessing the null hypothesis that $X_y$, for $y = 2015, \ldots, 2020$, are independent observations from the same distribution. When $r = 0$,

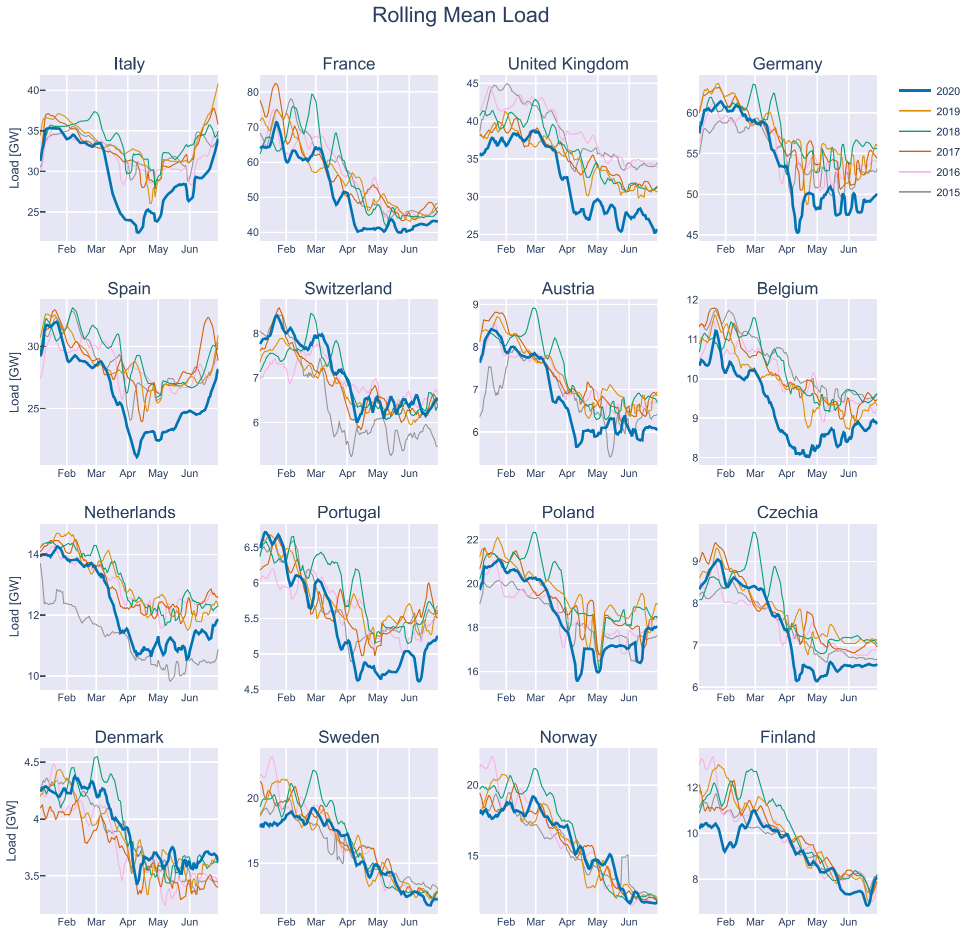


**Fig. 1.** Seven-days rolling mean of the load in 16 EU countries, superposing years from 2015 to 2020.

the test leads to the rejection of the null hypothesis, with a level of significance equal to $1/\#\{y: y \leq 2020\}$ (i.e. 0.2 or about 0.17 for 5 or 6 yearly data points, respectively). When $r > 0$, instead, the null hypothesis cannot be rejected. Note that this measure does not take into account special weather conditions.

## 3. Results

### 3.1. Correlation of load and stringency indices

After the spread of COVID-19 in Europe, lockdowns were imposed in several countries to oppose the epidemic. Simultaneously, large drops in electric load were reported (Fig. 1), which is mostly due to a reduction in industrial and commercial activities with a possible increase in residential sector [4]. For instance, for the month of April, all countries combined had a mean load drop of 37 GW, or 12% if compared to the 5 previous years. Yet, load levels did not revert to normality after the confinements ended, as observed in Fig. 1, and other limitations persisted throughout the pandemic and after strictest restrictions were lifted.

Two main questions emerged: (1) how much the duration and the severity of all these restrictions affected the load drops, and (2) which interventions had a greater impact. To address these questions, a measure of the extent of governmental interventions was elaborated using the indices provided by the OxCGRT dataset.

First, the OxCGRT indicators whose impact resulted in reduced load were identified. For every index, using the *Cumulative Index* and the *Cumulative Forecast Excess* from each country, the Spearman's correlation coefficient and the relative $P$-value were calculated. The indices with significant correlations ($P$-value $< 5\%$) were selected. Results are reported in Table 1. Only 4 indices showed positive and significant correlations: "School closing", "Workplace closing", "Restriction on internal movements", and "Stay at home". These four indices were then combined into a novel macro index named "*Energy Stringency Index*". This new index was then used to calculate its time of action, i.e. the time range where the index is greater than zero.

The days in 2020 when the *Energy Stringency Index* is not null, determine a period of active restrictions with a strong relation on a country's energy load. Thus, this temporal arc will be hereafter referred to as the "restrictions period". This procedure enabled a systematic determination of the interval of time to study how European countries modulated electrical energy generation, and transmission in order to balance for the reduced consumption. Each nation had its own time range, based on when the Energy Stringency index was greater than zero in that nation. They had different starting dates but the ending date is the same for every country, the 1st of July 2020, because the index happened to be greater than zero at least until that date. Finally, the Energy Stringency index was compared against the load drops, resulting in a strong and significant positive correlation (0.73 with $P$-value of 0.001), as outlined in Fig. 2.

Reported results suggest that the quantification of severity for governmental restrictions could be exploited to improve the forecast of the load, which became less predictable using standard models when the grid is stressed by extraordinary events.

The assessment of the energy scenario began with the national-wide electric load and how much it was affected by institutional interventions. Thus, using the Percent Deviation statistic (see Methodology), load records from different countries could be compared over the last 6 years. From Fig. 3 a remarkable load drop across Europe emerged clearly, with the exception of Scandinavia and Switzerland. As

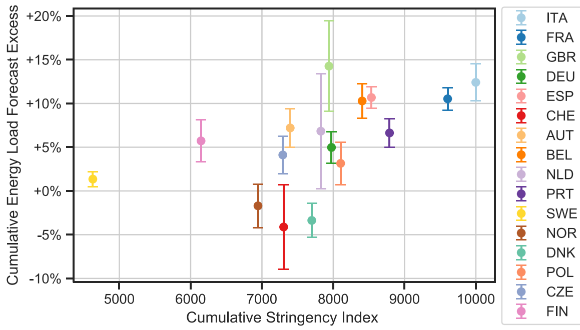


**Fig. 2.** Cumulative Energy Stringency index versus Cumulative Forecast Excess for different nations. Standard deviation of the five previous years gives a representation of the yearly variability. The Spearman's Correlation Coefficient is 0.73 with a *P*-value of 0.001.

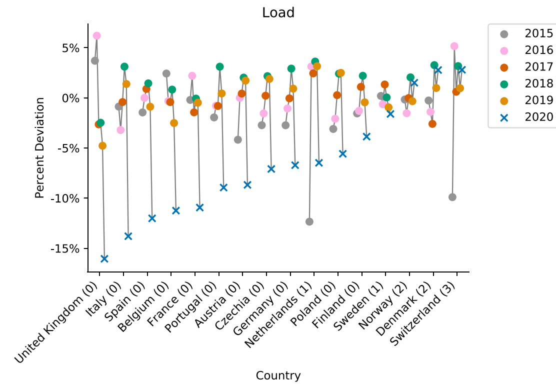


**Fig. 3.** Percent Deviation of load. Each point refers to a country's cumulative load in the restriction period, for different years. Baseline value (at 0%) corresponds to the average from years before 2020. Next to a country's name the r-value depicts how many years are more extreme, compared to others, than 2020.

a speculation, such anomaly might concern the mildness of confinement restrictions, which is the case of Sweden, where light COVID-19 limitations were implemented; other factors, however, might have played a role, such as the prevalence of electric heating in Scandinavia or the specific composition of the industrial sector. Yet, the lack of a significant total load drop might be a result of significant effects to residential, industrial and commercial loads [22,23], that cancelled out upon aggregation. Therefore, a more in depth study (with finer data) is required to pin down the actual causes and impact. Overall, 11 out of 16 countries present null r-value (in brackets next to each country's name), indicating 2020 as the most extreme year, with many loads reducing by 10% from past years average.

### 3.2. Impact on electricity generation

As energy load dropped in the restrictions period, significant changes were expected at the level of electricity generation. Observing the weekly rolling mean of generation from January to June 2020,

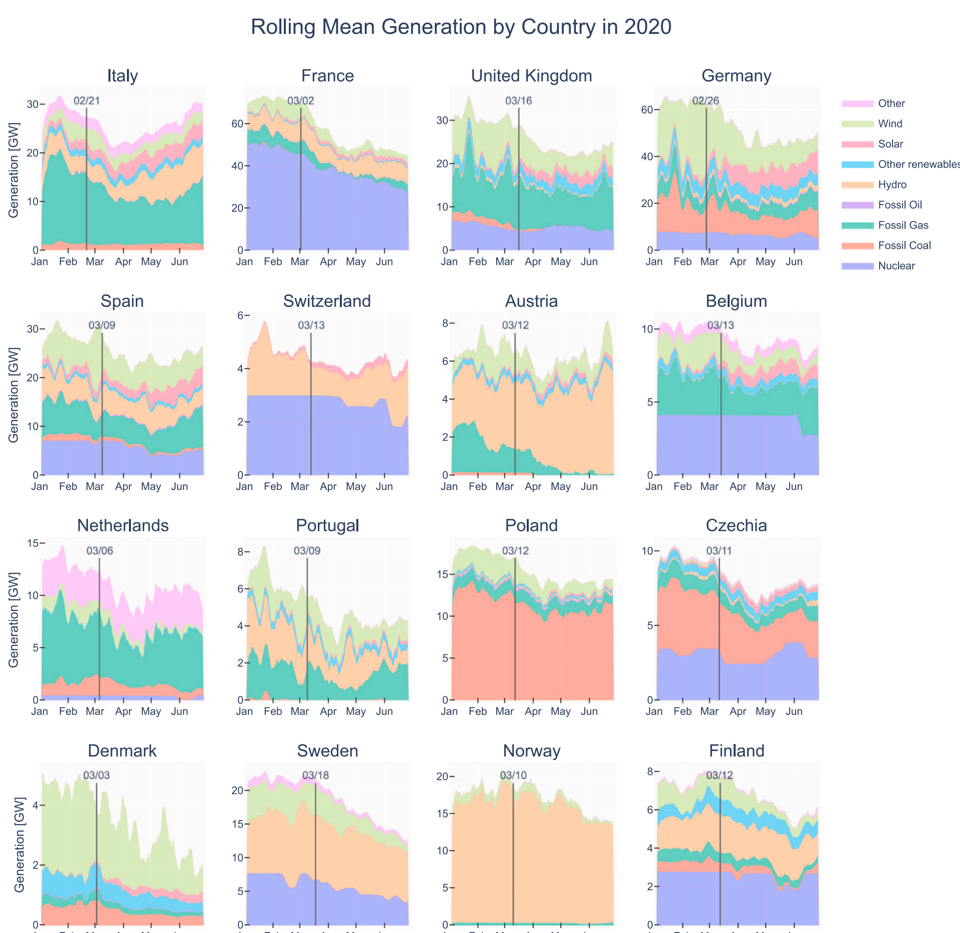


**Fig. 4.** Seven-days rolling mean of the generation by resource type for 2020. Vertical lines with dates indicate the begin of the restrictions period, namely when the *Energy Stringency* index became positive.

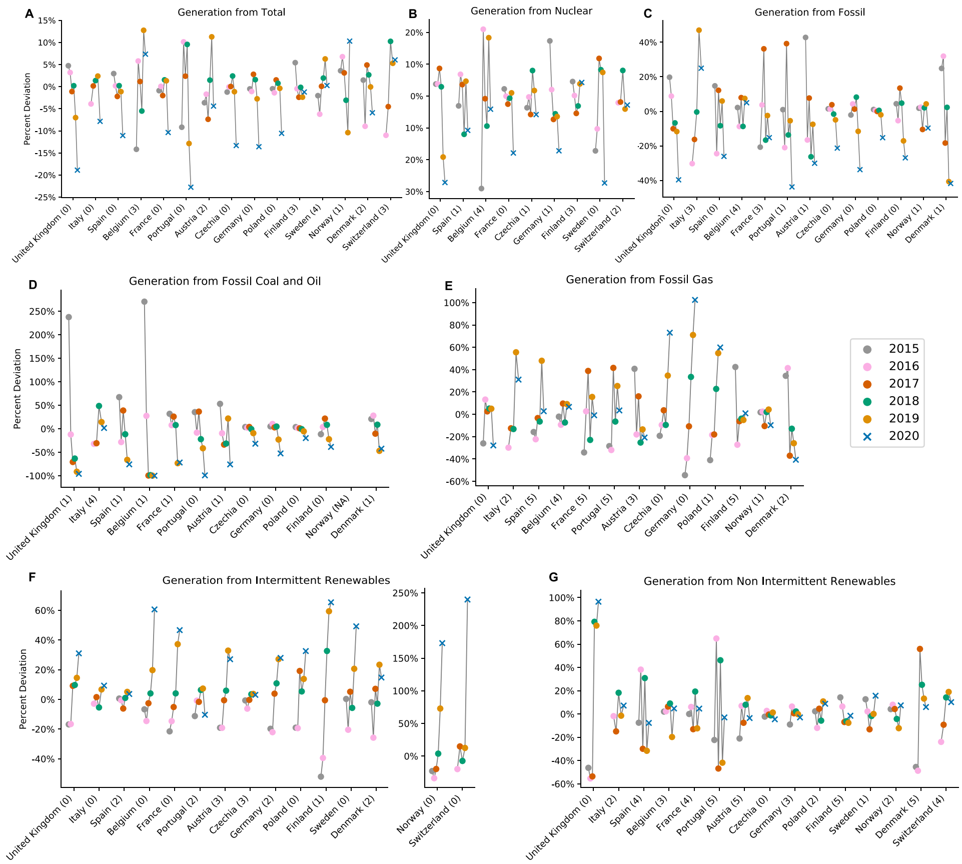


**Fig. 5.** Percent Deviation of total (A), nuclear (B), fossil (C), fossil coal and oil (D), fossil gas (E), intermittent renewables (F), and non-intermittent renewables (G) generation. Each point is a cumulative sum over a country's restriction period. Baseline value (at 0%) corresponds to the average from years before 2020 (excluded), by which all points relative to a given country are centred. Next to a country's name, within parentheses, the r-value depicts how many years are more extreme, compared to others, than 2020.

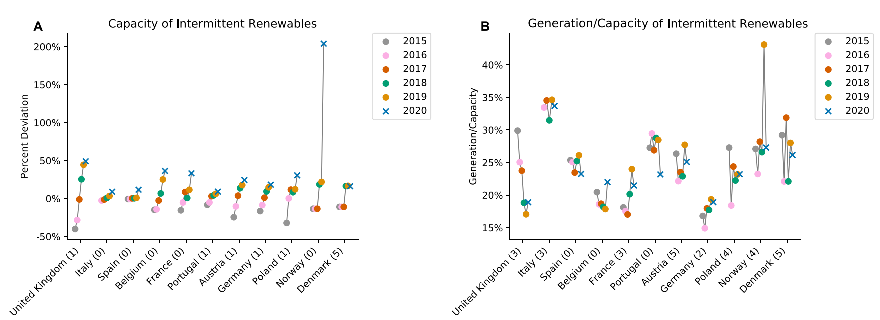


**Fig. 6.** Percent deviation of the national energy capacity (A), and percent of generation over total capacity, namely utilization (B) from intermittent renewable sources. The plot display follows the same rationale as in Fig. 5.

sorted by energy source, many countries presented a generation decrease, particularly in concomitance with March and April when most severe lockdown measures were imposed (Fig. 4). For some cases, such as Italy, the drop steepness suggested causes other than the changing of weather or seasons, when transitioning from winter to spring time energy production typically reduces with the increasing of atmospheric temperatures. For instance, during the month of April, the total mean generation, from all countries combined, decreased by 25 GW (−9%) compared to the 5 previous years averaged. During that same month, fossil fuel generation dropped by 24 GW (−28%), nuclear by 11 GW (−14%) while combined renewable generation increased by 15 GW (+15%). Also, more in general, the load comparisons presented in the previous section suggested that seasonality could not be responsible for all the variation observed.

In order to account for the seasonality, the data from the restrictions period for the generation (total and split by different source groups) were analysed using the Percent Deviation statistic. This procedure enabled the study of how generation was regulated among different energy sources, and which of these were reduced or curtailed. The difference between imported and exported energy, namely the net energy balance, was finally investigated to achieve a complete overview of the energy composition for each country.

*Total generation.* As hypothesised, most of the countries with significant load decrease also showed a significant generation decrease (Fig. 5A, $r$-value = 0), with two exceptions: Austria and Belgium. Austria, however, presented a remarkable change of trend with respect to the previous three years. Inference for Belgium, instead, was hindered by the high variability in its generation pattern, thus no conclusion could be drawn.

*Nuclear and fossil generation.* The non-renewable energy sources, such as nuclear and fossil (which includes gas, oil and coal) that typically cover the baseline load, were observed decreasing in generation for most countries, although yearly productions were quite variable (Fig. 5B, C). Still, nuclear output reduced significantly in France and the UK, two EU countries with large nuclear generation. This result suggested that COVID-19 related restrictions led to the exploitation below capacity for nuclear power plants, reducing their overall efficiency. Fossil generation plants, instead, are more flexible and therefore easier to modulate to reduce their output than nuclear. This agrees with the evidence that energy generation from fossil fuels was affected by largest Percent Deviation drops (Fig. 5C). In particular, coal and oil decreased over the past years (Fig. 5), replaced by cleaner alternatives (see Supplementary Material). Still, Germany, Poland and Czechia, countries whose production share of coal is still relatively high, shifted to more fossil gas generation over the years (Fig. 5E), a trend continuing also through 2020.

On a side note, Italy's growing trend for fossil generation is spoilt by the formal attribution to fossil, over the years, of a considerable proportion of electricity produced, previously classified as deriving from "other" sources (reported in Supplementary Material).

*Renewable generation.* Renewable energy has no fuel cost and should therefore be prioritised for both environmental and economic reasons. The variability and intermittency in generation from wind and solar, however, challenges the matching of supply and demand, and may result in curtailments. In particular, generation from renewables – specifically intermittent renewables – was queried about its full utilization even during the load drop. To analyse renewable sources, these were grouped into intermittent renewables (solar, wind onshore and wind offshore), and non-intermittent renewables (hydro, biomass, geothermal, waste), on the basis that the output from intermittent renewables cannot be shifted in time, but only curtailed. Indeed, as low load and favourable weather conditions co-occurred in April 2020, an unprecedented number of negative wholesale market prices was witnessed across Europe (especially in Germany) [5,24], thus raising the question whether intermittent renewable energy was extraordinarily curtailed due to COVID-19 restrictions. As new wind and solar generation capacity was progressively added over the years (Fig. 6A), generation from intermittent renewables steadily increased as well, and this trend seemed to continue in 2020, for all European countries but Portugal, Spain, Germany and Austria (Fig. 5F). A more in depth study of weather conditions and markets would be needed to determine reasons for this.

For another viewpoint, generation was divided by the installed capacity, which measures the proportion of utilization from the installed assets. For the 15 analyzed countries, no significant Percentage Deviation in generation/capacity was observed for the lockdown phase of 2020, except for Portugal and Spain (Fig. 6B). This could suggest that the 14 other countries did not recur to exceptional curtailments in 2020, and intermittent renewable output was consumed or exported similarly as previous years. As for Portugal (and to a lesser extent Spain), utilization seemed to have decreased, but a focused investigation would be necessary to analyse if and how much curtailment occurred.

About non-intermittent renewables (mostly hydro), their output considerably increased in the United Kingdom and slightly decreased in Czechia from previous years, but did not present outstanding deviations overall. In fact, being hydro a mature and flexible technology, its utilisation did not change significantly over the years (Fig. 5G).

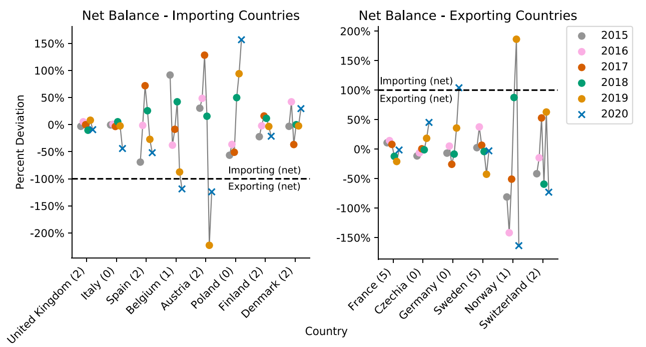


**Fig. 7.** Percent deviation of net energy balance from net importing (A) and net exporting (B) countries. The plot display follows the same rationale as in Fig. 5. Horizontal dashed bar indicate the threshold separating positive (net import) and negative (net export) net energy balance.

### 3.3. Net energy balance change

The unusual situation of 2020, showed that the European grid helps balancing between countries with often greatly different generation mixes or – in this case – government interventions leading to load drops. In general, both exports and imports were higher compared to previous years. To inspect the international exchange of electrical energy, countries were first separated into net importers and net exporters, respectively depending on the positive or negative sign of the net energy balance summed over the restrictions periods from years 2015 to 2019.

In Figure (Fig. 7), net balance naturally presented a larger percentage variations than load or generation, because of smaller amount of energy that is imported and exported, relative to the load (with Portugal being the most extreme example — see Supplementary Material). During the restriction period of 2020, Italy, traditionally a big net-importing country, diminished the net balance by 50%, indicating that imports were much reduced as the load dropped. For Belgium and Austria, instead, the declining trend, over the past years trade, slowed and inverted, respectively, and exports overcame imports by 2020. In this year, a significant increase in net balance occurred for Poland and Czechia, which are Fossil based, and for Germany. Strikingly, the latter country incremented so much as to become a net importer during the restrictions period related to the COVID-19.

## 4. Conclusion

The understanding of COVID-19 emergency is an important case study to prepare for scenarios of large load reduction, and high renewable output. The present paper investigates the impact of restrictions, related to the epidemic, on the electricity flows in 16 European countries. Using the OxCGRT indices, four limitation types, that significantly correlated with the load reduction observed during the crisis, were identified: "Stay at home", "School closing", "Restriction on internal movements", and "Workplace closing", ordered by increasing correlation. These findings highlighted how the daily severity of these interventions could be accounted for in energy consumption forecast models, to obtain more accurate predictions in the eventuality of successive waves or in future emergencies. In the period of active restrictions, most of Europe was characterized by a remarkable load drop, except for Scandinavia and Switzerland, whose consumption did not decrease significantly (possibly due to less restrictive limitations, peculiarities concerning the load compartments, or a country's industrial activity). Concurrently, energy generation by coal, oil and nuclear was reduced considerably, in favour of intermittent renewable sources and, in some countries, fossil gas. In most countries, no extraordinary curtailment was found concerning intermittent renewables, confirming the general trend of increasing exploitation of these sustainable sources, even in critical times. The energy transmissions between countries was also explored, showing a general increase of both imports and exports. Coal-based countries, such as Poland, Czechia and Germany, highly increased their net incoming energy, with Germany even becoming a net importer in 2020. Italy, instead, halved its net imports, which is significant for such a big net-importing country. Future studies are required to precisely model the impact of restrictions on generation, net balance and load, ideally split the latter by sector (residential, industrial, commercial). Such models will allow for a better long-term forecast, which could be strategic for policy-makers. Also short-term forecast will be improved by these models, supporting the activity of the electric grid stake-holders.

The results outlined above provide an overview on how energy dynamics in the European electric system played out, adapting to rapidly changing conditions as a consequence of the COVID-19 restrictions imposed by governments. Understanding the ramifications of COVID-19 responses provides unique insights not only on how different societies manage critical situations but also on how higher shares of intermittent renewables will impact the grid infrastructure, the energy markets and related investments. As Gillingham and colleagues pointed out [25], pushing back renewable investments would outweigh emission reductions from March to June of 2020 and only an energy policy response could change that. The path undertaken through this crisis will be incorporated into new policies and determine long-term consequences towards a more sustainable future and the avoidance of coming crisis.

## CRediT authorship contribution statement

**Annette Werth:** Conceptualization, Supervision, Visualization, Validation, Investigation, Writing - Original draft preparation, Writing - review & editing. **Pietro Gravino:** Supervision, Methodology, Software, Visualization, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Giulio Prevedello:** Supervision, Methodology, Software, Visualization, Formal analysis, Data curation, Writing - original draft, Writing - review & editing.

## 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.

## Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.apenergy.2020.116045.

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