ANALYSING ELECTRIC VEHICLE CHARGING POWER QUALITY IN LARGE-SCALE CHARGING SITES – A DATA-DRIVEN APPROACH

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ABSTRACT

Due to their various benefits, the number of electric vehicles (EVs) is increasing rapidly. Despite the extensive amount of EV charging related research, the power quality impacts of large-scale EV charging are still mostly unknown. In this paper, a data-driven approach is taken to assess the power quality quantities in large-scale commercial charging sites. The approach combines charging session data, high quality charging profile data and results from EV fleet development model to analyse various power quality quantities of the charging sites. The results show that EVs have notably different power quality characteristics. Additionally, the total demand distortion in large-scale EV charging is estimated to remain below 5%.

INTRODUCTION

Electric vehicles (EVs) are seen as a key solution to ensure environmentally friendly transportation. However, there remains some challenges that might prevent a smooth transition towards a wide EV adoption. One key challenge is the uncertainty of potential power quality issues caused by the wide adoption of EVs that may compromise efficient and reliable supply of power [1]–[3].

Related Research

EV charging is widely studied, and several studies have considered power quality issues imposed by the charging of EVs. Study [3] proposes an off-board charger that reduces power quality issues imposed by the EV charging. Study [4] proposes a control method that is able to mitigate harmonic currents of the EV charging. Study [5] presents an active compensation-based harmonic reduction technique to mitigate third harmonic component from the input current. Studies [6], [7] assess the impacts of harmonic EV charging currents in case of direct current (DC) or single-phase alternating current (AC) charging. Study [8] analyses voltage drops and unbalances and their mitigation with a local smart charging algorithm. Study [9] characterizes EV charging power quality for DC charging of Nissan Leaf including grid-to-vehicle and vehicle-to-grid operation modes. Study [10], compares uncontrolled charging and off-peak charging from voltage violations and power losses perspective. In [11], a methodology to assess EV hosting capacity in distribution grids is presented. The methodology takes into account voltage levels, component load capacities, and voltage distortions as limiting factors. Study [12] assessed the power quality in cases of four 40 kW chargers or seven 22 kW chargers operating simultaneously. In [13], measurements from an EV were analysed and used to form a harmonic spectra of the EV to study power quality in low voltage networks. The results show that third harmonics were the most significant one and the current harmonic distortion exceeded the standard IEEE 519-2022. The study also demonstrated that power quality variables depend on the state of charge, and thus, fixed power quality characterization over the whole charging session is seen inaccurate.

Based on the aforementioned studies, it can be seen that multiple different aspects related to the power quality of EV charging have been considered. However, the previous studies investigate small-scale charging sites [3]–[5], [7], [10], [12], [13], does not consider real EVs [3]–[6], focuses only on a few types of EVs [8], [9], [11]–[13], or assumes fixed power quality characterization over the charging sessions [10]. Thus, the potential power quality issues in large-scale EV charging are still mostly unknown. Studies [7], [9] note that power quality of large-scale EV charging should be investigated, but it is left as a future work. In [14], large-scale EV charging is investigated from phase load balance point of view, but an analysis of the power quality impacts is excluded from the study.

Contributions and structure

This study aims to fill the gap in the scientific literature by analysing the power quality in large-scale commercial EV charging sites. To ensure realistic results, a novel data-driven approach is used. The approach utilizes two data sets: (1) high temporal resolution (1 second) power quality charging profile measurements (including fundamental frequency reactive power, total distortion in current (TDI) and harmonic currents up to 20th order) from multiple different EVs; (2) charging session data (including plug-in times, connection times, and charging peak powers) from commercial charging site within a shopping centre premises. Additionally, results of a car fleet development model are used to predict the amount and type of the EVs at large-scale commercial charging sites in the future.

METHODOLOGY

This section describes the methodology of the paper. The following subsections separately discusses the charging session data, charging profile data, EV fleet development, studied cases, and the used simulation model.

Charging session data

Charging session data describes when EV charging takes place. This paper uses measurements from commercial charging sites located in REDI and Tripla premises. Both REDI and Tripla are shopping malls located in Helsinki, Finland. In the charging sites, there are over 200 charging points that provide three-phase charging powers up to 22 kW. The data include plug-in time, connection time and the peak power of each charging session. The used data is measured 1.11.2019–29.2.2020 and include 5107 sessions and 3518 sessions for REDI and Tripla, respectively. The data represents the average charging behaviour in the beginning of 2020 and is not expected to be influenced by the COVID-19 (restrictions started in March 2020 in Finland).

Charging profile data

Charging profile data is used to model how an EV charges during a charging session, i.e., how the currents and power quality quantities behave during the charging. As the charging profile data, this paper uses measurements from a charging site located in Tampere University premises. This data is measured with *eQL Laatuvahti3* measurement device in one second temporal resolution over 1.4.2022–30.6.2022. The measurement quantities used in this study are summarized in Table 1.

There are 8 publicly available charging points (type 2, 3×32 A, 22 kW) behind the meter. In order to form a charging profile for an individual EV, a snapshot of the measurements is used only when a single EV is charging at a time. Based on the data, 51 separate charging profiles were formed. These include 20, 12, 15 and 4 charging sessions with 0–4.5 kW (≈ 3.7 kW, 1×16 A, 230 V), 4.5–10 kW (≈ 7.4 kW, 1×32 A or 2×16 A, 230 V), 10–15 kW (≈ 11.0 kW, 3×16 A, 230 V), and 15–25 kW (≈ 22.1 kW, 3×32 A, 230 V), respectively. These power groups are considered here as they are quite distinctively separated according to [14].

From the data, it is not possible to determine what EV model was charging and in which exact charging point. Consequently, it is not possible to determine whether some of the charging profiles are from the same EV or EV model. However, since the charging points are available for public use, it is assumed that the 51 profiles include multiple different EV models. The results of the charging profile analysis support this claim.

Table 1. The measurement quantities used in this study

Quantity	Unit	Description
Active power (P)	W	1-second average in bandwidth 0-2 kHz
Fundamental frequency reactive power (Q_1)	var	1-second average in fundamental frequency
Apparent power (S)	kVA	1-second average in bandwidth 0-2 kHz
Harmonic current (I_X)	A	1-second rms of Xth order (up to 20th)
Total distortion in current (TDI)	A	1-second rms including harmonics and interharmonics in bandwidth 0-2 kHz
Total harmonic distortion of current ($THD_{2\text{-}20}$)	A	1-second rms including harmonics until 20th order

EV fleet development

This paper utilizes the results of the EV fleet development model presented in [14]. The model uses vehicle data combined with socio-demographic data of the vehicle owners to calculate when and what kind of cars will be acquired. More thorough description of the model can be found in [15]. The EV fleet development results focus on the Finnish capital region which is also the focus area of the studied cases in this paper. According to the results of the predicted EV fleet development, the number of EVs in the region will increase from 7,972 (year 2020) to 173,319 (year 2040). Another important result of the model is the estimated development of the EV types in terms of charging powers. In 2020, over 70% of the EVs supported maximum charging power of 3.7 kW. However, in 2040, the expected share of EVs that support maximum charging power of 3.7 kW is 12.9%, 7.4 kW is 38.2%, 11.0 kW is 24.5%, and 22.1 kW is 24.5%. The estimated EV fleet development is illustrated in Fig. 1.

Cases

This paper assesses the power quality in the charging sites at REDI and Tripla premises in 2040. To determine the number of charging sessions with certain maximum charging power (3.7, 7.4, 11.0, or 22.1 kW) at REDI or Tripla in a weekday in year 2040, the estimated EV fleet development is combined with the present state. It is assumed that the number of charging sessions at REDI and Tripla is linearly dependent on the number of EVs in the

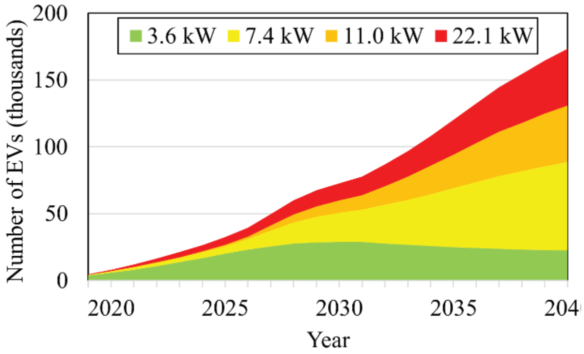

Fig. 1. The development of the EV fleet and the maximum supported charging powers in the Finnish Capital Region [14].

Table 2. The number of EVs and their maximum charging powers in each case

Charging power (kW)		3.7	7.4	11.0	22.1	Total
2040	**REDI**	130	378	245	240	993
	Tripla	71	197	130	125	523

Finnish Capital Region. The number and power group of the EVs in are presented in Table 2.
According to the data analysis in [14], there are no clear correlation between the charging powers of the EVs and the timings (i.e., arrival and departure time). Therefore, the timings are generated randomly for the EVs based on the distributions seen in the data to generate the charging session data for each case. Distributions are formed separately for REDI and Tripla for average weekdays. It is assumed that the distribution of the arrival times and connection times stay the same in the future. Illustrations of the timings on weekdays are presented in Fig. 2, where the average number of EVs arriving at each hour is presented along with the connection duration groups. The exact second of the arrival times and connection times are generated randomly for each charging session. Fig. 3 illustrates the formulation of the charging session case data used in the simulations. There are assumed to be 400 charging points in both cases. The maximum number of EVs simultaneously charging at REDI and Tripla are 356 and 108, respectively.

Simulation

This paper focuses on uncontrolled charging as there are no suitable data to directly investigate controlled charging. The simulations use 1-second temporal resolution and consider one full day per case. The simulation model starts by reading the charging session data of the studied cases to determine when EVs are plugged in and out. This data also includes the charging power group (3.7, 7.4, 11.0, or 22.1 kW). Then, the simulation model reads charging profile data to determine the charging currents and the power quality quantities for the charging sessions. The peak powers of the charging profiles are used to match a certain charging session with a certain charging profile. However, since the data include multiple profiles for each power group, a single profile from the corresponding group is chosen randomly for the charging session. Fig. 4 illustrates the operation of the simulation model.
The simulation assumes that the phase angles of the harmonic currents are equal between the charging profiles. Therefore, the aggregated harmonic currents of the charging profiles represent the worst-case scenario where the harmonic currents of separate EVs do not cancel each other out.
The simulation model assumes that phases of the three-phase charging points have been connected into the grid in an alternating order. This is a typical practice in real-life installations to promote more balanced loading in case some of the EVs utilize only single-phase charging.

RESULTS

This section starts by analysing the different charging profiles. Then, to determine the importance of the potential power quality issues of EV charging, the analysis of the simulation results focuses on the moments with a highest charging demand. The results focus on three seconds

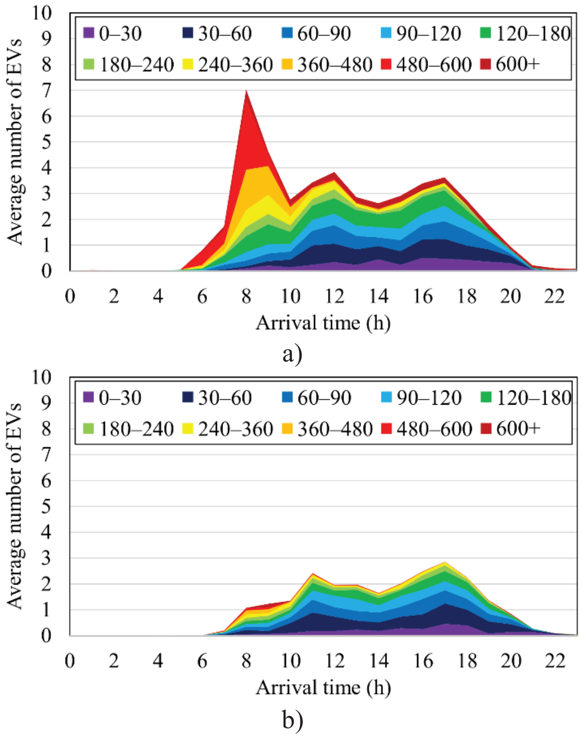

Fig. 2. Average number of EVs arriving each hour where the colours indicate connection time (min) in case of a) REDI and b) Tripla [14].

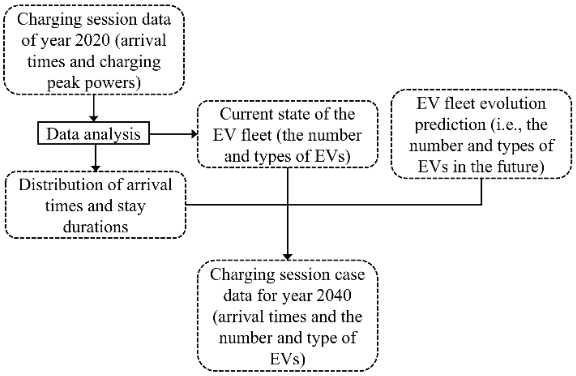

Fig. 3. Block diagram of the case data formulation.

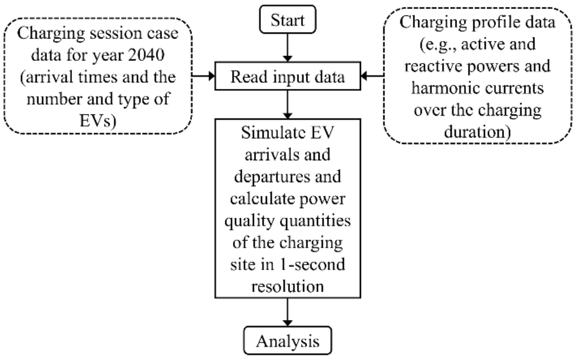

Fig. 4. Block diagram of the simulation model.

values since they are also considered in IEEE 519.

Charging profile analysis

By analysing the power quality quantities of the charging sessions, it was seen that multiple different characteristics exists. This is illustrated in Fig. 5 and in Table 3. In the figure, averaged values of 10-second snapshots from the start of the charging processes (after the start-up transients have settled) are shown for 5 EVs from the charging power group of 3.7 kW. For EVs 1 and 3, the 3rd harmonic current is the dominant one. However, the most notable harmonic current for EVs 2, 4 and 5 are 5th, 19th and 17th, respectively. Table 3 summarizes the most notable harmonic currents (absolute values and percentual values compared to the fundamental current) seen in the start of the charging profiles. Harmonics that were not the most significant are left out of the table. It is also worth noting that no notable differences were seen between the power quality quantities of different phases in case of three-phase charging (i.e., for EVs in power groups 11.0 kW and 22.1 kW).

Based on the Fig. 5 and Table 3, it is clear that the power quality quantities vary significantly between different EV models. This is assumed to be due to the differences of the on-board electronics of the EVs that determine their charging characteristics. Consequently, the influence of large-scale EV charging on power quality should be studied considering various different EV models to ensure reliable results.

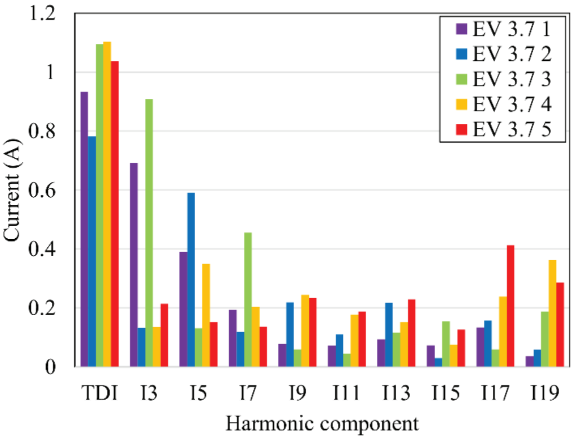

Fig. 5. Illustration of power quality characteristics of five EVs.

Table 3. The most notable harmonic currents in the charging profiles

Harmonic current	Number of EVs	Magnitude of the harmonic (A)	(%)
I_2	7	0.27–0.42	1.65–2.63
I_3	19	0.12–0.92	0.73–6.44
I_5	14	0.38–0.98	1.66–12.15
I_7	4	0.59–1.84	1.95–7.39
I_{17}	3	0.31–0.48	2.03–3.20
I_{19}	4	0.15–0.36	0.94–3.38

Simulation results

The highest values over a three-second period seen in the simulations are summarized in Table 4. In the table, subscripts 1–20 represents frequency (e.g., 1 is the fundamental). The values may not be from the same time steps. In the table, $THD_{2\text{-}20}$ represents the root mean square of the 2–20th order harmonics. Harmonics of 6th, 8th, 10th, …, 20th order are excluded from the table as their maximum values is below 2.4 A.

Table 4. The maximum values of the cases

Quantity	REDI			Tripla		
	L1	L2	L3	L1	L2	L3
S (kVA)	441	479	423	213	213	208
P (kW)	439	477	422	212	212	208
Q_1 (kVAr)	-12	-12	-12	-6	-5	-5
TDI (A)	104.2	110.8	100.9	58.8	53.6	56.5
$THD_{2\text{-}20}$ (A)	77.6	80.1	75.8	38.7	39.6	39.7
I_1 (A)	1880	2043	1802	908	908	888
I_2 (A)	8.1	8.2	8.0	3.8	4.1	4.1
I_3 (A)	28.7	33.8	27.6	11.7	12.7	13.1
I_4 (A)	4.0	4.3	4.1	2.3	2.4	2.5
I_5 (A)	52.2	54.6	49.9	26.1	26.6	27.1
I_7 (A)	37.8	38.7	38.9	20.9	21.2	21.3
I_9 (A)	10.9	10.7	10.0	5.2	4.1	4.8
I_{11} (A)	15.2	14.7	13.6	7.4	7.7	7.2
I_{13} (A)	19.0	18.3	18.1	10.1	9.5	9.5
I_{15} (A)	8.5	9.1	7.8	4.0	3.8	4.2
I_{17} (A)	14.3	13.6	13.0	6.8	6.7	7.5
I_{19} (A)	15.8	15.6	15.9	8.3	8.4	8.1

The simulation results show that charging produces (capacitive) fundamental frequency reactive power proportional to active power, and distortion in current has little impact to difference between P_L and S_L. For both cases and each phase, the highest TDI is around 5–7% of the highest fundamental current. Analysis of the simulation results according to IEEE Std 519-2022 showed that harmonics seems to be below even the most strict limits. The 5.0% limit for total demand distortion (TDD) was exceeded for 10-minute values of TDI slightly (max. 5.12% for REDI and 5.45% for Tripla). Considering the fact that TDI also includes interharmonics, the corresponding TDD value including only harmonics might be within the limit. The highest $THD_{2\text{-}20}$ was 3.90% for REDI and 4.27% for Tripla. For comparison, the highest 3-second values that have double the limit were 5.60% (TDI) and 4.05% ($THD_{2\text{-}20}$) for REDI and 6.92% (TDI) and 4.67% ($THD_{2\text{-}20}$) for Tripla. These results indicate that EV charging would have considerable amount of interharmonics or harmonics between 20th and 40th order. Conversely to the results shown in [13], 5th harmonic current is the most notable one almost the whole simulated duration instead of 3rd harmonic. However, it is worth noting that since different EVs have notably different charging characteristics from power quality perspective, the most notable harmonic current may very well vary from day to day. Consequently, it is possible that especially TDD occasionally exceeds the limit of IEEE Std 519-2022. Charging characteristics depend on the rectifier design of the EV. Based on the data, single-phase rectifier often generates more 3rd harmonics and three-phase rectifier generates more 2nd, 5th, and 7th harmonics. Even harmonics, such 2nd seen in the measurement data, indicates problems in charging. Presence of DC current is an unwanted phenomenon in AC networks.

CONCLUSIONS

This paper assesses power quality in large-scale EV charging sites using a data-driven approach. Firstly, charging profile data from 51 charging sessions is analysed. Secondly, the charging profile data is combined with charging session data from commercial charging sites and results of a car fleet development model to form realistic basis for the simulations.

Analysis of the charging profiles from power quality perspective shows that different EVs may have notably different characteristics. Depending on the EV, the most notable harmonic may be, e.g., 2nd, 3rd, 5th, 7th, 17th, or 19th order, of which 2nd, 17th and 19th were not expected, and thus, require further investigations. The magnitude of the most notable harmonic varies between 0.12–1.84 A (0.73–12.15% of the fundamental current). Consequently, it is imperative to consider various EV models when assessing the influence of EV charging on power quality to ensure reliable results. The analysis according to IEEE Std 519-2022 suggests that TDD is the significant quantity rather than a harmonic. This may be explained with the wide variety of rectifier implementations of the EVs that distribute harmonic currents to various frequencies. It was also shown that TDI was considerably higher than the partial index $THD_{2\text{-}20}$, which encourages to measure interharmonics and 20–40th order harmonics of EV charging.

Since the power quality quantities of a charging site depends on the EV models that are present, future work should carry out thorough Monte Carlo simulations to determine how the power quality quantities vary. Additionally, future work should analyse the impact of the harmonic currents on voltage quality and consider the influence of different smart charging solutions from power quality perspective because the rectifiers of the EVs may generate more harmonic currents when charging current is limited below nominal. Lastly, the degree of harmonic cancellation at charging sites could be estimated by comparing combined charging profile and session data to the supply measurement of a charging site.

REFERENCES

[1] Y. Wu, Z. Wang, Y. Huangfu, A. Ravey, D. Chrenko, and F. Gao, 2022, “Hierarchical Operation of Electric Vehicle Charging Station in Smart Grid Integration Applications — An Overview,” *Int. J. Electr. Power Energy Syst.*, vol. 139, 108005.

[2] A. Khan, S. Memon, and T. P. Sattar, 2018, “Analyzing Integrated Renewable Energy and Smart-Grid Systems to Improve Voltage Quality and Harmonic Distortion Losses at Electric-Vehicle Charging Stations,” *IEEE Access*, vol. 6, 26404–26415.

[3] M. R. Khalid, M. S. Alam, M. Krishnamurthy, E. A. Al-Ammar, H. Alrajhi, and M. Syed Jamil Asghar, 2022, “A Multiphase AC-DC Converter With Improved Power Quality for EV Charging Station,” *IEEE Trans. Transp. Electrif.*, vol. 8, no. 1, 909–924.

[4] A. Verma and B. Singh, 2021, “AFF-SOGI-DRC Control of Renewable Energy Based Grid Interactive Charging Station for EV with Power Quality Improvement,” *IEEE Trans. Ind. Appl.*, vol. 57, no. 1, 588–597.

[5] A. Kazemtarghi, A. Chandwani, N. Ishraq, and A. Mallik, 2022, “Active Compensation-based Harmonic Reduction Technique to Mitigate Power Quality Impacts of EV Charging Systems,” *IEEE Trans. Transp. Electrif.*, Early Access.

[6] D. Alame, M. Azzouz, and N. Kar, 2020, “Assessing and mitigating impacts of electric vehicle harmonic currents on distribution systems,” *Energies*, vol. 13, no. 12, 3257.

[7] M. Di Paolo, 2018, “Analysis of harmonic impact of electric vehicle charging on the electric power grid, based on smart grid regional demonstration project - Los angeles,” *IEEE Green Energy Smart Syst. Conf. IGESSC*, 1–5.

[8] S. Martinenas, K. Knezovic, and M. Marinelli, 2017, “Management of Power Quality Issues in Low Voltage Networks Using Electric Vehicles: Experimental Validation,” *IEEE Trans. Power Deliv.*, vol. 32, no. 2, 971–979.

[9] Â. Casaleiro, R. Amaro e Silva, B. Teixeira, and J. M. Serra, 2020, “Experimental assessment and model validation of power quality parameters for vehicle-to-grid systems,” *Electr. Power Syst. Res.*, vol. 191, 106891.

[10] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, 2010, “Voltage profile and THD distortion of residential network with high penetration of plug-in electrical vehicles,” *IEEE PES Innov. Smart Grid Technol. Conf. Eur. ISGT Eur.*, 1–6.

[11] A. Supponen, A. Rautiainen, J. Markkula, A. Makinen, P. Jarventausta, and S. Repo, 2016, “Power quality in distribution networks with electric vehicle charging - A research methodology based on field tests and real data,” *11th Int. Conf. Ecol. Veh. Renew. Energies, EVER* , 1–11.

[12] J. Baraniak and J. Starzyński, 2020, “Modeling the impact of electric vehicle charging systems on electric power quality,” *Energies*, vol. 13, 3951.

[13] S. Torres, I. Durán, A. Marulanda, A. Pavas, and J. Quirós-Tortós, 2022, “Electric vehicles and power quality in low voltage networks: Real data analysis and modeling,” *Appl. Energy*, vol. 305, 117718.

[14] T. Simolin, K. Rauma, R. Viri, J. Mäkinen, A. Rautiainen, P. Järventausta, 2021, “Charging powers of the electric vehicle fleet : evolution and implications at commercial charging sites,” *Appl. Energy*, vol. 303, 117651.

[15] R. Viri, J. Mäkinen, and H. Liimatainen, 2021, “Modelling car fleet renewal in Finland: A model and development speed-based scenarios,” *Transp. Policy*, vol. 112, n63–79.