Impact of Electric Vehicle Integration on an Industrial Distribution Network: Case Study Based on Recent Standards

Ana Simarro-García Ana.Simarro@uclm.es
Raquel Villena-Ruiz Raquel.Villena@uclm.es
Andrés Honrubia-Escribano Andres.Honrubia@uclm.es
Emilio Gómez-Lázaro Emilio.Gomez@uclm.es

Renewable Energy Research Institute and Department of Electrical, Electronic, Automatic and Communications Engineering, ETSII-AB, University of Castilla-La Mancha (UCLM), Albacete, Spain

***Abstract*—Efforts are being made to transform the transport sector towards a much less polluting model. In recent years, electric vehicles (EV) have made significant progress, and are becoming a increasing popular choice for consumers. This, coupled with new regulations and roadmaps for the near future, explains the exponential rise in EV sales worldwide. Regarding the electrical power systems to which EV charging stations will be connected, a scenario that was not foreseen emerges. This paper assesses this future scenario on an industrial distribution network, to which EV charging stations based on different technologies and power levels are added. For this purpose, a typical electric system designed by IEEE is modeled and quasi-dynamic simulated in DIgSILENT PowerFactory software. Results for power flows and voltage time profiles are analyzed and discussed to identify the challenges to be addressed for widespread adoption of EVs. Therefore, early verification of whether these electrical systems are prepared to support a higher demand for this type of transport vehicle is carried out.**

***Index Terms*—distribution network, electric vehicle, fast charging, PowerFactor, power system simulation, renewable energy.**

I. Introduction

As the latest study by the International Energy Agency (IEA) indicates in [1], transportation is the sector most dependent on fossil fuels. In addition, according to the European Environmental Agency (EEA) in [2], road transport represents 77% of the greenhouse gas (GHG) emissions in the European Union (EU). To stay on track with the net-zero emissions (NZE) scenario, the electric vehicle (EV) sales are expected to rise from 8% in 2021 to 58% in 2030, based on [3] (last updated in September 2022). Governments around the world are providing various incentives to encourage the adoption of EVs. For example, almost all EU member states offer some type of incentives to stimulate the acquisition of EVs and/or their infrastructure [4]. Additionally, the United States (US) Environmental Protection Agency (EPA) issued the Executive Order 14057 on December 8, 2021 [5], mandating that federal fleets achieve 100% NZE vehicles by 2035. In addition, the EU reached an agreement on October 28, 2022 to ban the sale of new gasoline and diesel cars from 2035 onwards [6], obtaining the formal response from the Parliament and the Council on February 14, 2023.

Regarding EV charging infrastructure, although it has improved in recent years, the work in [7] exposes that the amount of public charging stations planned to be installed in the next few years may be insufficient to feed the size of the targeted EV market. The European Commission is working to accelerate the implementation of an efficient infrastructure to reduce GHG emissions [8]. According to this approved text, by 2026 there should be at least one electric charging point for every 60 km along the main roads of the EU. Taking an EU member country as example, Spain, Spanish regulations mandate, as of January 1, 2023, a minimum number of EV charging stations in public areas [9]. This also applies to residential buildings in [10], establishing the minimum provisions for EV charging stations in new buildings and those with works on their electrical system. All of the above sets an unprecedented scenario, putting the emphasis on EVs as an alternative to conventional combustion vehicles.

By consulting the work published by other authors, valuable information on the current situation of EVs has been provided in [11]. From a technical point of view, limitations of transformers in a residential distribution network are illustrated in [12]. A similar review is done in [13], where a MATLAB model including solar photovoltaic (PV) input and EVs is studied. A large dataset of Swedish and Norwegian charging data for residential profiles is analyzed in [14]. In addition, publications related to EV fast charging have also been reviewed, such as [15], which introduce the concept of extreme fast charging (XFC). These contributions help to learn about the general situation of the field of knowledge. However, they do not cover the new requirements recently imposed by governments, or address with electrical systems with other types of consumers. Therefore, in this work, highly relevant nowadays, the impact of EV charging stations is studied to assess whether the electrical infrastructure of an industrial distribution network is capable of operating correctly with this increase in electricity demand.

II. Methodology

In this study, a distribution network has been implemented in DIgSILENT PowerFactory calculation software, one of the most widely used and versatile tools for analyzing electrical power systems, such as transmission and distribution grids. Besides, the potential of this software is even more relevant when implementing smart grid based solutions, such as the integration of EV charging stations and distributed generation (DG) units based in renewable energy sources (RES).

To perform quasi dynamic simulations with DIgSILENT PowerFactory, different load flows spaced at a user-defined time are considered for this study. Thus, a number of network operating parameters are modified with a given profile and, by solving for various load flows, the time dependence of the system can be analyzed and its future behavior predicted. In this case, all quasi-dynamic profiles have been defined with an hourly time step, in relation to the load or generation values to which they are associated. Hence, the nominal power demanded or generated is scaled according to the time of day.

Once all the elements of the distribution network have been defined and validated, simulations are conducted to evaluate and analyze the impact on the node voltages and power flows of the electrical system caused by EV charging stations.

A. Power Distribution Network

The industrial distribution network published in IEEE Std. 399–1997 [16], shown in Fig. 1, has been modeled and validated in DIgSILENT PowerFactory. The electrical distribution network consists of 42 nodes with voltages ranging from 0.48 kV to 69 kV, divided into two feeders. Once the model has been validated, previous work has been carried out by the authors to provide RES in the system, both solar PV (buses 8, 11, 17–23, 28–30, 33–37, 39, 41, 49) and wind energy (buses 1 and 2), based on worldwide installed capacity scenarios forecasted for 2050 [17].

B. EV Charging Infrastructure

Based on the overview published by Tu, Feng and Lukic in [15], the charging station models described in Table I have been considered for this study. Due to the proximity between buses in the electrical distribution network in Fig. 1, it has been assumed unnecessary to have EV charging facilities at all consumption nodes. Therefore, of the 21 buses that represent industries, fast charging stations are installed in those 10 with the highest power consumption (buses 8, 17, 18, 19, 20, 29, 36, 37, 39 and 49). According to (1) obtained by the authors in [18], and assuming a conservative state-of-charge (SOC) and capacity of the batteries, 40% and 75 kWh, respectively, the charging time (in minutes) of an EV (whose characteristics correspond to Tesla's most advanced models) is calculated for each type of charger, and presented in Table I.

$$t_{charge} = \left(1 - \frac{SOC}{100}\right) \cdot \frac{Capacity_{battery}}{Power_{charger}} \cdot \frac{1}{\eta_{charger}} \quad (1)$$

where t_{charge} is the charging time of EVs (in hours), SOC is the state-of-charge of the batteries (%), $Capacity_{battery}$ is the battery capacity of EVs (in kWh), $Power_{charger}$ is the maximum power of charging stations (in kW) and $\eta_{charger}$ is the charger efficiency (%).

TABLE I
TECHNICAL CHARACTERISTICS OF EV CHARGING STATIONS

Fast Charger Model	**Power**	**Efficiency (η)**	**Charging Time**
ABB Terra 53	50 kW	94.0%	58 minutes
PHIHONG Integrated Type	120 kW	93.5%	25 minutes
ABB Terra HP	350 kW	95.0%	9 minutes

As it has been verified in Table I, none of the models exceed a charging time of one hour. Considering a highly adverse scenario, an hourly time-load profile is designed, in order to establish a maximum charge of one hour.

III. CASE STUDIES

To assess the impact of fast charging stations in the industrial power network shown in Fig. 1, case studies with and without EV infrastructure are analyzed. In all the nodes where EV charging infrastructure is installed, a power corresponding to five fast charging stations of 50 kW each (ABB Terra 53 model) has been considered. As an additional consideration, XFC infrastructures are installed on the three buses with the highest industrial consumers, i.e. buses 8 (6,361 MW), 19 (2,650 MW) and 20 (2,650 MW). For further clarification, Table II details the infrastructure installed at each node, considering the efficiency of each charger calculating the nominal power. Based on these values, a time profile associated with each type of load in the industrial distribution network is adopted to perform quasi-dynamic analysis. Fig. 2 illustrates the time profiles implemented in DIgSILENT PowerFactory associated with all types of loads connected to the power system, each one determined with an hourly time step. In this way, the nominal power of each load is affected by a scaling factor (value in per unit, pu), which is modified hourly throughout the day.

TABLE II
EV CHARGING STATIONS OPERATING AT EACH NODE

Buses	**Charging Infrastructure**	**Nominal Power**
8	5 ABB Terra 53 model, 1 ABB Terra HP	567.50 kW
19, 20	5 ABB Terra 53 model, 1 PHIHONG Integrated Type	347.20 kW
17, 18, 29, 36, 37, 39, 49	5 ABB Terra 53 model	235.00 kW

IV. RESULTS

Quasi-dynamic simulations using DIgSILENT PowerFactory software have been confucted to assess the impact of installing fast and XFC stations in the industrial power system based on IEEE Std. 399–1997. As a result of these simulations, the node voltages and the loading percentages of elements connected to the distribution network are obtained.

The values in Table III reveal that, as a result of the increase in demand associated with EVs, the voltages of the electrical system nodes are decreased, thus endangering the quality of

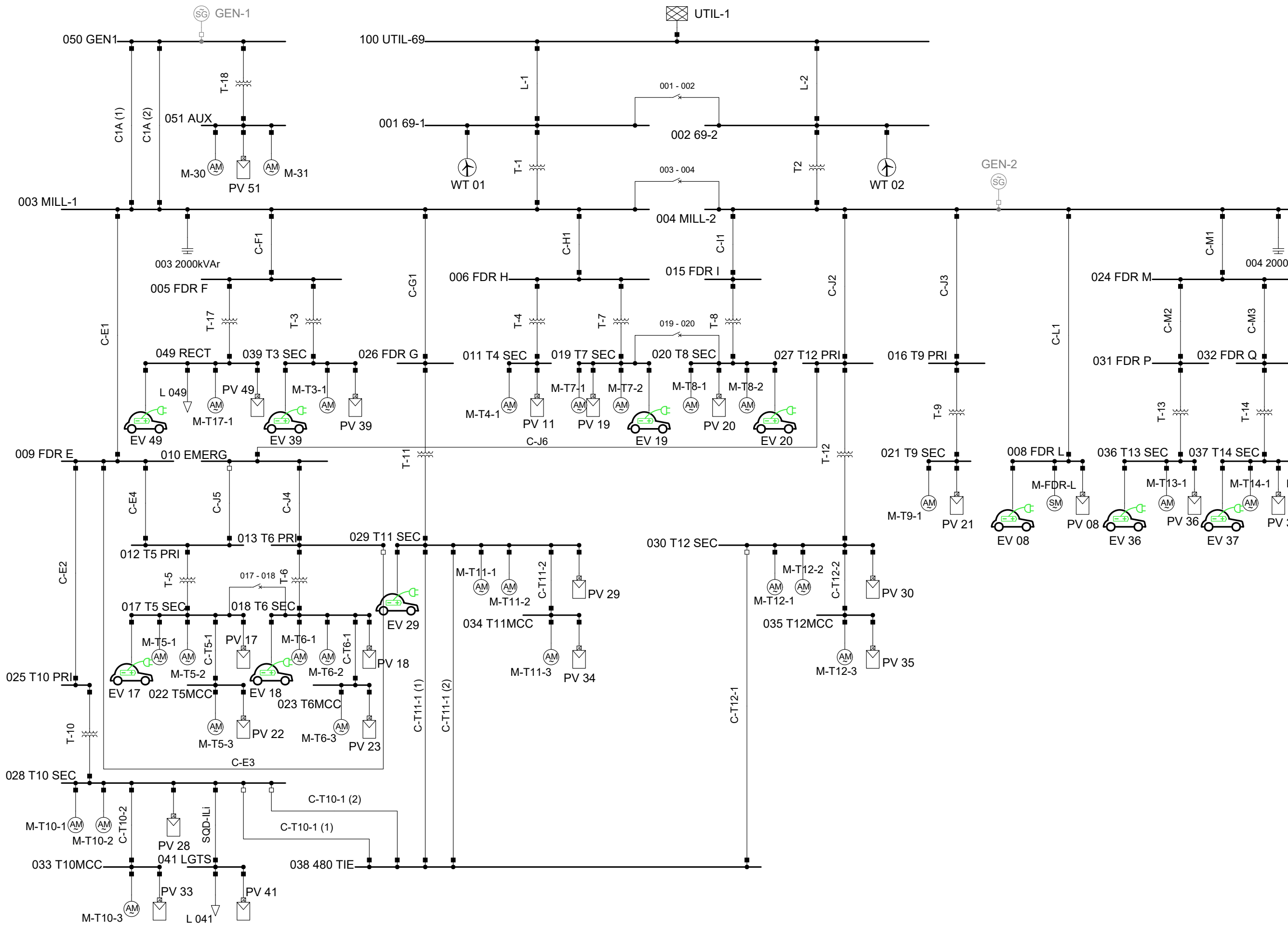

Fig. 1. Industrial Power System based on IEEE Std. 399–1997

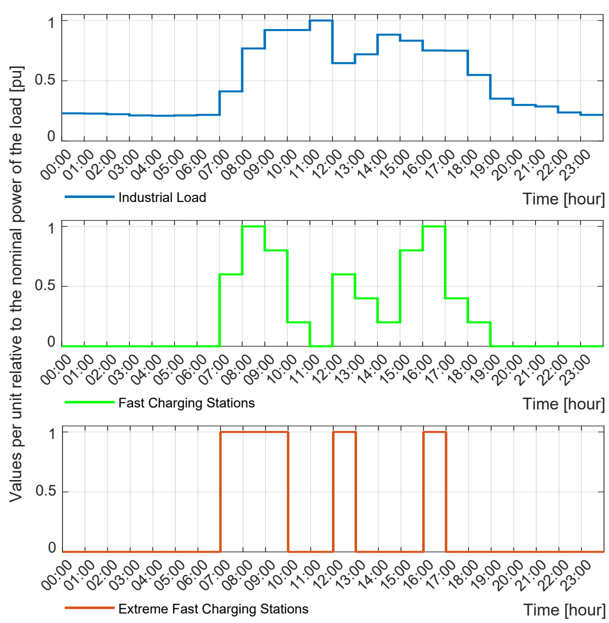

Fig. 2. Time-Load Profiles for Quasi-Dynamic Simulations

TABLE III
QUASI-DYNAMIC SIMULATION: MINIMUM VOLTAGE OF NODES

Terminal	Baseline	EV Case Study	Decrease
037 T14 SEC	0.9543 pu	0.9493 pu	0.52%
018 T6 SEC	0.9564 pu	0.9528 pu	0.38%
017 T5 SEC	0.9510 pu	0.9476 pu	0.36%
049 RECT	0.9591 pu	0.9561 pu	0.32%
029 T11 SEC	0.9607 pu	0.9577 pu	0.31%
036 T13 SEC	0.9562 pu	0.9535 pu	0.28%
039 T3 SEC	0.9533 pu	0.9506 pu	0.28%
020 T8 SEC	0.9575 pu	0.9550 pu	0.26%
019 T7 SEC	0.9567 pu	0.9548 pu	0.20%
008 FDR L	0.9817 pu	0.9799 pu	0.19%

the power supply. Considering as a design requirement a voltage range between 0.95 pu and 1.05 pu, integrating the EV infrastructure, slightly lower voltages are observed at buses 17 (0.9476 pu) and 37 (0.9493 pu). However, this situation occurs in a punctual manner, from 09:00 h to 10:00 h, as shown in Fig. 3, which illustrates the temporal distribution of node voltages during the simulated day.

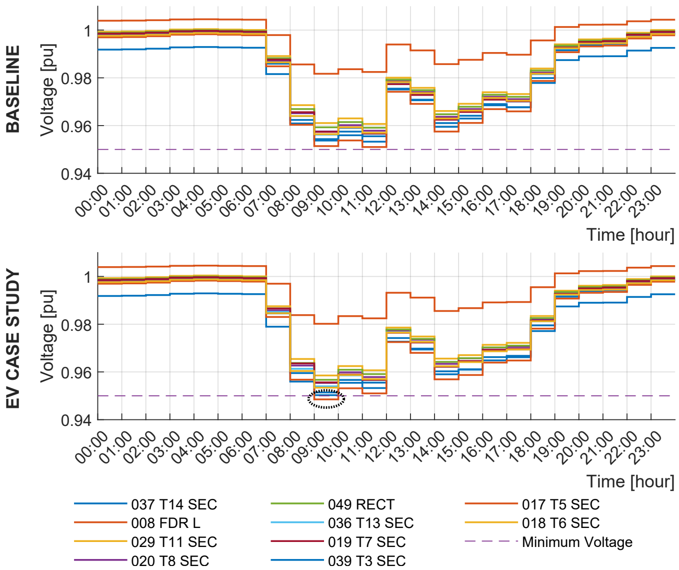

Fig. 3. Quasi-Dynamic Simulations: Time-Voltage Profiles

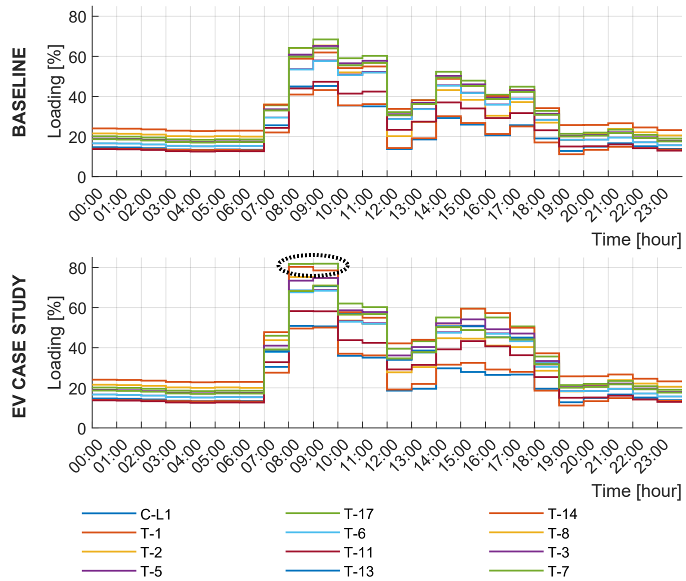

Fig. 4. Quasi-Dynamic Simulations: Time-Loading Profiles

On the other hand, Table IV shows the loading percentages of the distribution network elements that experience the most impact with the integration of EV charging stations. A significant increase appears in some of the transformers, such as T-17 (85.42%) or T-14 (82.96%), which might experience damage if these operating conditions are maintained or exceeded. Fig. 4 shows the loading profile of these elements, proving that, as well as the voltage values, the high loading of elements occur temporarily, from 08:00 h to 10:00 h.

Analyzing these results demonstrates the influence that the integration of EV charging points has on the power system, and, although the consequences may not seem very alarming, in the case of a widespread increase, as expected, the electrical power systems will suffer supply shortages due to low voltages and damage to the elements due to overloading.

TABLE IV
QUASI-DYNAMIC SIMULATION: MAXIMUM LOADING OF ELEMENTS

Element	Baseline	EV Case Study	Increase
T−14	61.93%	82.96%	34.0%
T−11	47.31%	61.04%	29.0%
T−17	68.44%	85.42%	24.8%
T−5	57.95%	71.61%	23.6%
T−6	57.64%	71.24%	23.6%
T−1	43.20%	51.61%	19.5%
T−3	65.16%	77.29%	18.6%
T−2	65.39%	76.45%	16.9%
C−L1	45.21%	51.14%	13.1%
T−13	64.04%	72.36%	12.9%
T−8	63.98%	72.13%	12.7%
T−7	63.99%	72.11%	12.7%

V. CONCLUSIONS

The emergence of initiatives and new regulations applied to EVs and the electric infrastructure of charging points is currently setting an unprecedented scenario, putting the emphasis on EVs as an alternative to conventional combustion vehicles. Therefore, in view of the widespread increase in the sales of EVs worldwide, it is necessary to identify the challenges that electric power systems must face in order to ensure the electrical power supply and quality.

This work has demonstrated that current power distribution systems, where infrastructure dedicated to EV charging and based on different technologies and power levels has been installed, require additional measures for supporting the increasing number of EVs in cities. As a result of higher loads on the IEEE industrial distribution network, low voltages and high loading on the elements are obtained, which threaten the quality of the power supply, and reduce the useful lifetime and operation of the elements. Therefore, the widespread increase in the number of EV charging points makes it necessary to consider a modification of the existing power networks to support higher loads than those for which they were designed, in order to ensure an adequate power supply.

ACKNOWLEDGMENT

This research was partially funded by the Council of Communities of Castilla-La Mancha (*'Junta de Comunidades de Castilla-La Mancha'*, JCCM) through Project SBPLY/19/180501/000287; by the State Research Agency (*'Agencia Estatal de Investigación'*, AEI); by the European Regional Development Fund (*'Fondo Europeo de Desarrollo Regional'*, FEDER) through project PID2021-126082OB-C21; and by the French Embassy in Spain and Campus France, for granting a doctoral mobility scholarship to Ana Simarro-García.

REFERENCES

[1] International Energy Agency (IEA), "Transport," Available online: https://www.iea.org/topics/transport, last accessed on 12 March 2023.

[2] European Environmental Agency (EEA), "Indicators - Greenhouse gas emissions from transport in Europe," Available online: https://www.eea.europa.eu/ims/, last accessed on 12 March 2023.

[3] International Energy Agency (IEA), "Reports - Cars and Vans," Available online: https://www.iea.org/reports/cars-and-vans, last accessed on 12 March 2023.

[4] European Automobile Manufacturers' Association (ACEA), "Overview – Electric vehicles: tax benefits and purchase incentives in the European Union," Available online: https://www.acea.auto/fact/, Tech. Rep., 2022.

[5] US Environmental Protection Agency (EPA) [Joe Biden], "Executive Order 14057: Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability," 8 Dec. 2021, *Federal Register*, Vol. 86, No. 236, Monday, December 13, 2021, pp. 70935-70943.

[6] European Commission, "Zero emission vehicles: first 'Fit for 55' deal will end the sale of new CO2 emitting cars in Europe by 2035," Brussels, 28 Oct. 2022, *Press release*.

[7] International Energy Agency (IEA), "Global EV Outlook 2022," Available online: https://www.iea.org/reports/global-ev-outlook-2022.

[8] Council of the European Union, "European Green Deal - Fit for 55," Available online: https://www.consilium.europa.eu/en/policies/green-deal/, last accessed on 12 March 2023.

[9] Official State Journal of Spanish Government (*Boletín Oficial del Estado*), "Real Decreto-ley 29/2021, de 21 de diciembre, por el que se adoptan medidas urgentes en el ámbito energético para el fomento de la movilidad eléctrica, el autoconsumo y el despliegue de energías renovables," 22 Dec. 2021.

[10] Technical Building Code of Spanish Government (*Código Técnico de la Edificación)*, "Sección HE 6: Dotaciones mínimas para la infraestructura de recarga de vehículos eléctricos," 19 March 2022.

[11] A. Ahmad, Z. A. Khan, M. S. Alam, and S. Khateeb, "A Review of the Electric Vehicle Charging Techniques, Standards, Progression and Evolution of EV Technologies in Germany," *Smart Science*, vol. 6, no. 1, pp. 36–53, 2018.

[12] M. A. Awadallah, B. N. Singh, and B. Venkatesh, "Impact of EV Charger Load on Distribution Network Capacity: A Case Study in Toronto," *Canadian Journal of Electrical and Computer Engineering*, vol. 39, no. 4, pp. 268–273, 2016.

[13] M. Akil, E. Dokur, and R. Bayindir, "Energy Management for EV Charging Based on Solar Energy in an Industrial Microgrid," in *International Conference on Renewable Energy Research and Application (ICRERA)*, 2020, pp. 489–493.

[14] T. Gnann, S. Funke, N. Jakobsson, P. Plötz, F. Sprei, and A. Bennehag, "Fast charging infrastructure for electric vehicles: Today's situation and future needs," *Transportation Research Part D: Transport and Environment*, vol. 62, pp. 314–329, 2018.

[15] H. Tu, H. Feng, S. Srdic, and S. Lukic, "Extreme Fast Charging of Electric Vehicles: A Technology Overview," *IEEE Transactions on Transportation Electrification*, vol. 5, no. 4, pp. 861–878, 2019.

[16] Industrial Power Systems Standards Development Committee, "IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (Brown Book)," *IEEE Std 399-1997*, pp. 1–488, 1998.

[17] International Energy Agency (IEA), "Net Zero by 2050: A roadmap for the global energy sector," *IEA Reports*, pp. 45–46, 113–121, 198, 2021.

[18] A. Simarro-García, R. Villena-Ruiz, A. Honrubia-Escribano, and E. Gómez-Lázaro, "Effect of penetration levels for vehicle-to-grid integration on a power distribution network," *Machines*, vol. 11, no. 4, 2023.