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Impact of Smart Charging of Electric Vehicles in the Distribution Power System

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ABSTRACT
The rise of electric vehicles significantly affects electricity distribution networks by increasing the demand for electricity, requiring infrastructure improvements and better grid management. Planning electricity demand in distribution networks operating under conditions of increased electric vehicle penetration presents a major technical and economic challenge. This new load is not distributed uniformly and may lead to high penetration of EVs in certain parts of a given distribution network, which can cause asset overload in such areas. At the core of the analysis is the assessment of the impact of electric vehicle penetration on electricity distribution networks. As an example, the distribution network of Tirana has been taken, representing about 35% of the total load. This paper addresses the projections of EV development in the market and statistical models for assessing the level of demand development for EV chargers and understanding the potential impacts of EVs on the distribution system. To determine the probability of the number of EVs per household according to the Albanian Government's objectives for 10% penetration by 2030, a binomial distribution method was used. The results highlight that electricity demand even exceeds the high-load growth scenario, which requires immediate measures regarding charging infrastructure standards and their management.

Keywords
Distribution grid, electric vehicles, forecasting, electric load, energy supply, smart charging.

1. INTRODUCTION
The European Union has set ambitious targets for reducing carbon emissions and decarbonizing transport. For this reason, the EU has adopted a series of laws and regulations supporting the transition to electric vehicles [1, 2]. The EU and its member states provide funds such as the Connecting Europe Facility (CEF), Recovery and Resilience Facility, etc. They subsidize the purchase of electric cars and the construction of charging infrastructure. The “Fit for 55” package - 2021 aims to reduce emissions by 55% by 2030 and to ban the sale of vehicles with internal combustion engines after 2035, and rules on chargers, infrastructure, and the use of alternative fuels [3]. Table 1 gives the main deadlines for the EU objectives, while Fig. 1 shows the total number of electric cars. Their growth is visible over the last 5 years.

Table 1. Key deadlines for EU objectives

Year	EU objective
2025	Public charger every 60 km on the TEN-T network
2030	55% reduction in emissions in the transport sector
2035	Ban on the sale of vehicles with CO_2 emissions
2050	Full climate neutrality in the EU

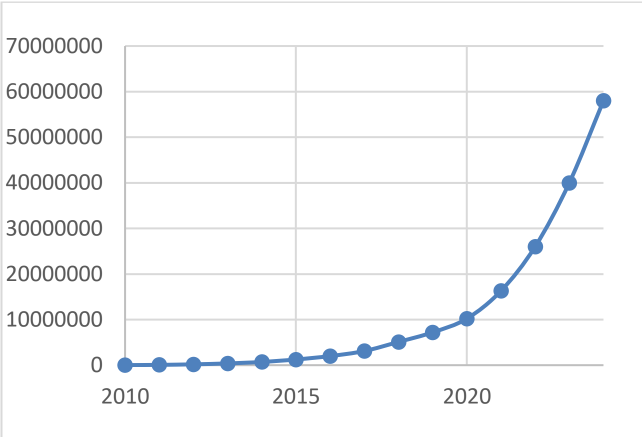
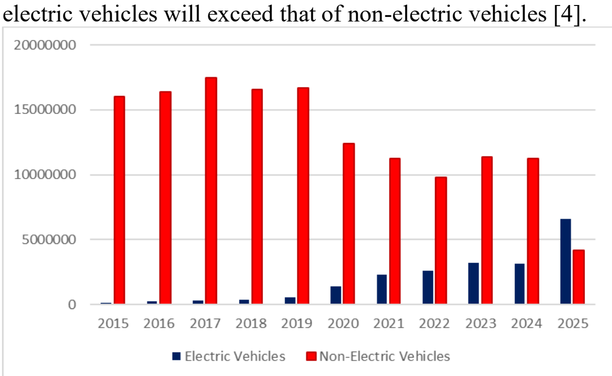


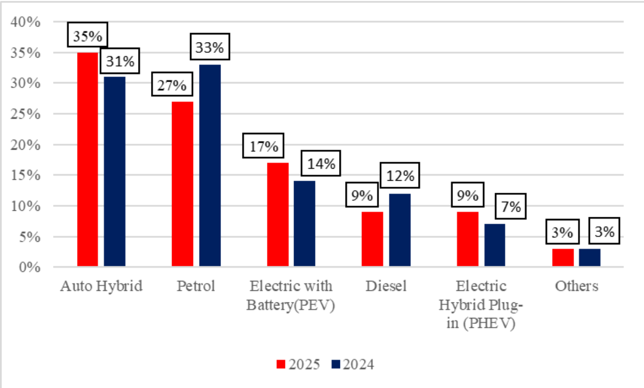
Fig 1: Number of electric vehicles (EVs) worldwide

Fig. 2 shows the production of electric/non-electric vehicles in total (a) and by type in the last 2 years (b).

From Fig. 2a, it can be seen that in 2025, the production of electric vehicles will exceed that of non-electric vehicles [4].



(a)



(b)

Fig 2: Total number of new vehicles (a) and by type in the last 2 years (b)

While electric vehicles (EVs) may still make up a small percentage of the vehicle market, their adoption is accelerating. For several reasons, such as financial, social, cultural, and political, this growth in EV deployment varies across countries, cities, and even neighborhoods. This can lead to high penetration of EVs in some parts of a given distribution network, which can cause overloading of network assets in such areas [5]. Plug-in electric vehicles (PEVs) are a family of electric vehicles capable of using the electric power grid. The commercialization of PEVs has created an urgent need for utilities to support their adoption by consumers, to prepare residential, commercial, and private infrastructure in their territories, and to manage the impact of these new loads on the electric distribution system [6, 7]. Understanding and addressing these potential impacts on the distribution grid is important for electric vehicles and a key driver of PEV adoption and maximizing the benefits of transportation electrification. Charging time is a key factor in the impact on the grid. PEVs generally include Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs). Many papers have addressed the negative effects of PV charging on the power grid, including increased load, losses, and the impact on the voltage profile [8-11]. Given that power systems are interconnected, understanding and mitigating these impacts is essential for ensuring the reliability and sustainability of power grids. Consequently, there is an urgent need for coordinated strategies and innovative solutions to optimize the integration of PEVs within the electricity grid infrastructure [12-14].

This paper presents forecasts of PEV market development using statistical models to assess the level of demand for PEV chargers and to understand the potential impacts of PEV on the distribution system.

2. FACTORS AFFECTING THE DISTRIBUTION NETWORK

2.1 Models of charging

The charging time of EVs can create both positive and negative impacts on the electrical system. If a significant amount of EV chargers are connected to the system's peak load, it would create the need for additional generation. On the other hand, if charging is performed continuously during off-peak hours, this would reduce system costs. PV can have different charging patterns, which would cause different impacts on generation and transmission levels [15, 16]. In this paper, statistical models will be discussed. Initially, loading models are analyzed, which are divided into two groups: 1) Uncontrolled loading, and 2) Peak load management control.

2.2 Uncontrolled charging

The arrival of vehicles at home is related to the peak load, so it is often assumed that vehicle charging can coincide with the peak load. Fig.3 shows the cumulative percentage of vehicles that have arrived at home at a given time, which corresponds to the assumed peak load during the hours of 17-18°°.

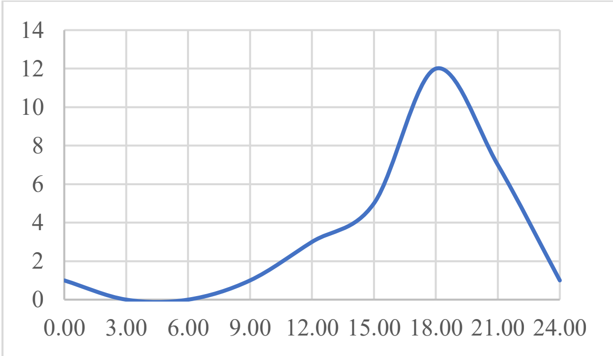


Fig 3: Percentage of vehicles arriving home within a given time

Further analysis of this data shows that without smart charging, the electric vehicle charging would load the grid during peak load periods. It is assumed that the group of vehicles is charged with a 7.4 kW charger and that they start charging immediately upon arrival at home.

Fig. 4 shows the load distribution for uncontrolled vehicle charging. Arrival at home coincides with the peak load, which can cause problems for the grid. Poorly designed load control strategies can also cause problems for generation.

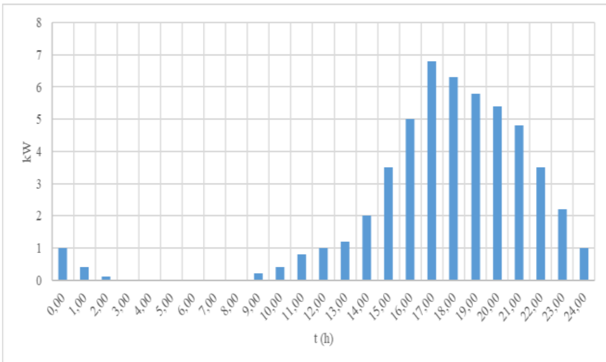


Fig 4: Load distribution during a day for uncontrolled charging

2.3 Control and management of peak charging

In the case of controlled charging, various strategies are proposed. In Fig. 5, a control strategy is given, which shifts the charging of the load to the night, and spreads it relatively evenly over 6 hours [17]. This can be achieved by organizing the start of the vehicle charging during the hours of 21°° and 3°°.

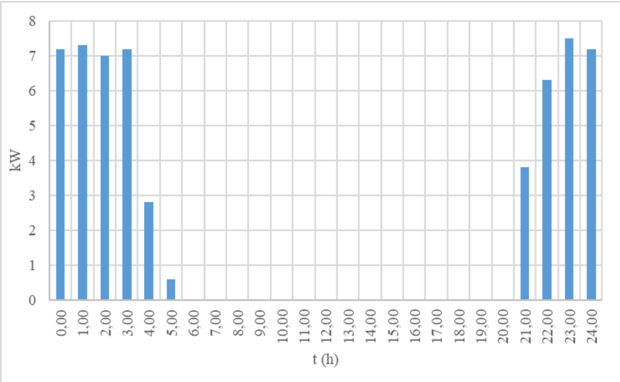


Fig 5: Relatively uniform distribution of electrical charge for controlled charging

3. PEV ESTIMATION AND IMPACT ON DISTRIBUTION GRID

While technological development related to PEV continues to grow, the impact of PEV on the electrical system has not been fully assessed.

Electrification of the transport sector has the potential to provide numerous social and economic benefits. Some of the possible benefits include reduced greenhouse gas emissions, reduced dependence on imported oil, and a lower-cost alternative to gasoline. However, the adoption of electricity as a "transport fuel" could have a major impact on distribution networks and the distribution system operator. The assessment of these effects is necessary for planning measures to supply this new load. During the planning of the distribution network, spatial and temporal variations in the load of plug-in electric vehicles, the overload of assets, and the aging of all distribution system equipment must be recognized. To accurately assess the impact of PEV on the distribution system, these changes must be accounted for when performing the distribution system analysis. Initial studies focused primarily on the impact of PEV consumers on the capacity of the supply network. In 2025, electric vehicles (EVs) will account for 17.4% of vehicles [18], still a small percentage, but their market share is growing. Reference [19] shows how different levels of EV penetration would accelerate the aging of transformers in a residential building.

3.1 PEV characteristics

PHEVs combine the operational aspects of both battery electric vehicles (BEVs) and hybrid electric vehicles. Similar to a BEV, a PHEV can store significant energy in an onboard battery for use and recharge the battery from the electrical grid. From a grid perspective, a BEV will be similar to a PHEV, but will have a larger battery and therefore will take longer to charge. Another possible use of PEVs is as a source of electricity. Therefore, the analysis of the impact on the distribution grid should consider the following factors:

- Changes in PEV charging model (battery type, charging type)
- PEV penetration levels for different consumers (residential, municipal)
- Time profiles and customer charging periods
- Battery charge status based on kilometers traveled.

3.2 Load profiles of electric chargers PEV

PEVs are similar to existing hybrid electric vehicles (HEVs), with the main difference being the energy storage in the battery that allows the PEV to move. PEVs require methods for charging the battery based on regulations. As proposed in [20], bridge charging is a method for connecting the power grid to the PEV in order to transmit power to charge the battery. Table 2 gives three charging levels based on voltage and power levels.

Table 2. Characteristics of charger models

Type of charging	Voltage (V)	Current (A)	Demand (kW)
AC N1	120 V	12-16 A	1.44-1.92kW
AC N2	208-240V	12-80 A	2.5-19.2kW
DC N1	200-450V	≤ 80 A	≤ 19.2 kW
DC N2	200-450V	≤ 200 A	≤ 90 kW
DC N3	200-600V	250, 350 &400A	≤ 240 kW

The electrical power requirement and charging profile are determined by the battery size, charging efficiency, prescribed distances, and the type of charger.

3.3 Estimation of impact on the distribution grid

The Electric Distribution System Operator manages 102 substations and approximately 16,350 km of lines extending across the country. The high rate of deterioration of distribution assets is mainly due to their age (between 35 and 50 years), lack of investment, and periodic maintenance [21-23]. The distribution network in Albania has faced difficulties in network management, which are reflected in the quality of supply to customers: the number of interruptions and their duration. After a restructuring process, it has focused on management and administration policies. The impact on the distribution system should be assessed in function of the different characteristics of the PEV as follows:

- Overheating - to what extent components are in normal and emergency modes (number of events, typical asset overloads, duration, and magnitude)
- Voltage - to what extent does the PEV load negatively affect the system voltage (voltage fluctuations, etc)
- Asymmetry - possible disproportionate penetrations for each phase and the results on the asymmetry of the system
- Losses - impact of PEV on losses in the distribution system
- Energy quality - generation of high-order harmonics

3.4 Penetration as a residential customer

The Albanian government aims for over 10% of vehicles on the road to be electric by 2030 [24]. It is also expected that 20% of public transport in Tirana will be electrified by 2030. Customers of this service may have multiple vehicles; the penetration levels of PEV in the market should be read as the expected penetration of PEV among all customers of this service. For each municipality in [25], data are given regarding the number of existing vehicles (Fig. 6).

While Fig. 7(a, b) shows the types of road vehicles by fuel, 2019-2024, and the penetration of PEV [26].

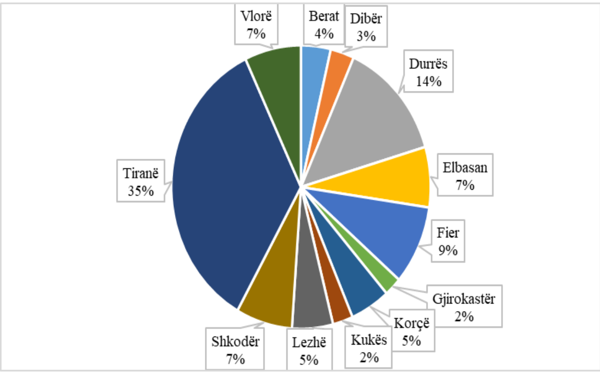
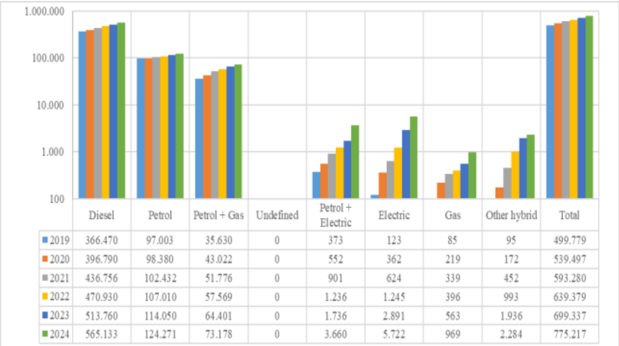


Fig 6: Vehicles by region in % - Census 2023



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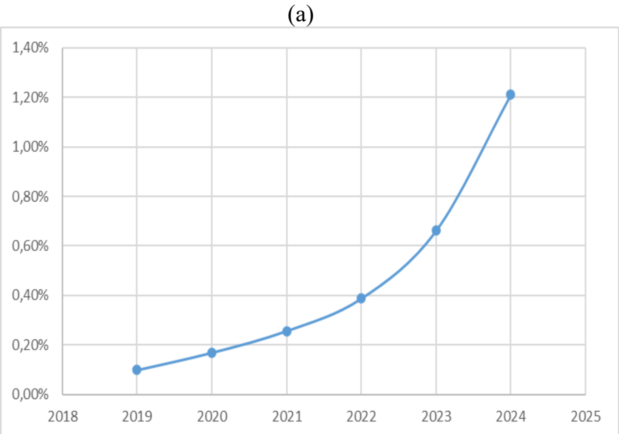


(b)

Fig 7: (a) Types of vehicles by fuel, 2019-2024, (b) PEV penetration

Currently, in the Albanian distribution network, they are a small percentage (Fig.7b), but the vehicles that use the electric grid PEV are increasing over time, and it can be expected that the percentage of households that own more than one PEV will also increase.

According to the 2023 Census, the total number of vehicles is 699,337, while Tirana, with a population of 758,513, uses 243,340 vehicles or about 35% of existing vehicles per household, and on average, 1 vehicle for 2-3 inhabitants. Table 3 provides data for households, as well as the average number of vehicles per household.

Table 3. Household data in statistics for the Tirana region (Census 2023)

Tirana	Total	1 person	2 people	3 people	4+ people
Household economy	247,466	40,437	66,937	49,378	90,714
Household economy (%)		16.3%	27.0%	20.0%	36.7%
Population	758,513	40,437	133,874	148,134	436,068
Average vehicle for household economy	243,340	0	1	1-2	2-3

Based on the data in Table 3, the ownership of vehicles in % by households for the Tirana region was determined, as shown in Table 4.

Table 4. Ownership in % of vehicles per household in statistics for the Tirana region

Vehicles for household economy in Tirana				Vehicles for household economy	Household economy
0	1	2	3+		
16.3%	37.0%	28.35%	18.35%	243,340	247,466

Based on the data on vehicle ownership per household, given in Table 4, the probability of PEV penetration for each household was determined using the binomial distribution method. Denoting by m the PEV penetration in %, the probability that a vehicle is a plug-in electric (PEV) for the average distribution of vehicles per household q and the random variable x, was determined using the binomial distribution given in equation (1):

$$f(x,q,m) = \binom{q}{x} \cdot m^x \cdot (1-m)^{q-x} \qquad x=0,1..q \qquad (1)$$

$$\binom{q}{x} = \frac{q!}{x! \cdot (q-x)!}$$

Table 5 shows the probability that a vehicle is a plug-in electric vehicle (PEV) for residential households for the values **x=0, 1, 2, 3; q=3** for the three different penetration levels **m=2%, 4%, 10%.**

Table 5. Probability distribution of PEV for residential customers in the Tirana region

Penetration in the market	PEV for household economy			
	0	1	2	3
2%	94.12%	5.76%	0.12%	0.00%
4%	88.47%	11.06%	0.46%	0.01%
10%	72.90%	24.30%	2.70%	0.10%

The ownership in % of vehicles per household that would be replaced by EVs in the case of a 10% penetration for the Tirana region is estimated based on Tables 4 and 5 in the case of a 10% penetration of EVs, and is presented in Table 6.

Table 6. The ownership percentage of vehicles per household that would be replaced by EVs in the case of a 10% penetration for the Tirana region

Penetration in the market	PEV for household economy		
	1	2	3
10%	8.99%	0.77%	0.03%

4. ANALYSIS OF IMPACT IN DISTRIBUTION GRID

The methodology study aims to identify the potential impacts on the distribution system in response to the adoption of a new load type. The current capacities and loads for the MV network in Tirana [27] are given in Table 7.

Table 7. Actual capacity and load in Tirana

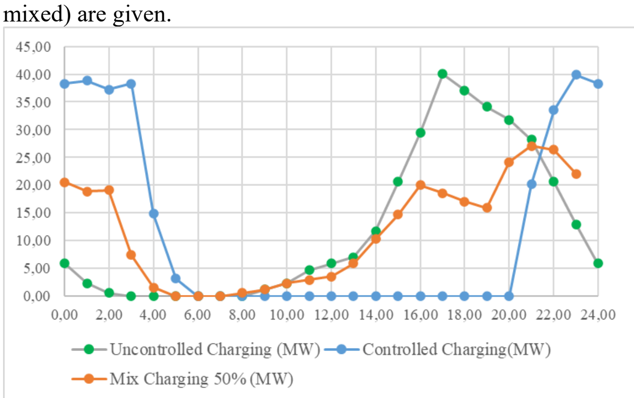
Parameter	**Average value**
Annual electricity supply	2,528,530 MWh
Daily maximal load	~300 – 350 MW
Number of substations	> 15 active
Medium voltage lines	> 500 km
Low-voltage lines	~2,000 km

Capacities are currently sufficient for urban consumption, but an increase in load is expected due to the electrification of transport and rapid urbanization. The Albanian government aims for over 10% of vehicles in circulation to be electric by 2030. Tirana, with a population of 758,513, has 243,340 cars. For short-term planning, we consider only those characteristics that are expected from most first-generation PEVs. In particular, PEVs are modeled as simple loads. The impact of electric vehicles on the distribution network, if we accept that the peak hour on the network in Albania is: Evening: 18:00 – 22:00. During this time, other loads are also active, such as: lighting in homes, electrical appliances, electric heating in winter, or cooling in summer.

The additional electrical load from charging the EV at home will be estimated as follows:

- Average power of a home charger: 3.6 kW – 7.4 kW.
- Average charging time in the evening: 3–4 hours.
- Assuming an average duration of 3.5 hours, the additional energy for 10% penetration of PEV ranges from 302,400 MWh to 621,600 MWh.
- The average additional power for uniform distribution would be 12.6MW (3.25%) to 25.9MW (6.61%).

In Fig.8(a, b), the additional electrical loads from charging PEV at home for the two types of chargers, 3.6 kW – 7.4 kW for the three charging regimes (uncontrolled, controlled, and 50% mixed) are given.



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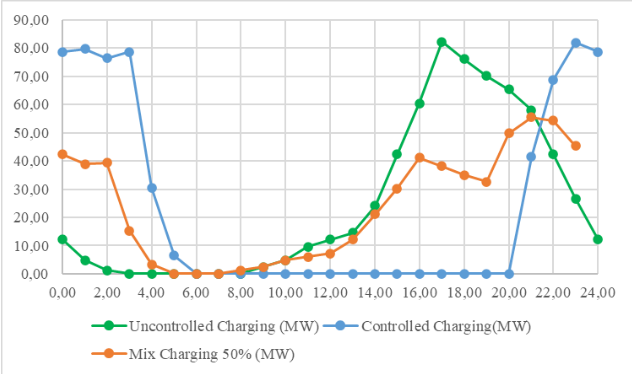

(b)

Fig 8: Additional electrical load from charging a PEV at home for charging power (a) 3.6 kW (b) 7.4 kW

Fig. 9 shows the additional electrical load from charging a PEV (7.4 kW charger) at home for the three charging regimes, while Fig. 10 shows the maximum electrical overload for the different charging regimes for the two types of chargers, 3.6 kW – 7.4 kW.

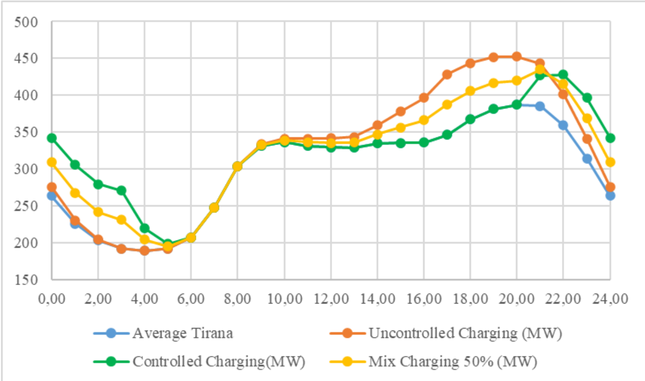

Fig 9: Additional electric load from charging a PEV at home for a charger power of 7.4 kW

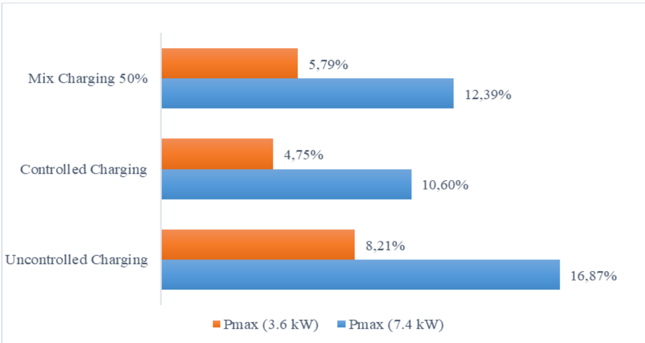

Fig 10: Overload in PEV charging regimes (%) of the two types of chargers 3.6 kW – 7.4 kW

In [21], it is given that the forecast of the electricity demand for the year 2030 in the case of the high scenario is about 11%. The overload of the network for 10% penetration of PEV is about 17% (Fig.8), which exceeds even the high scenario of the electricity demand, while the maximum overload for the chargers with a power of 3.6 kW does not exceed this forecast. The Distribution System Operator should carefully manage the charging equipment so that, in the residential part, chargers that exceed the value predicted in the high scenario are not installed. A smart distribution network would provide, among other things, a controlled load regime, contributing to the reduction of grid congestion. The use of data generated by smart meters also provides data for short-term load forecasting.

5. CONCLUSIONS

This paper deals with the impact of electric vehicles (PEVs) on the electricity grid. Based on the results shown, the following conclusions can be deduced.

It is proposed that using the binomial distribution method, the probability of the number of PEVs per household can be determined.

Moreover, the impact of different types of PEV chargers on the additional electrical load on the electrical system has been analyzed. At the same time, three types of charging regimes have been analyzed, such as uncontrolled, controlled, and 50% mix. The results demonstrate that these factors affect the overload in the electrical grid due to PEV charging.

The analysis under conditions of 10% penetration of PEV, which represents the objective of the Albanian Government until 2030, shows that only from PEV charging the overload of the network for chargers with a power of 7.4 kW and uncontrolled charging goes up to about 17%, which exceeds even the high scenario of electricity demand of 11%, while for chargers with a power of 3.6 kW and uncontrolled charging it goes up to about 8.2%.

The analysis under conditions of 10% penetration of PEV, but for controlled charging, goes up to 10.6% for chargers with a power of 7.4 kW and 4.75% for chargers with a power of 3.6 kW.

In conclusion, the results highlight the necessity for the Distribution System Operator to carefully manage the power of charging devices in the residential sector. A smart distribution network would ensure, among other things, a controlled charging regime, contributing to the reduction of grid congestion.

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