A Quantitative Analysis of the Short-Term and Structural Impact of COVID-19 Measures on Electric Vehicle Charging Patterns

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***Abstract*—Charging patterns of electric vehicles (EVs) are affected by the global COVID-19 lockdown, which forced people to stay home. This impacts the daily operation of grid operators, as different EV charging patterns could affect grid congestion levels. In addition, this effect could partly be structural, as the COVID-19 lockdown could induce a permanent shift in travel patterns, for instance when a larger share of the working activities are shifted to home. For this reason, this paper analyzes the effect of various phases of the lockdown on the charging volumes and patterns of EVs at three case study locations. In addition, this paper provides insights in future grid congestion levels with different adoption rates of EVs and different shares of the working activities permanently shifting to home after the COVID-19 lockdown. Results show a substantial drop in EV charging volumes; compared to the pre-lockdown phase, charging volumes decreased by almost 75% in the first lockdown phase, and to 60%-70% in later phases. In addition, the outcomes indicate that if a share of the working activities are structurally shifted to home, grid congestion problems in low-voltage grids could be dramatically reduced in the future.**

***Index Terms*—COVID-19, Corona Virus, Electric Vehicle Charging, Charging Profiles, Grid Impact**

NOMENCLATURE

Indices and sets

- $s \in \mathcal{S}$ Set of scenarios with different shares of working activities shifting to home after the COVID-19 pandemic.

Symbols

- α_{red} Reduction in annual charging demand when shifting working activities to home.
- β_{adoption} EV adoption rate
- γ_{home} Share of working activities permanently shifting to home after the COVID-19 pandemic.
- $E_{\text{agg,home}}$ Aggregated future charging demand of EVs that will follow similar travel behavior during and after the COVID-19 pandemic.
- $E_{\text{agg,org}}$ Future EV charging demand in a LV grid with 100% EV adoption before the COVID-19 pandemic.
- $E_{\text{agg,pre-COVID}}$ Aggregated future charging demand of EVs that will follow similar travel behavior before and after the COVID-19 pandemic.
- E_{agg} Aggregated annual charging demand of EVs in a LV grid.

I. INTRODUCTION

The lockdowns imposed by national governments to prevent further transmission of COVID-19 directly and indirectly affected the energy sector [1]. Studies on the early impact of COVID-19 indicated that the electricity demand in different countries decreased drastically by up to 29% compared to the year before [2]–[4], while the global energy demand in 2020 has decreased by 6% [5]. This decrease in energy demand has lead to a global emission reduction of between 7 to 9% [5]–[7] and to lower energy prices [8]. On the other hand, the COVID-19 pandemic could result in higher emissions on the long run, caused by lower investments in clean energy innovation [9]. In addition, COVID-19 results in considerable changes in the energy demand patterns of households, due to more people working from home [10], [11].

Simultaneously, COVID-19 has serious impact on passenger road transport. Worldwide road passenger transport activity was at some moments during the lockdown over 60% lower than in 2019 [12], while the car intensity on the road decreased by up to 46% in the Netherlands [13]. Over 80% of the global population reduced mobility movements by over 50% [14], causing a reduction in surface transport emissions of 36% [6].

The day-to-day operations of distribution system operators (DSOs) could be affected on both the short and the long term by COVID-19. On the short term, the direct effects of COVID-19 lockdowns on the energy sector and the transport sector change the electricity flows in the low-voltage (LV) and medium-voltage (MV) networks of DSOs, since energy demand profiles of households change [10], [11], while the lower number of cars on the road also affects the electric vehicle (EV) charging demand. In an increasing number of grids, DSOs need to actively manage grid assets to avoid grid congestion problems due to increased electrification of the system and increased EV charging [15], [16]. Managing the grid during COVID-19 is more complicated due to the higher unpredictability of grid flows. In addition, the use of EVs as a flexibility resource for grid operators changes with different connection times, charging volumes and charging locations.

The COVID-19 lockdown could also permanently affect the grid flows in LV and MV grids, since it could cause that a larger share of the population will structurally work more from home even after the COVID-19 lockdowns [17], [18]. DSOs currently use future projections of the grid load to make grid reinforcement decisions to facilitate EV charging. If working from home becomes the new standard, these grid load projections could be impacted, causing that DSOs need to re-evaluate their grid reinforcement decisions.

Refs. [10] & [11] already looked into the effect of COVID-19 on the electricity consumption patterns of households. Ref. [19] has analyzed how EV charging patterns were affected by the COVID-19 lockdown in Utah, United States, but only performed the analyses on a state level and did not look into the effect at different location types. To the authors' knowledge, no studies analyzed the effect of COVID-19 lockdowns on EV charging in Europe at different types of locations, even though EV charging will make up an increasing share of the grid load. This analysis provides insights in the effect of different phases during the COVID-19 lockdown on EV charging patterns, using case studies of a residential area, office area and event location in Utrecht, the Netherlands. In addition, this study indicates how projections on future grid congestion are affected if the COVID-19 pandemic causes a structural change in travel patterns of the population. The results guide DSOs in grid reinforcement decisions by providing insights in the future grid load and in the future availability of EVs as a flexibility resource with more people working from home in the future.

This paper is outlined as follows: Section II presents an overview of the different phases of the COVID-19 lockdown in the Netherlands. Subsequently, Section III provides an outline of the considered EV charging data in this analysis. The impact of COVID-19 on EV charging patterns is presented in Section IV. Section V analyzes the impact of a permanent change in travel behavior induced by COVID-19 on future grid congestion. Lastly, a discussion and conclusion are presented in Section VI.

II. Phases of COVID-19 lockdown in the Netherlands

The number of measures and the strictness of measures during the COVID-19 lockdown in the Netherlands changed in the course of time. This section distinguishes six phases: one pre-lockdown phase followed by five lockdown phases of varying strictness. EV charging patterns will be presented for each of the different phases.

- *Phase 1 - Pre-lockdown - before 12 March 2020*: The first COVID-19 patient in the Netherlands was diagnosed on 27 February 2020, but no major national restrictions were in place until 12 March 2020.
- *Phase 2 - First partial lockdown - 12 March 2020 - 11 May 2020*: From 12 March 2020 onwards, the government cancelled all big events and people were urged to work from home. The restrictions imposed by the government were expanded on 15 March 2020 by closing i.a., all schools, bars and other public places. Shops could remain open under strict conditions.
- *Phase 3 - Relaxations of lockdown - 11 May 2020 - 28 September 2020*: First relaxations were imposed on 11 May 2020. Primary schools and different shops and public places re-opened. Further relaxations were imposed on 1 June 2020: Restaurants, bars, cinema's and high schools could re-open under strict conditions. On 24 June 2020, more events were allowed and people were no longer stimulated to stay home.
- *Phase 4 - Second partial lockdown - 28 September 2020 - 14 December 2020*: New restrictions were imposed by the government on 28 September 2020. The opening hours of restaurants and bars were limited, and the number of people that could come together was reduced. Also, people were again strictly urged to work from home. The government imposed a second partial lockdown on 13 October. Restaurants and bars were closed and events were prohibited.
- *Phase 5 - Lockdown - 14 December 2020 - 23 January 2021*: A full lockdown was imposed on 14 December 2020. Schools, sport facilities and non-essential shops were closed and the number of visitors that a person could receive was reduced to two.
- *Phase 6 - Installation of a curfew - 23 January 2021 - March 30*: A curfew imposed on 23 January 2021 caused that people were not allowed to be on the streets between 21:00-4:30 (later changed to 22:00-4:30) without a valid reason. Primary schools re-opened on 8 February 2021.

During Phase 2, 3, 5 and 6, the government urged employees to work from home as much as possible.

III. EV charging data

Data from 8 January 2019 to 30 March 2021 from charging stations in three areas in the Utrecht province (the Netherlands) is used as a case study in this analysis. The three different studied areas have different functions (residential area, office area and event location), which allows us to get insight in the effect of COVID-19 in EV charging behavior at charging locations with different functions. The first studied location is the Lombok district in the city of Utrecht, a residential area with 24 charging stations, each with two charging sockets. The second set of 50 charging stations with two charging sockets is located in the city of Zeist at the parking lot of the headquarters of a banking company, providing insight in the impact of COVID-19 on EV charging at office locations. The last location is the parking lot of a major congress and event center in the city of Utrecht with 19 charging stations with 2 charging sockets.

All studied charging stations log the arrival time, departure time, charging volume, car-ID and charging card ID of each charging transaction. All charging stations in the studied residential area also log the charging power over time with a 5-minute resolution, which makes it possible to determine the average charging power, maximum charging power and actual charging duration per charging transaction.

Fig. 1: Charging volume per day for all charging stations in the studied areas during different phases of the COVID-19 lockdowns. Results are presented for both regular and shared EVs. The different phases are indicated using different colors.

IV. Impact of COVID-19 on EV charging

Fig. 1 shows the total daily charging volume of all considered charging stations in the three studied areas during the different phases of the different lockdowns. It indicates that the first lockdown (Phase 2) had a very considerable impact on EV charging volumes, which reduced by 73.6% in the studied residential area, by 89.6% in the studied office area and by 99.2% at the studied event location. As expected, the most dramatic decrease in charging volume occurs at office and event locations. Offices were closed for most employees, while all events at the event location were cancelled, reducing the number of visitors to almost zero. The charging volume at the studied residential area is almost halved during the first lockdown, indicating that people stayed more at home during the lockdown, but did not completely refrain from car usage during the COVID lockdown.

With increasing relaxations of the first lockdown in Phase 3, EV charging demand rose slightly in most locations. However, the charging demand in Phase 3 was still 68.1% lower compared to Phase 1 at the studied residential area, 84.9% lower at the studied office area and 88.1% lower at the studied event location. The second lockdown imposed by the Dutch government during Phase 5 and 6 had a direct effect on EV charging volumes at all locations, indicating that this lockdown caused people to stay more home. However, charging volumes during Phase 5 and 6 were higher than during the first lockdown, indicating higher car usage in the second lockdown compared to the first lockdown.

To consider seasonal trends when analyzing the impact of COVID-19 on EV charging, Fig. 2 compares the daily charging volumes at the studied residential area during the first year of the COVID-19 pandemic with the charging volumes of the same day the year before. The figure shows that the average daily charging demand before the COVID-19 lockdown (Phase 1) increased by 50.4% between 2019 and 2020. This can be attributed to high EV adoption at the end of 2019 and a higher market share of battery electric vehicles compared to plugin hybrid electric vehicles [20]. Normally, one would expect similar or higher increases in charging demand during the remainder of the year. However, the average daily charging demand reduced by 12.5% in 2020 compared to 2019 after imposing the COVID-19 lockdown during Phase 2. Also with more relaxations of the lockdown during Phase 3, the average daily charging demand did not increase compared to 2019. During the second lockdown in Phase 5 and 6, the decrease in charging demand compared to the year before was more considerable (¿50%). This can be attributed to higher charging volumes at the end of 2019 due to high EV sales in this period, which causes a high relative decrease in charging volumes.

Fig. 3 provides insights in charging characteristics before and during the COVID-19 pandemic in the studied residential

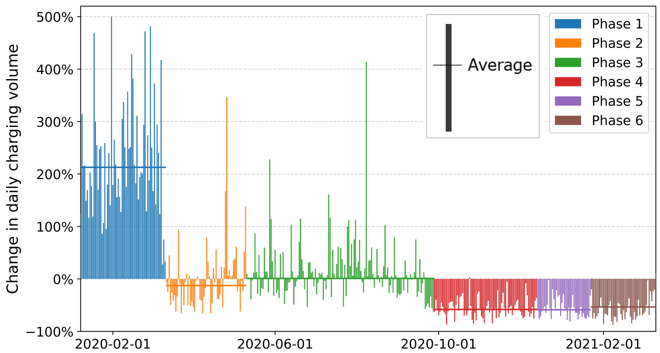

Fig. 2: Percentage change in total charging volume for all charging stations in the studied residential area compared to the same day of the year the year before. This comparison considered the same day of the week one year earlier, i.e., the charging volume of Saturday 1 February 2020 was compared with the charging volume of Saturday 2 February 2019.

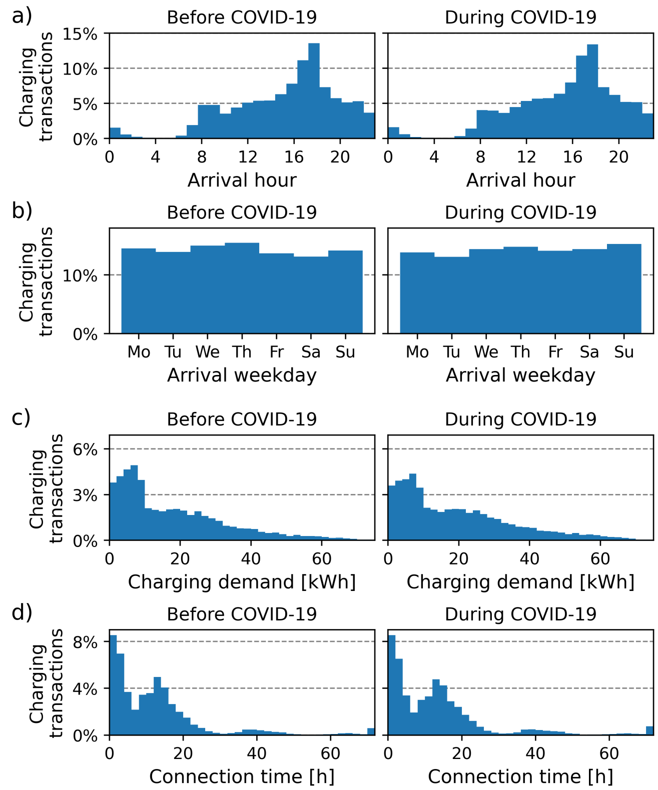

Fig. 3: Histograms comparing key EV charging characteristics of before and during the COVID-19 pandemic in the studied residential area.

area. The figure shows that the utilization of EVs in weekends is relatively higher, but overall there are no considerable differences in the arrival hour, charging demand and connection time before and during the COVID-19 pandemic. This could indicate that reduction in the usage of EVs is relatively uniform among all types of trips; i.e., the COVID-19 lockdown has not only resulted in lower usage of EVs for commuting purposes, but also resulted in a similar reduction in EV usage of EVs for other trip types.

V. Simulation of Future Impact of COVID-19 on Grid Congestion

People have experienced the benefits of working from home during the COVID-19 pandemic. As a consequence, the number of people working from home could be structurally higher after the COVID-19 pandemic compared to the years before the pandemic. This will affect charging schedules of EVs and thus affect future grid congestion levels. To guide DSOs in making grid reinforcement decisions, the grid load in a residential grid is simulated for different scenarios with different shares of the working activities shifting to home.

A. Methods

1) Charging transaction simulations: In the first step of the analysis, future sets of charging transactions are simulated for scenarios with different shares of the working activities shifting to home after the COVID-19 pandemic has ended. A shift to working from home has major impact on the overall charging demand of all charging transactions in a grid (see Fig. 1) and minor impact on the distribution of arrival times, departure times and charging demand of transactions in a grid (see Fig. 3). For every future scenario s, two subsets of charging transactions are simulated using a probabilistic model described in [21], which uses a total aggregated annual charging demand in a LV grid (E_{agg}) and the distribution of charging characteristics like in Fig. 3 as an input. The first subset consists of charging transactions of EV owners that will follow similar travel behavior compared to the pre-COVID situation. For this set of charging transactions, the transaction simulation model uses the distribution in charging characteristics before the COVID-19 lockdown and the following aggregated charging demand ($E_{\text{agg,pre-COVID},s}$) as an input:

$$\mathrm{E}_{\text{agg,pre-COVID},s} = \mathrm{E}_{\text{agg,org}}\beta_{\text{adoption}}(1-\gamma_{\text{home},s}), \quad (1)$$

where $\mathrm{E}_{\text{agg,org}}$ is the expected future annual charging demand with 100% EV adoption in one LV grid before the pandemic, β_{adoption} is the EV adoption rate and $\gamma_{\text{home},s}$ is the share of the working activities shifting to home. The study uses a value of 530 MWh for $\mathrm{E}_{\text{agg,org}}$ for the studied grid, based on a car ownership ratio of 0.6 cars/household in the studied residential area [22] , an average annual car mileage of 13,000 km in the Netherlands before the pandemic [23] and a fuel consumption of 0.2 kWh/km [24].

The second subset of charging transactions consist of EV owners that shift part of their working activities to home after the pandemic. It is assumed that these charging transactions follow the same distribution of arrival times, departure times and charging demand as during the pandemic. The used aggregated charging demand in the simulation model ($\mathrm{E}_{\text{agg,home},s}$) is determined as follows:

$$\mathrm{E}_{\text{agg,home},s} = \mathrm{E}_{\text{agg,org}}\beta_{\text{adoption}}\gamma_{\text{home},s}\alpha_{\text{red}}, \quad (2)$$

where α_{red} represents the reduction in annual charging demand when shifting working activities to home. The used value of α_{red} is 0.32, based on the ratio in average daily

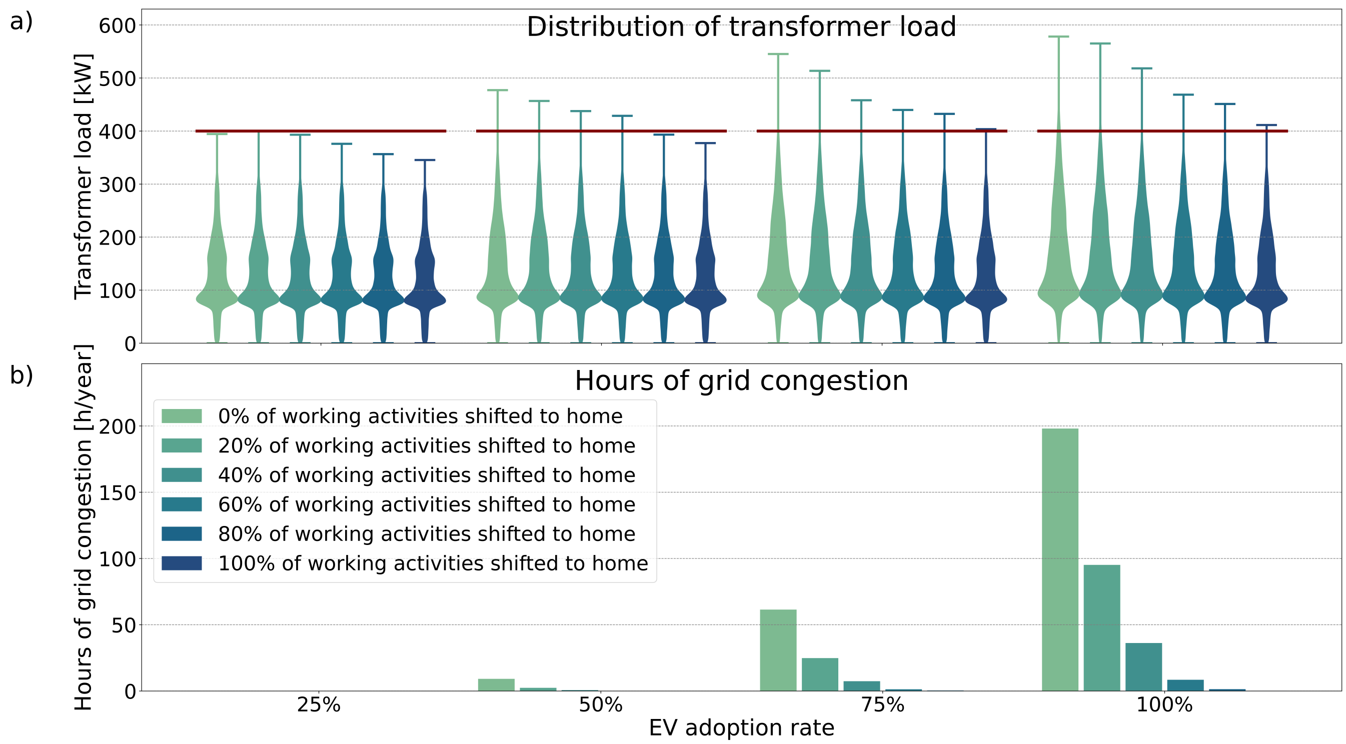

Fig. 4: Violin plot of the annual distribution of the absolute transformer load and the number of hours with transformer congestion for different EV adoption rates and for different shares of the future working activities moving to home.

charging demand during the pandemic and during the last three months before the pandemic.

2) Simulation of grid load: The transformer load ($P_{\text{transformer},t}$) at time t is determined as follows:

$$P_{\text{transformer},t} = P_{\text{residential},t} - P_{\text{PV},t} + \Sigma_{n=1}^{N} P_{\text{ch},n,t}, \tag{3}$$

where $P_{\text{residential}}$ is the accumulated residential load in one LV grid, P_{PV} is the accumulated photovoltaic (PV) generation in one LV grid and $P_{\text{ch},n}$ is the total charging demand of the set of charging transactions $n \in \mathcal{N}$. In the simulation of the EV charging power over time, all EVs charge at maximum charging power after arrival until their charging demand is met.

3) Grid data inputs and model simulations: This study considers a grid with 340 connections and a 400 kVA transformer as a case study to analyze the grid impact of a permanent shift of working activities to home. The grid impact is analyzed on a transformer level; i.e., the study analyzes power flows through the transformer and power flows through cables behind the transformer are not considered.

This analysis requires residential load, PV generation and EV charging transaction data of the considered LV grid as an input. Residential load profiles for the grid are generated using standardized NEDU profiles [25], while PV generation profiles are generated using normalized PV generation profiles from a three PV systems in a residential area in Utrecht, the Netherlands [26]. This study assumes a future installed PV capacity of 200 kWp in the considered grid.

The used modelling resolution Δt equals 15 minutes. For every scenario, the simulation of charging transactions was repeated 10 times to get insight in the variability in results.

B. Results

The impact of shifting different shares of the working activities to home is presented in Fig. 4 for different EV adoption rates. Fig. 4a presents violin plots which show the distribution of transformer loads during the year. The higher tails of the violin plot with higher EV adoption indicate a positive relationship between the time with high transformer loads and the EV adoption rate, induced by the higher overall charging demand in this case. Fig. 4a also indicates that the share of time with high transformer loads decreases with higher shares of the working activities shifting to home.

As a consequence, the number of hours in which the transformer load exceeds the transformer capacity decreases with a higher share of the working activities shifting to home. This is reflected in Fig. 4b, presenting the annual number of hours with grid congestion for every scenario. If no working activities are shifted to home after the pandemic, the first minor grid congestion problems appear at 50% EV adoption. With 100% EV adoption, congestion problems appear for approximately 200 hours per year in this scenario, while almost no congestion problems appear with 100% EV adoption if 80% of the working activities are shifted to home. Also, even if only 20% of the working activities are shifted to home (i.e., working one day per week at home), congestion problems are reduced by over 50%, indicating that this minor shift has major impact on grid congestion levels.

VI. DISCUSSION & CONCLUSION

This paper studied how the different COVID-19 lockdowns in the Netherlands affected EV charging demand and flexibility at three case study locations. The start of the lockdown directly resulted in a reduction in charging demand of 74% at residential areas, of 90% at office locations and of 99% at event locations. The charging volumes did not get close to pre-lockdown volumes during different relaxations of the lockdown. A second lockdown again caused a small reduction in EV charging demand, but the effect was slightly less pronounced compared to the first lockdown.

The results are interesting from a grid operation perspective as they indicate that DSOs can expect a considerable reduction in charging demand peaks with future lockdowns, in particular at office and event locations. If this lockdown caused a structural change in the number of people working from home, this analysis indicated that this could delay grid congestion problems for DSOs, already when a minor share of the working activities are shifted to home. In that case, previous analyses on the future grid impact of EV charging should be revised and DSOs should reconsider their grid reinforcement decisions. As COVID-19 restrictions were active during any of the studied phases in this analysis, it is too early to determine whether a high number of people will be structurally working from home in the future.

While interpreting the results, the reader should bear in mind that the results are based on three case studies with a limited number of charging stations. The effect of the COVID-19 lockdown on EV charging at office locations could differ between different types of offices. The results are based on data from charging stations at a banking company, but the effect could be less pronounced for work locations where employees cannot work from home, such as hospitals.

In addition, this study did not consider that the residential load can increase when a larger share of the working activities are shifted to home. Consequentially, the decrease in grid congestion in Fig. 4 when shifting working activities to home could be lower in practice. Generally, it can be expected that the decrease in grid congestion when working activities are shifted to home will still be very considerable if the changing residential load patterns are also considered, as the power and simultaneity of demand is significantly higher for EV charging compared to the residential load.

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