Unlocking the Impacts of COVID-19 Lockdowns: Changes in Thermal Electricity Generation Water Footprint and Virtual Water Trade in Europe

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ABSTRACT: Drastic changes in electricity demand have been observed since March 2020 in Europe, after several countries implemented lockdown-like measures to contain the spread of COVID-19. We investigate the sensitivity of the electricity–water nexus in the European electric grid to large-scale behavior changes during the COVID-19 pandemic lockdown-like measures. We quantify changes in the blue virtual water trade between five European countries heavily affected by COVID-19 during the same period. As a result, the consumptive water footprint of thermal power plant operations in Europe decreased by 1.77 × 10^6 m^3/day during the COVID-19 lockdowns, compared to the average of the past four years. Reduced electricity demand accounts for 16% (0.29 × 10^6 m^3/day) of the decrease, while the remainder is attributable to changes in the electricity generation mix toward less water-intensive technologies before 2020 and during lockdowns. Virtual water transfers associated with electricity were also affected: Italy, a hotspot of COVID-19, reduced its water footprint by 8.4% and its virtual water imports by 70,700 m^3/day. Germany and France slightly reduced their domestic water footprint of electricity but increased their virtual water imports. These findings improve our understanding of the impacts of large-scale behavior and technological changes to the European electricity–water nexus.

INTRODUCTION

Since the appearance of a pneumonia of unknown cause in Wuhan, China, at the end of December 2019, the new coronavirus disease COVID-19 has spread worldwide with an outbreak that was declared a pandemic by the World Health Organization (WHO) on March 11, 2020.1 As of April 19, 2020, the rapid spread of COVID-19 caused nearly 2.5 million confirmed cases in 185 countries worldwide, as reported by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU).2 During March and April 2020, four of the five countries with the highest count of confirmed cases were located in Europe (Spain, Italy, France, and Germany).

As COVID-19 started its exponential spread in Europe in March 2020, nearly all European countries implemented quarantine and lockdown-like measures to contain the transmission. Recent studies analyzed the effectiveness of such measures on the spread dynamics of the COVID-19 pandemic,3,4 as well as their consequences on several socioeconomic sectors, including lifestyles, telecommunications, and environment (e.g., 6–9 and references therein). Flights to and from Europe reduced.10 European stock indices plummeted.11 Schools closed in most of the regions,12 and economic activities slowed down13 as countries started implementing preventive quarantine and lockdown interven-

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Drews\textsuperscript{27} studied the water use of electricity production in Europe and its changes over the long-term (1980–2015). Electricity trade in Europe was investigated by Abrell and Rausch.\textsuperscript{28} The most recent and detailed study on the water footprint in the EU is provided by Vanham et al.\textsuperscript{26} Chini and Stillwell\textsuperscript{29} combined the topics of water footprint and electricity trade and calculated the virtual water embedded in electricity trade throughout Europe at a monthly scale (2010–2017). However, most of the above studies do not consider subannual dynamics of electricity demand and generation and model the system under normal operating conditions. An exception is a recent article in which seasonal water intensities of electricity generation were considered.\textsuperscript{30} Here, we aim to contribute to the literature by evaluating the short-term changes of the European water footprint of thermal electricity and related impacts on virtual water trade during the COVID-19 pandemic.

We limit the scope of our analysis to the operational phase of thermal power plants, similar to previous research,\textsuperscript{7} and query European electricity demand and generation data to address the following two research aims. We first investigate how changing electricity demand, and hence changing electricity generation, impacted the consumptive water footprint of thermal power plant operations in Europe during the COVID-19 pandemic quarantine and lockdown-like measures. Second, we quantify changes in the virtual water trade among five European countries strongly affected by COVID-19 during the same period.

Analyzing the impact on water resources of an exceptional, drastic, and rapid change in the electricity demand and generation in Europe represents a unique opportunity to improve our understanding of the sensitivity of the electricity–water nexus in the European electric grid to large-scale behavior changes, as compared, for instance, to technological improvements or adoption of different energy mixes. Understanding the subannual dynamics in the electricity–water nexus in the European electricity grid and rapid climate, technological, and collective behavior changes can ultimately facilitate the inclusion of nexus considerations in adaptive planning and management strategies. Adaptation strategies are key to ensure the resilience of critical systems and networks, especially in those parts of Europe, such as its Mediterranean basins, e.g., in Italy and Spain, already experiencing seasonal water scarcity, which will likely see increased pressure on water resources due to reduced precipitation and increased temperatures.\textsuperscript{31,32}

\section*{Materials and Methods}

We first investigated whether Europe as a whole showed any change in its electricity generation after the implementation of quarantine and lockdown-like measures. We computed the time series of daily electricity load from January 1, 2020, to April 19, 2020, and then analyzed its deviation from the average values observed in the same period between 2016 and 2019.

Second, we calculated the consumptive water footprint of thermal power plant operations in Europe and its changes during the COVID-19 lockdown-like measures. The concept of water footprint is described in \textit{The Water Footprint Assessment Manual}\textsuperscript{33} and has been often applied to evaluate the embedded water resources of agricultural products (e.g., in refs 33 and 34). Water footprint refers to the amount of water consumed to create a product or process, including three categories: green water (i.e., rainwater stored in the soil and available to plants), blue water (i.e., consumed surface water or groundwater), and gray water (i.e., to dilute pollution). Here, we limit our analysis to the consumptive blue water footprint of electricity production in thermal power plant operations. The blue water footprint for hydropower is not included in our analysis, due to the lack of data availability at subannual temporal resolution. However, different studies reference the large contribution of hydropower to electricity water footprints; thus, future investigations to quantify the subannual water footprint of hydropower generation in Europe are needed to overcome the limitations of our results.\textsuperscript{33,34} Green water is generally negligible in electricity production, when only power plant operations are considered.\textsuperscript{35} Calculating the gray water footprint requires temperature data from rivers and cooling water that, to our knowledge, are not consistently available at the European scale. The water footprint of the energy fuels from a life cycle perspective is beyond the scope of this study.

Within this scope, the water footprint (WF) in m\textsuperscript{3}/MWh is calculated for each country (c) and day (d) as the product of daily electricity generation (\(e_{c,d}\)) from different fuel types (f) and the average water intensity per type (\(i_{f}\)).

\[ \text{WF}_{c,d} = \sum_{f} i_{f} \times e_{c,d} \]  

To compute WF (eq 1), we consider the same water intensity values (\(i_{f}\)) adopted by Macknick et al.,\textsuperscript{20} averaged over different cooling technologies (further details are reported in Table S1).

Third, we analyze virtual water (VW) trade, which refers to the fraction of WF that is imported and exported by a country.\textsuperscript{19} That fraction is calculated as the ratio between the exported electricity (x) and the generated electricity (g). We thus calculated VW as shown in eq 2.

\[ \text{VW}_{c,d} = \frac{x}{g} \times \text{WF} \]  

We completed the virtual water of electricity analysis using the electricity data published in the European Network of Transmission System Operators for Electricity (ENTSO-E) Transparency Platform. ENTSO-E publishes different electricity data sets with hourly or subhourly time resolutions for all European countries at the national scale.\textsuperscript{19} The data sets from the past five years on load, generation aggregated by type, and physical flows over 25 European countries were used in this study. In particular, for the load analysis, we focused on the five countries with the highest absolute number of COVID-19 cases as of March 15, 2020, namely, Italy, Spain, France, Germany, and Switzerland. For the calculation of the WF and VW, some countries from the ENTSO-E data set were excluded from this study due to incomplete data sets in March 2020 (see Table S2 for a list of included/excluded countries). With regard to data processing, variables were summed to daily values and shifted in time to match the dates of the previous years with the same day of the week in 2020.

Given the time series of one of the analyzed variables of interest (e.g., the 2020 time series of water footprint of electricity generation in Europe), its mean values in 2020 before and after the lockdown-like measures were compared to their baseline values, i.e., the average values of the same variable computed over the past four years (2016–2019). The temporal change of a variable was then calculated as a
difference between the anomalies of its 2020 average values and the average 2016−2019 baseline values before and after the lockdown-like measure start date. This calculation is shown in the Supporting Information (eq S1). We disaggregated changes in the WF in Europe due to changes in the electricity mix during the lockdown-like measures as described further in the Supporting Information (eqs S2−S6).

Finally, we included data on the number of COVID-19 cases published by John Hopkins University,3 while we gathered details on preventive quarantine and lockdown-like measures and policies from different European newspapers or government announcements (Table S3). We investigated the five most affected countries as of March 15, 2020, namely, Italy (24,747 confirmed COVID-19 cases), Spain (7,798), Germany (5,795), France (4,499), and Switzerland (2,200) (Table S4).

## RESULTS AND DISCUSSION

### Changes in Electricity Generation in Europe.

In the last 3 weeks of March 2020, most European countries implemented quarantine- and lockdown-like measures spearheaded by Italy on March 10, 2020. Later that week, the electricity generation in Europe started to decrease considerably, especially in the countries more intensively affected by COVID-19.14 As Figure 1a shows, the electricity generation in Europe (red line) at the beginning of 2020 followed a similar pattern of those observed in 2016−2019, while a sharp decrease is registered as the number of confirmed COVID-19 cases increased and countries implemented lockdown-like measures. While interannual changes in energy generation and usage might be due to changing seasonal conditions, the observed exceptional changes can be primarily attributed to the imposed restrictions to contain COVID-19 spread. In April
2020, electricity generation in Europe during working days reduced to previous weekend levels, confirming that the decreasing energy demand due to slower economic activity outweighs a possibly increased usage in private homes. This dynamic is also confirmed in the recently published Global Energy Review 2020.36 Changes of the Water Footprint in Europe. As a consequence of changing electricity demand, and thus generation, our results show changes of thermal power plant operations in Europe as evident by a lower WF (see blue line in Figure 1b). After March 15, 2020, the consumptive WF of Europe’s thermal power plant operations decreased on average by 8.2% compared to the baseline years 2016–2019. We observe that the decline in electricity demand during the COVID-19 pandemic reduced consumption of water resources for electricity generation. Interestingly, the WF was lower than previous years at the beginning of 2020, before the spread of COVID-19 and lockdown-like measures, because the electricity generation has been recently changing to a less water-intensive mix. The share of water-intensive thermal cooling technologies decreased from 68.5% in the baseline years to 62.2% in early 2020 prior to lockdowns and to 61.1% during lockdowns. At the same time, the share of nonwater-consuming technologies (i.e., primarily renewables) increased from 31.5% to 37.8% in early 2020 and to 38.9% during the lockdowns. However, such general figures must be handled with caution. They neither show how the share of different thermal technologies changes (e.g., nuclear) nor do they prove that only an absolute reduction of electricity generation can significantly reduce the water footprint. The Global Energy Review 2020 describes that the increase in renewables is mainly caused by coal and gas being phased out of the electricity mix due to lower demand.36

Despite the limitations of these values, our results indicate two critical issues. First, the changing energy mix in the past years has generally reduced the European consumptive WF for thermal power plant operations. However, this change has not necessarily decreased virtual water trade of electricity between countries.35 Second, the reduction in water footprint during the COVID-19 lockdown-like measures is not only a consequence of a reduced generation but also includes the combined effect of changing generating technologies. Compared to baseline values in 2016–2019, the consumptive WF for thermal power plant operations in Europe has decreased by 21% on average during the lockdowns (equivalent to 1.77 × 10⁶ m³/day). Of this total reduction, we estimated (eqs S1–S5) that 1.25 × 10⁶ m³/day was due to changes in the energy mix until 2020 and an additional reduction of 0.52 × 10⁶ m³/day during the lockdowns (0.23 × 10⁶ m³/day from the changing energy mix during lockdown and 0.29 × 10⁶ m³/day from lower electricity demand).

Changes in European resident behaviors due to lockdown-like restrictions and technological changes in electricity generation almost equally contribute to the additional WF reduction during the lockdown period. Our results suggest that short-term behavior changes during an emergency situation or under lockdown restrictions contribute to achieving an immediate reduction in the European WF. However, technological changes in electricity generation and shifting energy mixes appear to reduce water resource consumption more in the longer term.

Changes in Virtual Water Trade between COVID-19 Hotspots in Europe. To understand the virtual water
dynamics between the five European countries considered in this study, we investigated the shifts in their domestic WF for electricity in combination with the calculated changes of VW transfers due to electricity import and export. Figures S2–S6 illustrate examples of the dynamics of electricity generation, WF, and VW transfers between the five countries. Italy especially shows a decrease in electricity generation and its related WF and a sharp decline in electricity imports and related virtual water transfers.

Our results for all five considered countries are given in Figure 2. First, the map (Figure 2a) shows that the reduction in electricity load during the lockdowns led to a reduced WF in four of the five nations, with France reducing its WF by more than 68,000 m³/day. However, when considering relative figures, Italy reduced its WF by approximately 8.4%, followed by Switzerland (4.5%), and France (3.3%), and Germany (2.5%), while Spain shows somewhat stable behavior (<1%).

Considering the virtual water trade network (Figure 2b), Italy appears to not only avoid water consumption domestically, but its decrease in electricity imports also avoided water consumption mainly in Switzerland (~47,400 m³/day import to Italy) and France (~22,800 m³/day import to Italy). Italy was the only country that reduced its net foreign water consumption during the lockdown, accounting for differences between imports and exports (Figure S2). The other countries, especially Germany and France, increased their VW imports (Figures S4 and S6). Notably, Germany increased the virtual water consumption in France and Switzerland by 16,200 and 30,500 m³/day, respectively.

## DISCUSSION AND CONCLUSION

With the results obtained in this analysis, we conclude that the short-term impact of COVID-19 lockdown-like measures on the consumptive WF of thermal power plant operations and virtual water trade in Europe primarily emerges from domestic WF reductions due to decreased electricity generation. In addition to this observed common behavior for all countries considered, Italy reduced its water footprint abroad because it relied less on electricity imports, while under normal operating conditions it has a strong dependence on electricity from Switzerland and France. The changes in VW trades that are visible in this specific case study are due to the highly interconnected structure of the European electric grid. The COVID-19 hotspot countries considered in this study are located in a cluster of neighboring countries; therefore, strict lockdown-like measures (like those implemented in Italy) can significantly influence VW transfers from and to other countries.

In summary, our analysis contributes to improving the understanding of the sensitivity of the electricity–water nexus in the European electric grid to short-term large-scale behavior changes and can be used to inform future demand-management actions during or prior to emergency situations, as well as planning of infrastructural and technological changes to improve the resilience of the European electric grid and reduce its impact on water resources. Other state-of-the-art studies provided a comprehensive overview of the existing water footprint of European electricity and energy generation. Here, we added to these studies by providing knowledge on the short-term changes of water footprint observed during the COVID-19 lockdowns in Europe within our defined scope of consumptive water footprint due to thermal power plant operations. Within this scope, we compared the effects of technological changes (changing electricity mix) with sudden behavior changes (reduced electricity demand due to lockdown-like measures) on water footprint and virtual water transfer. These two components act on different temporal scales, where the first one is driven by a controlled technological process, while the second is more uncertain as it depends on the sum of collective, potentially very heterogeneous, behaviors. This finding suggests that future climate adaptation strategies for improved resilience of coupled water–energy systems should focus on both dimensions. The combined action of both demand-side interventions and a shift toward a less water-intensive electricity mix is needed to reduce pressure on water resources.

On the basis of our scope of investigating the consumptive water footprint of thermal power plant operations during the COVID-19 lockdowns in Europe, we acknowledge that results from future analyses may differ. Conclusions may change if the water footprint of electric fuel life cycles, the water footprint of hydropower generation, and gray water footprints are included as suitable data become available. More comprehensive and holistic analyses would help derive generalizable assessments on the total influence of the energy mix or energy efficiency improvements on the water footprint of the European electricity grid and its individual countries, also as compared to other socio-economic determinants of electricity demand. Finally, while we only considered total thermal electricity generation and related water footprint values, future studies could investigate how changing economic activities and lifestyles during the COVID-19 lockdowns affected the efficiency of electricity usage in relation, for instance, to economic outputs. One question to be answered in this regard is why some countries studied here actually increased their electricity imports during the lockdowns, while most economic activities slowed down.

## ASSOCIATED CONTENT

**Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.0c00381.

Additional remarks on the methodology (temporal changes of water footprint and virtual water in Europe) (eqs S1–S6 and Figure S1), relevant data used for calculations (Tables S1–S5), and results for individual European countries (Figures S2–S6) (PDF)

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Author Contributions
A.C., M.R., C.M.C., and A.S.S. designed the research and developed the paper. M.R. compiled the data and performed the analysis. M.R. and A.C. designed the visual elements of the paper. A.C., C.M.C., and A.S.S. supervised the research. All authors reviewed the manuscript.

Notes
The authors declare no competing financial interest.

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