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Assessing the Impact of Transport Electrification on Distribution Networks - A Case Study of the Croatian Region of Istria

Tomislav Antić, Klemen Knez, Miljan Lenić, Anđelko Tunjić, Darko Hecer, Goran Jerbić, Lara Buljan, Denis Brajković, Zoran Pećarić

***Summary* — The increasing number of electric vehicles (EVs) introduces significant challenges for distribution networks planning and operation, including higher loading levels, voltage deviations, and potential transformer and line overloads. These challenges are amplified by the requirements of European Union Directive 2014/94/EU on alternative fuels infrastructure and Croatia's National Energy and Climate Plan for the period 2021–2030. This paper analyzes the impact of transport electrification on the distribution network of the Croatian region of Istria, selected due to its pronounced seasonality and specific geographical conditions. The analysis is based on a detailed network model consisting of nearly 2,500 medium to low voltage substations and more than 170,000 end users, incorporating real data on existing and planned charging stations, tourism related load variations, and EV growth projections. The methodology applies a k-medoids approach to identify representative low voltage networks, enabling the assessment of load increases and the identification of necessary grid reinforcements. The results show that EV growth combined with uncoordinated infrastructure deployment leads to voltage and current congestion. Based on these findings, the paper proposes a timeline of required investments, including conductor replacements and the construction of new and replacement of existing substations, to ensure reliable and efficient network operation as transport electrification progresses.**

***Keywords* — charging points, distribution networks planning, e-mobility, k-means clustering, network reinforcement**

(Corresponding author: Tomislav Antić).

Tomislav Antić is with University of Zagreb Faculty of Electrical Engineering and Computing, Zagreb, Croatia (e-mail: tomislav.antic@fer.unizg.hr).

Klemen Knez is with Faculty of Electrical Engineering, University of Ljubljana, Ljubljana, Slovenia (e-mail: klemen.knez@fe.uni-lj.si).

Darko Hecer is with Ekonerg Ltd., Zagreb Croatia (e-mail: dhecer@ekonerg.hr).

Lara Buljan and Goran Jerbić are with Institut za elektroprivredu d.d., Zagreb, Croatia (e-mail: lara.buljan@ie-zagreb.hr, goran.jerbic@ie-zagreb.hr)

Miljan Lenić, Anđelko Tunjić, Denis Brajković and Zoran Pećarić are with HEP-Operator distribucijskog sustava d.o.o., Zagreb, Croatia (e-mails: miljan.lenic@hep.hr, andelko.tunjic@hep.hr, denis.brajkovic@hep.hr, zoran.pecaric@hep.hr)

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I. Introduction

Accelerated electrification of road transport, driven by environmental protection policies, represents one of the major challenges of today for European distribution system operators, including the Croatian DSO. The increasing number of electric vehicles (EVs) leads to higher electrical loads and electricity consumption, which may pose significant challenges for the planning and operation of distribution networks. These emerging challenges increase pressure on both transmission and distribution networks and can cause network congestion, ultimately resulting in interruptions in electricity supply. The impact is also evident in other sectors, such as construction, particularly in the development of new residential buildings and urban areas. Such issues are already observable in Western European countries with a high penetration of electric vehicles, such as the Netherlands [1].

Despite these challenges, transport electrification continues to be actively promoted, and the number of EVs has been increasing over the years, as reported by the International Energy Agency [2]. Further growth in the EV fleet is expected in 2025; however, projections indicate a slowdown in growth, reaching 7.7% in 2025 compared to 48% in 2024 [3]. One of the reasons for the reduced growth rate is the insufficient development of charging infrastructure, specifically, an inadequate number of charging stations that cannot meet overall charging demand, which significantly affects endusers' decisions to invest in EVs due to convenience concerns and potential travel challenges [4]. To address this issue, the European Union adopted the Regulation on the deployment of alternative fuels infrastructure, which defines targets for the construction of charging stations for light- and heavy-duty EVs along roads belonging to the core and comprehensive transport networks [5]. The regulation considers the period up to 2035 and periodically specifies increases in installed charging power at each designated charging location. This regulation is not the only EU document addressing electromobility. The European Green Deal identifies 2035 as the target year for achieving zero emissions from passenger vehicles and establishes the need for significant CO_2 emission reductions by 2030 [6].

In addition to EU-level policies, the importance of electromobility is also reflected in national legislation in Croatia. The update of the Integrated National Energy and Climate Plan for the Republic of Croatia from 2025 [7] provides detailed measures related to road vehicles, charging infrastructure, and the deployment of zero-emission technologies and associated infrastructure in rail transport, seaports, and airports. This plan has been positively assessed by the European Commission with certain steps already being implemented.

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Beyond high-power charging stations installed along major transport corridors, the growth in EV adoption requires the development of charging infrastructure in the parking areas of both residential and non-residential buildings. Amendments to construction legislation define the requirement for installing charging stations and ensuring the availability of cable infrastructure to enable future EV charger deployment in parking facilities in Croatia [8] but also in other European countries, e.g., the United Kingdom [9]. For residential EV chargers, clearly defined rules and guidelines are still lacking; however, relevant standards specify typical charger power ratings and grid connection requirements [10]. Consequently, it can be expected that the connection of EV chargers to residential low-voltage networks may lead to current and voltage-related network issues, as demonstrated in several analyses reported in the published [11], [12]. These papers assess the impact of transport electrification on real-world case studies defined for Croatia and Malta and also propose solutions related to the operation domain that might help DSOs to resolve voltage and current issues that occur when EVs integration is uncoordinated.

Technical challenges in distribution networks caused by accelerated transport electrification can be mitigated through proper distribution network development planning and investment in upgrading network components in areas affected by increased EV charger penetration. The importance of such analyses has been recognized by the Croatian DSO, motivating comprehensive assessments of the impact of electromobility on distribution networks. Regions with strong seasonal demand variations, such as tourist areas, are of particular interest due to higher expected EV usage by visitors from countries with already high EV adoption rates. As a result, the impacts of transport electrification in such regions are expected to be more pronounced than in other parts of the country.

In the literature, solutions addressing technical challenges in electric vehicle (EV) charging tend to focus on operational management and reactive problem-solving, rather than on anticipation and prevention. Common approaches include vehicle-to-grid (V2G) strategies [13] and smart, price-based charging schemes [14]. However, these methods largely remain confined to the research domain, as their practical implementation is limited by factors such as insufficient financial incentives and potential user discomfort. Furthermore, many proposed solutions lack robustness, as they are difficult to replicate or generalize across different case studies.

This paper presents a structured methodology for assessing the impact of electric mobility on distribution networks, with a particular focus on anticipating and mitigating EV-related technical issues. The paper summarizes key findings of "The Impact of Transport Electrification on the Development of HEP ODS's Distribution Network: A Case Study of the Elektroistra Pula Distribution Area" [15] and builds on top of our previous work presented in [16], [17], [18]. Unlike previous studies that primarily address operational problems, our approach operates in the planning domain, projecting the growth of EVs and analyzing grid conditions for relevant future years. By identifying potential current and voltage issues, we propose specific mitigation actions that distribution system operators (DSOs) should take to ensure network reliability. A central contribution of this work is a robust and transferable methodological framework: although the case study focuses on the Croatian distribution area of Istria, the methodology can be applied and replicated in other regions, providing a generalizable tool for proactive e-mobility planning.

The paper outlines the key steps defined within the methodology. Separate procedures are distinguished for MV and LV network analyses. Each section provides a detailed description of the corresponding methodological step, forming a comprehensive framework that supports future practical application.

Section 2 presents the detailed methodology, including the procedure for selecting representative LV network models, projections of EV growth and their contribution to network loading, and the calculation of the EV charging simultaneity factor. Section 3 describes the results of the LV network analysis, including a detailed example of the medoid network and the replication of these results across other LV networks within the same cluster. Section 4 summarizes the key findings for both MV and LV networks. Section 5 presents the methodology for assessing critical network assets, along with a detailed explanation of how the proposed approach can be applied to other distribution areas. Conclusions are provided in Section 7.

II. Methodology

A. Representative LV Network Models

The analysis of the impact of the growing number of electric vehicles on current and voltage conditions in the medium-voltage and low-voltage networks of the Elektroistra Pula distribution area is performed using network models that accurately reflect existing conditions. Models of the mediumvoltage network are available because this network is regularly planned and used in development studies and other planning analyses. In contrast, the low-voltage network is not examined in detail in development studies, and for a large part of the low-voltage system there are no models in planning simulation tools such as NEPLAN. However, low-voltage network data are documented in various DSO's and other databases, which enables the construction of low-voltage network models in specialized simulation tools using the available information.

An assessment of the collected data shows that the Elektroistra Pula distribution network contains more than 2,400 medium-voltage to low-voltage substations, each associated with a corresponding low-voltage network. Even after excluding 386 substations classified as part of the commercial group, more than 2,000 low-voltage networks remain to be modeled.

Modeling each network individually would be impractical, and for this reason a clustering procedure was applied to the available dataset. The main purpose of this procedure is to identify the low-voltage network whose characteristics best represent the networks within the same group or cluster.

Clustering provides a methodological simplification that primarily reduces the number of networks that must be modeled in NEPLAN, the tool used for all analyses in the referenced study [10]. This reduction is achieved by grouping networks into clusters according to the similarity of their technical attributes. The number of clusters is selected to achieve the highest possible level of internal similarity. For each cluster, one low-voltage network is chosen as the representative or average network, and this network is then modeled in NEPLAN. The total number of low-voltage networks modeled therefore corresponds to the number of clusters.

The clustering method applied in this study is the k-medoid method. Based on statistical processing, this method selects an actual low-voltage network from the dataset as the medoid, or the cluster center. This ensures that the representative network is a real system rather than a synthetic model created from average values of technical parameters. The k-medoid method is a classical clustering technique that partitions a set of n objects into k clusters, where the value of k is defined in advance. The objective is to minimize the dissimilarity of objects within a cluster relative to the representative medoid. Membership of an object in a cluster is determined by its distance from the medoid. Along with the ma-

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trix of objects and their characteristics, the algorithm must also be provided with the desired number of clusters.

1) Clustering algorithm: The input data for the algorithm consist of a matrix of objects with their associated characteristics. In the context of this analysis, the low-voltage networks represent the objects, while the selected technical parameters of the network represent the corresponding characteristics, that is, the coordinates of these objects. The dimensionality of the system is equal to the number of selected technical parameters used to evaluate similarity. Thus, if only two technical parameters are selected, each object occupies a position in a two-dimensional coordinate system; if three parameters are selected, the object is placed in a three-dimensional coordinate system, and so forth.

At the beginning of the procedure, the algorithm randomly selects a set of objects to serve as the medoids. The number of medoids is equal to the number of clusters specified by the user as an input parameter. All remaining objects are assigned to the medoid to which they are closest. The medoid together with its assigned objects forms a cluster, and the total number of clusters equals the number of medoids. The algorithm then randomly selects new candidate medoids and evaluates whether they are more suitable as final medoids. Suitability is determined by calculating the sum of distances between the medoid and the objects assigned to it, that is, the objects within the cluster. The medoids that minimize the total distance to their associated objects are selected as the final medoids.

The output of the algorithm consists of vectors representing the coordinates of the final medoids, along with the assignment of each remaining object to the corresponding medoid. In the context of this analysis, the final medoids represent actual lowvoltage networks, and the algorithm provides the classification of all remaining low-voltage networks into the appropriate medoid, that is, cluster. Fig. 1 presents a schematic illustration of the clustering algorithm described above.

2) Optimal number of clusters and selection of attributes: To apply the clustering algorithm, it is necessary to define the number of clusters within which the low-voltage networks will be grouped. Although the number of clusters may be chosen arbitrarily, such an approach raises concerns regarding the justification of the selected number, as the user may choose either too many or too few clusters. To avoid this issue, statistical methods such as the silhouette coefficient are used to determine the optimal number of clusters. The silhouette method is particularly suitable for this analysis because it evaluates the similarity or cohesion of objects within their clusters in comparison with objects in other clusters, that is, their separation.

The silhouette coefficient is calculated for different numbers of clusters. In this study, the coefficient was computed for every value between 2 and 20. The highest silhouette coefficient was ob-tained for three clusters, indicating that this is the optimal number. It is important to note that the clustering process was not applied to the low-voltage networks previously assigned to the Commercial cluster.

As previously explained, clustering is performed based on available technical attributes that describe each low-voltage network. The known attributes include: rated MV/LV substation power, feeder length, share of overhead line length in total feeder length, impedance of the longest feeder section, total number of end-users' connections in the network, total end-users' connection power, average end-users' connection power per connection point, total annual electricity consumption, average annual consumption per connection point, total number of metering points, average number of metering points per connection point, and average an-nual consumption per metering point.

The silhouette coefficient was calculated for ten different com-binations of technical attributes. Although it may initially seem reasonable to use all available attributes, the statistical analysis in-dicates otherwise. Among all observed combinations, the lowest silhouette coefficient (0.26) was obtained when all attributes were used. The highest value (0.51) was achieved for the combination of attributes rated MV/LV substation power, share of overhead line length in total feeder length, and average annual consumption per metering point.

Clustering using these three attributes resulted in three clusters. A detailed examination of the networks in each cluster shows that they correspond to the following categories: »Urban networks – houses«, »Urban networks – buildings«, and »Rural networks«.

The »Urban networks – buildings« cluster contains a total of 643 low-voltage networks. These networks are characterized by higher substation installed power, a lower share of overhead lines, and generally higher average annual energy consumption per con-nection point.

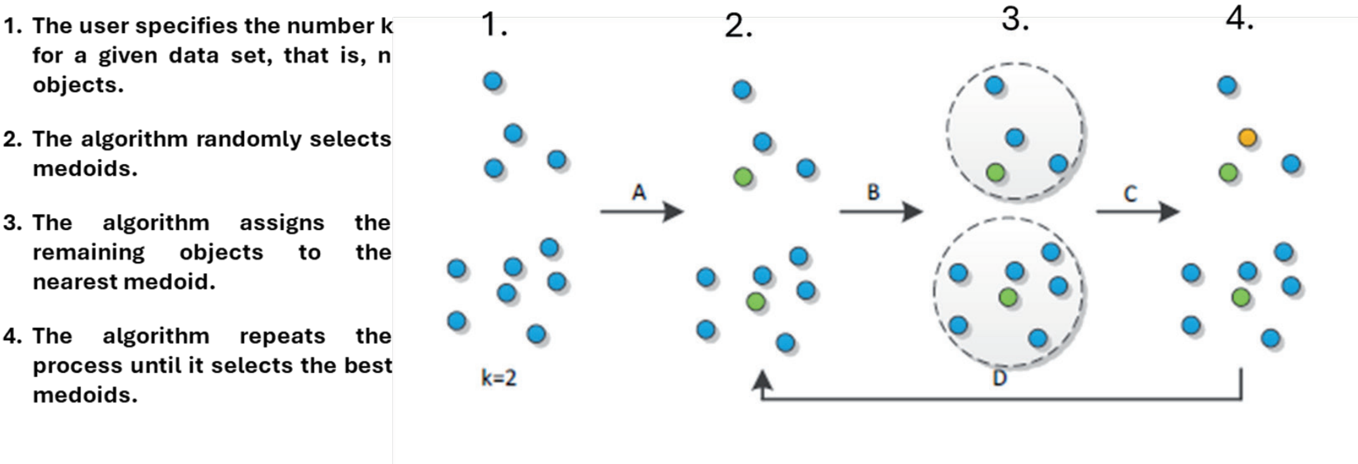

Fig. 1. Clustering approach

The »Urban networks – houses« cluster contains 625 low-voltage networks. These networks have somewhat lower installed transformer power, a slightly higher share of overhead lines, and lower average annual consumption per connection point. The »Rural networks« cluster consists of 772 low-voltage networks. These networks are characterized by low installed transformer power, a high share of overhead lines, and low average annual consumption per connection point. Also, 386 networks were not part of the clustering algorithm and were predetermined as the industrial type of network based on the information from the DSO.

B. Projection tf the Increase in the Number of Electric Vehicles in the Area of Istria

To determine the contribution of electromobility to the increase in load in the area of Istria, it is necessary to create a projection of the growth in the number of electric vehicles over the observed period. The process of determining the increase in the number and total power of charging stations for electric vehicles in Istria consists of three main steps.

The first step concerns establishing the current situation, and involves detailed research of available data aimed at identifying the main characteristics of Istria in terms of vehicles—both those using fossil fuels and electric ones. A comprehensive approach is used, meaning that the population structure and seasonal patterns are analyzed, given the strong infLuence of tourism in the region. Additionally, publicly available demographic data, statistics from tourist boards, data from the Croatian Auto Club (HAK) and motorway operators regarding traffic fLows are used. To obtain the most accurate data on the current state of electromobility in Istria, available electric vehicle charging curves are also utilized. All relevant documents that provide a solid foundation and discuss plans for introducing electric vehicles are taken into consideration.

The second step involves assessing future trends and determining projections for the coming period based on the situation established in the previous step and the expected increase in the share of various types of electric vehicles and vessels over a twenty-year period. For specific projections, in addition to the increase in the share of electric vehicles, demographic developments and tourism growth in the region are also considered. To enable more precise modeling, a wide range of literature and reference materials is taken into account. This includes the European Union's plans for promoting electromobility, historical population trends in Istria, the penetration rate of electric vehicles in the Republic of Croatia, as well as in the countries from which tourists visiting Istria most commonly arrive.

The third step focuses on segmenting the overall observed period of the next twenty years. Initially, a series of microanalyses are carried out for one-year intervals for the first ten years of the observed timeframe, while the second ten-year period is based on somewhat broader five-year estimates.

Additionally, it is important to closely examine certain statistical indicators characteristic of Istria and on which the projection must be based. The first indicator relates to the total number of vehicles in Istria, consisting of vehicles owned by the local population and vehicles brought by tourists. As mentioned earlier, one reason for choosing Istria for this analysis is the number of tourists—particularly those from developed countries where the rate of electromobility is already significant. Besides the number of cars, demographic parameters such as the number of inhabitants and tourism indicators such as the number of arrivals and overnight stays are also observed. Along with statistical parameters, it is necessary to review relevant documents from the European Union and the Republic of Croatia, such as EU regulations on the deployment of alternative fuel infrastructure or the Integrated National Energy and Climate Plan.

Furthermore, information on the LV (low-voltage) network is required, especially for determining the growth in the number of lower-power charging stations, given that the projection for the LV network is carried out separately for each cluster and then scaled to the level of the entire distribution area. Fig. 2 and Fig. 3 show the results of the projection for the observed twenty-year period. It is important to note that the projection corresponds to the area of Istria and that, in the case of analyzing another area, it must be adjusted to match the characteristic indicators of that area.

It should be noted that changes in the European and

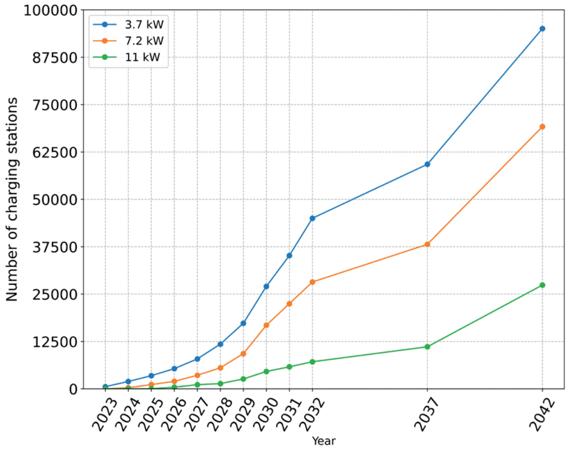

Fig. 2. Projection of the EV charging stations increase - 3.7 kW, 7.2 kW, 11kW

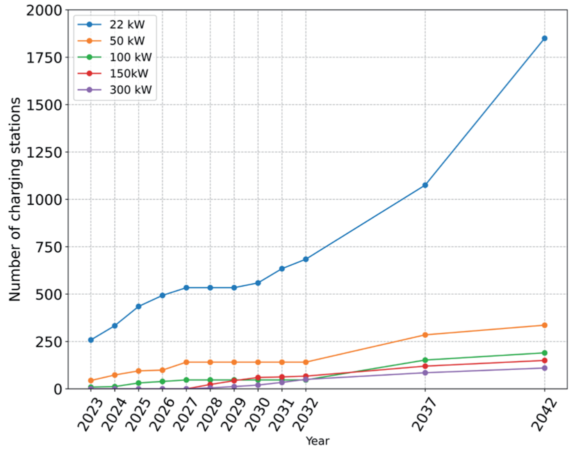

Fig. 3. Projection of the EV charging stations increase - 22 kW, 50 kW, 100 kW, 150 kW, 300 kW

Croatian regulatory environments may affect the projection results, which would directly influence the contribution of EV charging to peak demand and the timing of potential technical issues. Consequently, conclusions regarding the specific year in which network reinforcements are required may change. However, beyond identifying the timing of necessary investments, the projections also define the demand levels at which such actions become necessary. Therefore, even if the growth in the number of EVs is delayed or occurs earlier than expected, distribution system operators (DSOs) can monitor the total installed EV charging power and implement the same mitigation measures accordingly.

C. EV charging simultaneity factor

After determining the installed power of aggregated charging stations at each MV node, it is necessary to determine the simultaneity factor of electric vehicle charging. The simultaneity factor must be defined because the probability that all charging stations are loaded at a level equal to their installed power is extremely low. The simultaneity factor $k_{EV,i}^{simultaneity}$ is defined as the ratio of the charging power at a given moment to the total installed power of the charging infrastructure, as defined with eq. (1).

$$k_{EV,i}^{simultaneity} = \frac{S_{EV,i}^{charging}}{S_{EV,i}^{installed}} \tag{1}$$

The simultaneity factor is determined separately for each cluster, since the level of transport electrification as well as the characteristic charging power differ for each cluster. For the purposes of the analyses conducted within the study, two scenarios are defined:

- High simultaneity factor scenario (Scenario 1)
- Scenario with the simultaneity factor defined based on real data (Scenario 2)

In Scenario 1, the simultaneity factor for all clusters is equal to 1. Since the study considers the case of maximum system loading, a simultaneity factor of 1 corresponds to the maximum theoretical utilization of an individual charging station, i.e., the case in which the maximum charging power is equal to the installed power of the charging station. This is also the case in which EV charging power contributes the most to the total system load. As the system load is also defined as maximum, in Scenario 1 the highest voltage drop values as well as the highest current loading of transformers and lines/cables in the observed distribution network can be expected. Furthermore, if no current–voltage issues occur in this case, they will not occur in any other case either.

Given that the scenario with $k_{EV,i}^{simultaneity} = 1$ represents a worst-case scenario and it is not realistic to expect the charging power to be equal to the installed power of each charging station, a more realistic case needs to be defined. Although it is possible to determine the simultaneity factor for each cluster using a rule-of-thumb approach, the charging simultaneity factors were determined based on real data available in the literature. Data were found for two clusters—«Urban networks – houses« and »Urban networks – buildings«. The data for houses are based on Denmark, while the data for buildings are based on Norway. Finally, data from Finland were used to calculate the simultaneity factor for the cluster »Industrial/commercial networks« Denmark and Norway are among the leaders in transport electrification and the share of electric vehicles, and as such represent a good example of what can be expected in the Istria region, where a somewhat higher number of electric vehicles is anticipated due to tourism compared to the rest of the Republic of Croatia. Simultaneity factors different from 1 also indicate that it is not necessary to ensure simultaneous charging of all electric vehicles. Although the existing infrastructure may be sufficient to allow all electric vehicles to charge without waiting, such a situation is not realistic and does not need to be guaranteed. This also means that not all parked electric vehicles require charging at the same moment.

Values of calculated simultaneity factors for each cluster, with the reference to the original data which was the basis for the factor calculation are presented in Table I.

Table I.
Ev Charging Simultaneity Factor of Different Clusters

Cluster	Value	Reference country	Reference
Urban networks - houses	0.385	Denmark	Multiple sources
Urban networks - buildings	0.218	Norway	[19]
Rural networks	0.367	Germany	[20]
Industrial/commercial networks	0.192	Finland	[21]

III. Low Voltage Network Results

After defining the medoids of the LV networks, the growth of the base load, the increase in load due to the connection of EV charging stations, the increase in load due to the connection of heat pumps, and the increasing impact of distributed generation, it was necessary to proceed with the analysis of the medoid networks over the observation period. For each year of the observed period, an analysis of each medoid was carried out using the Neplan software package. In order to identify network congestion, checks were performed on MV/LV transformer loading, line loading, and voltage drops. For the identified congestion issues, the necessary mitigation measures were defined. This analysis was repeated for medoids in all cluster, however, in this paper we only present the results for one representative cluster, »Urban networks - houses«.

Fig. 4 presents the most important results of the analysis conducted for the medoid LV network. The figure shows the total electricity demand, along with the contributions of household baseline demand, photovoltaic (PV) generation, HVAC systems, and EV charging. It also indicates the nominal power of the transformer. Unlike all other demand sources, the contribution of PVs is zero, as the period under consideration corresponds to peak demand during evening hours, when there is no PV generation. This period also represents the worst-case scenario for the distribution network. In addition, the years in which voltage and current congestion occur, as well as the year in which the transformer needs to be replaced, are shown.

Total electricity demand exceeds the transformer's nominal power in 2030, and replacement of the installed 250 kVA transformer with a 630 kVA unit is recommended, as demand surpasses 400 kVA—the next typical transformer rating after 250 kVA. In addition to transformer replacement, upgrading lines and/or cables in the LV network is also necessary. Such replacements are required due to either voltage or current congestion. The results indicate that voltage drops exceed 10% in 2033 and 2034, while line currents surpass the lines' ampacity in 2037.

The analysis results from a locational perspective are presented in Fig. 5, showing both current and voltage congestion. Areas marked at the beginning of the network highlight lines and cables most affected by the increased power demand from EV charging. Since the highest power flows through the initial lines, these observations are expected. The marked area at the end of the network identifies nodes experiencing the largest voltage drops, i.e., the lowest voltage magnitudes. This location of minimum voltages is also expected due to the unidirectional power flow and the natural voltage decrease with increasing electrical distance.

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A. PROJECTING MEDOID RESULTS ON OTHER LV NETWORKS WITHIN A CLUSTER

The results of the analysis of LV networks apply exclusively to the medoid of each cluster. Although there are certain similarities between the medoid and the other networks within the cluster, they also differ in many respects. For this reason, the conclusions drawn for the medoid cannot be directly transferred to all other networks within the cluster.

Based on the differences in technical attributes between the medoid and the other networks in the cluster, the analysis results can be projected in a way that accounts for these differences. In this way, an investment will not always be proposed in the same year; instead, it will change depending on the technical attributes of each LV network.

To make the medoid's results applicable to all other networks within the cluster, it is necessary to design and define a methodology that would adapt the medoid's results to any other network, taking into account its specific characteristics. During the analysis, three indicators of the need for investment in the network were defined: transformer overload, exceeding the current load of lines/cables, and an excessively high voltage drop.

B. REPLACEMENT OF MV/LV TRANSFORMERS

For determining the replacement year of MV/LV transformers, no methodological approach is required; in other words, the year can be determined independently of the medoid results, based on other known data. For each transformer, its rated power is known. The annual load growth has been determined, as well as the additional increase in load caused by the integration of air conditioners and heat pumps, and electric vehicle charging stations. Using these data, it is possible to determine the load of each LV network according to eq. (2):

$$S_{total,year}^{load} = S_{base,year}^{load} + S_{HVAC,year}^{load} + S_{EV,year}^{load} \qquad (2)$$

By comparing the total load of the network with the rated power of the substation, it is possible to determine whether the transformer needs to be replaced in the observed year, i.e., whether the

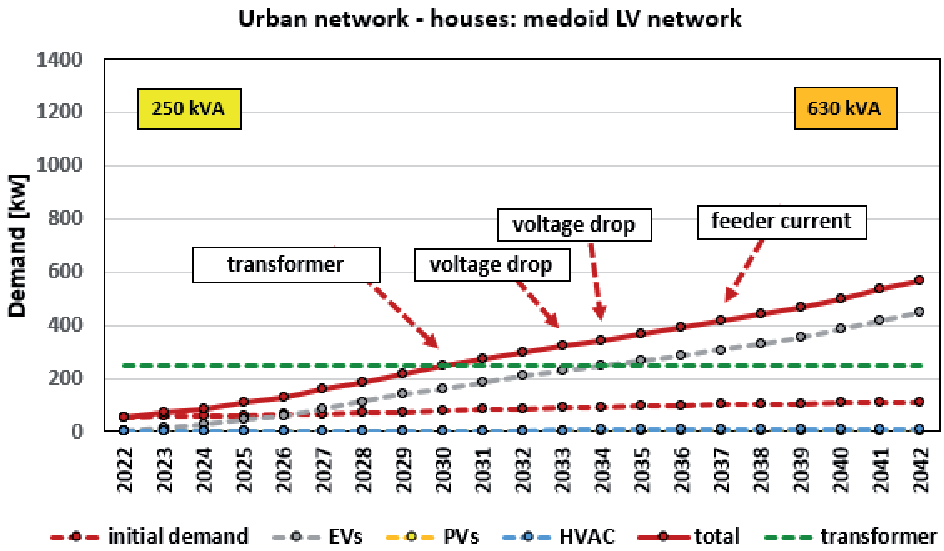

Fig. 4. Congestion location in the medoid LV network

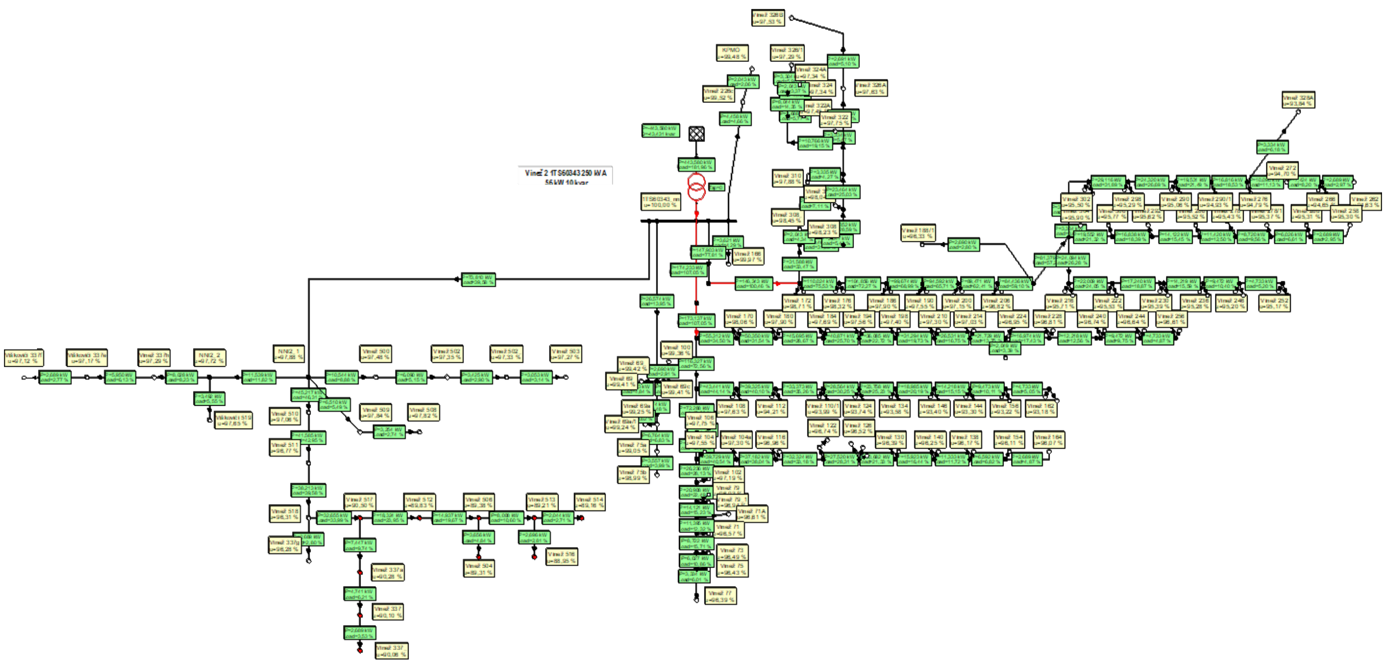

Fig. 5. Congestion location in the medoid LV network

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condition in eq. (3) is satisfied:

$$S_{total,year}^{load} \geq S_{nominal,year}^{MV/LV substation} \tag{3}$$

The potential replacement of transformers in substations is considered for each year, meaning that a replacement will not be proposed solely on the basis of the network load in the final year. For example, if the total network load in 2027 is 430 kVA, and the rated power of the transformer is 400 kVA, the first transformer replacement will occur in 2027, and the 400 kVA transformer will be replaced with a 630 kVA unit. Then, the network load in subsequent years will be observed to determine whether there is a year in which the load exceeds the new rated power of the transformer. In this paper, the results of replicating the results for themedoid LV network on other networks in a cluster will be shown only for the cluster »Urban networks – houses«, since the methodology remains unchanged for the other clusters. Also, we present the results only for Scenario 2 as this is more realistic scenario that considers real-world EV charging patterns in defining simultaneity factor. Fig. 6 shows the results of the transformer replacement analysis for the cluster »Urban networks – houses«.

Based on the results of the analysis in Scenario 2, it is evident that there is a need for at least one replacement of a larger number of transformers, caused by the electrification of transport and the increase in the number of charging stations in low-voltage networks. In addition to transport electrification, the continuous growth in the number of air conditioners also contributes to the number of overloaded substations. The electrification of transport and heating and/or cooling requires the distribution system operator to invest in new transformers. These results enable investment planning by year, while it is up to the system operator to decide whether the proposed replacements will be carried out in cycles or whether only the final proposed replacement will be considered, with existing transformers replaced by those with the highest proposed capacity.

C. Replacement of Low Voltage Lines And Cables

The analysis of the need for investment in the replacement of lines in the LV network is somewhat more complex compared to the analysis for transformers, since it cannot be carried out solely on the basis of load values. The calculation of investment needs was made using the methodology presented in several previous studies that dealt with the similar problems. Methods in these studies assess the impact of the increasing number of different DERs on the distribution network. In these methods, projecting of medoid results to other networks within the cluster was performed based on the *kdU* factor, defined as the sum of all products of the connection point power and the sum of the impedances of the lines and/or cables leading from the substation to the connection point.

A similar approach was used in this study, where the *kdU* factor was also used to project medoid results, with its calculation adapted to the available data provided as input for the analysis. For LV networks, line and/or cable impedances were not determined in the initial step—only their lengths. More precisely, the corresponding attribute table contains only the total line length, and this value will be used in calculating the *kdU* factor.

Although the type of line or cable plays a significant role in the voltage drop value, the assumption is that each cluster uses standard line types with similar unit resistance and reactance values. For this reason, the *kdU* factor will depend more on line length than on the line and/or cable type.

In addition to network length, the total network load will also be used. The load has been pre-determined, and the same parameter was used in the analysis of required transformer replacement. The detailed mathematical formulation of the *kdU* factor is given in equations (3)–(6).

Equations (3) and (4) are commonly used to calculate the squared voltage drop magnitude ΔU_{ij} of a line *ij*, where S_j s the power at the endpoint of the line/cable, and Z_{ij} is the impedance of the line/cable calculated from the per-unit resistance and reactance values r_{ij} and x_{ij} and the line length l_{ij}. The *kdU* factor is calculated using equations (5) and (6) as the total voltage drop, i.e., as the sum of the demand *d* of all connection points CP $\sum_{d \in CP} S_l$ and the sum of all impedance in the network. As already mentioned, the use of standardised components affects only the magnitude of the *kdU* factor. Assuming that the per-unit nominal impedance is approximately the same for all networks within the same cluster, i.e., it is a constant, its contribution to the *kdU* value will always be identical. In other words, although neglecting the exact value of impedance will change the factor, this change will be the same across all networks and will therefore not influence the conclusions drawn.

$$\Delta U_{ij} = S_j \cdot Z_{ij} \quad [V^2] \tag{4}$$

$$\Delta U_{ij} = S_j \cdot (r_{ij} + x_{ij}) \cdot l_{ij} \quad [V^2] \tag{5}$$

$$kdU = \sum_{d \in CP} S_l \cdot (r_{ij} + x_{ij}) \cdot \sum_{l \in L} l_{ij} \quad [V^2] \tag{6}$$

$$kdU = \sum_{d \in CP} S_l \cdot \sum_{l \in L} l_{ij} \tag{7}$$

The results of the medoid analysis provide insight into the years in which line and/or cable replacements are required, i.e., they provide information on the network investment cycles. For all years in which a replacement is needed, the medoid's *kdU* factor is calculated for the given year. Since lines and cables are replaced, after investing in new network elements, the network can handle a higher *kdU* value. For this reason, the medoid's *kdU* is calculated for each year in which a replacement is needed. For all other networks within the cluster, the *kdU* factor is calculated for each year. The annual *kdU* values are compared with the medoid's *kdU* values. A year in which a network's *kdU* exceeds the medoid's *kdU* in the year when investment is required is identified as the year when investment is necessary. This procedure is repeated as long as there are needs for investment in new network elements within the observed twenty-year period.

As in the case of the transformer replacement analysis, this report presents the results for the »Urban networks – houses« cluster in Scenario 2. Fig. 7 shows the results of projecting the medoid onto the other networks within the cluster. The results indicate a significant number of LV networks that require intervention already in the first year, even when the share of EVs is not yet substantial. This means that certain current–voltage issues can be expected in the initial state if a number of existing lines are not replaced. The need for replacing network elements in subsequent years is lower and increases gradually with time from the initial year, which is expected given the dynamics of EV growth. The majority of investments will be required over a period of more than 20 years, indicating that it is possible to avoid risks in operating distribution networks amid transport electrification.

Only one investment cycle in new lines and/or cables has been identified, given that the medoid results indicate that voltage drop issues occur during the period between 2032 and 2037, and for this

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five-year period a single *kdU* factor value was calculated. Considering the assumption that certain networks may potentially require an additional investment cycle, the number of networks for which the *kdU* factor in any year exceeds the medoid's factor in the final year will be determined. Since the medoid network does not experience current–voltage constraints in 2042, even for Scenario 1, the *kdU* factor calculated for that scenario will be used, as it is of a higher value. This approach ensures that fewer networks need to be analyzed in more detail. The results show that all 205 networks in which the *kdU* in the final year is higher than that of the medoid potentially require analysis over the other ten years of the observed period. There is a high probability that additional investment in line and/or cable replacement will not be necessary, particularly for 47 networks for which potential replacement falls within the period between 2037 and 2042.

IV. Analysis of System-Level Results

Based on the results of the MV network analysis, analyses of medoid LV networks and replication of those results on other networks within a cluster, system-level conclusions were made. The conclusions mostly relate to investments needed by the DSO, in terms of replacing existing assets and building new substations. Follwoing conclusions were made:

- The total number of HV/MV transformers in the Elektroistra distribution area is 36. The analysis shows that during the observed period, 19 transformers (53%) will need to be replaced, of which 11 replacements (60% of all planned) will occur in the last five-year period. The situation is somewhat more favorable for MV/MV transformers – out of a total of 59 transformers, 19 (32%) will need to be replaced.

- The total length of the 35 kV network in the analyzed distribution area is 133 km, including 72 km of overhead lines and 61 km of cable lines. According to the results, no investments will be needed in this network during the first 5 years. In the second five-year period, more than 40% of overhead lines will need to be replaced, while in the remaining period, almost the entire overhead network will be replaced. Cable lines will require investment only in the last 5 years, accounting for 7% of the total length.

- The total length of the 20 kV network is approximately 2,900 km, of which about 1,700 km are overhead lines and 1,200 km are cable lines. No additional investments are needed during the first 5 years. In the next 5 years, approximately 2% of overhead lines are planned to be replaced, while in the remaining period, an additional slightly more than 2% will need replacement. For cable lines, a total of 6% of the network is planned for replacement over the entire observed period.

- Based on the results, the following number of MV/LV transformers (total of 2,425) will need to be replaced during the study period:

  — 428 transformers (68%) in the »Urban networks – houses« cluster

  — 277 transformers (43%) in the »Urban networks buildings« cluster

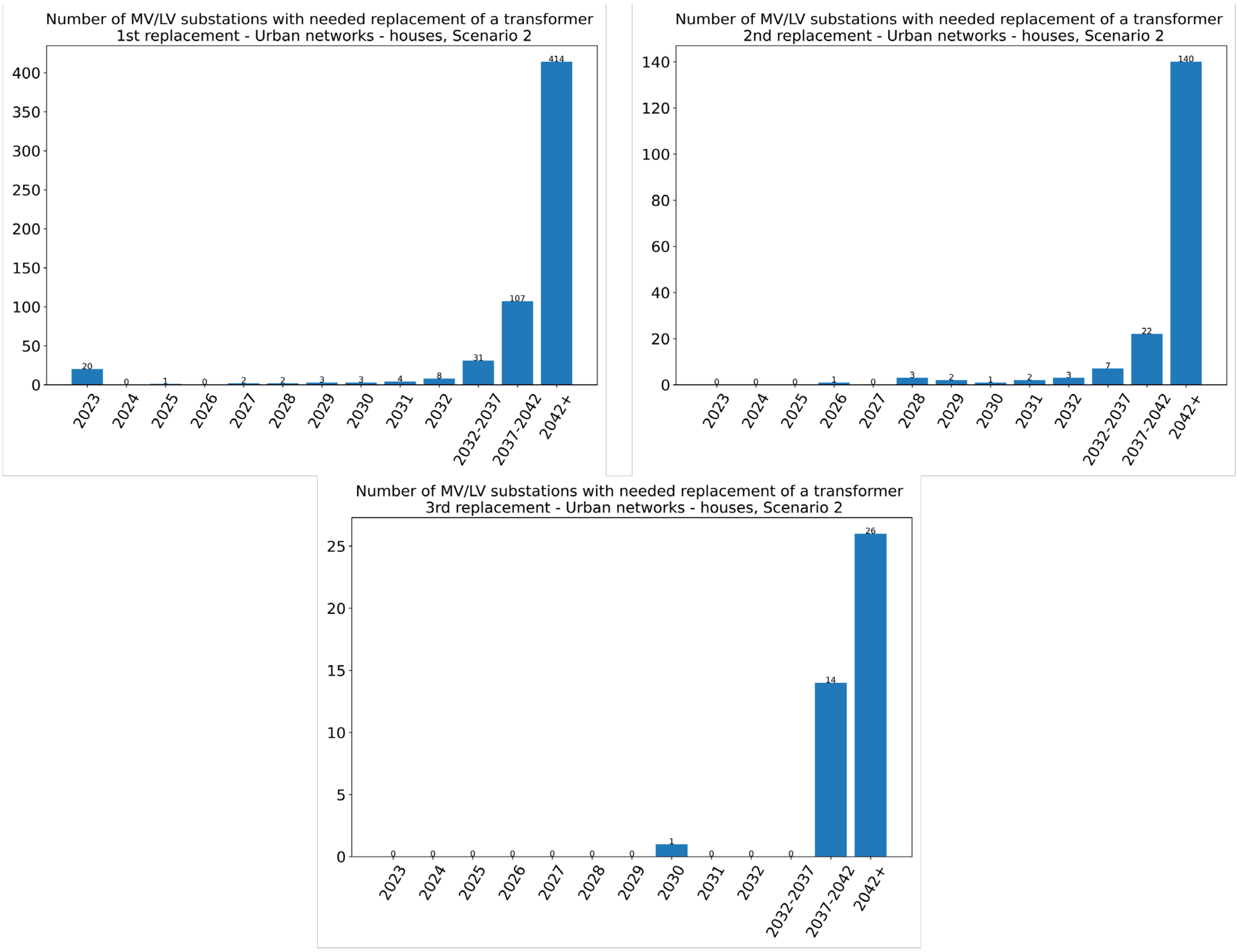

Fig. 6. Replacement of transformers in 20-year period: »Urban networks-houses« cluster

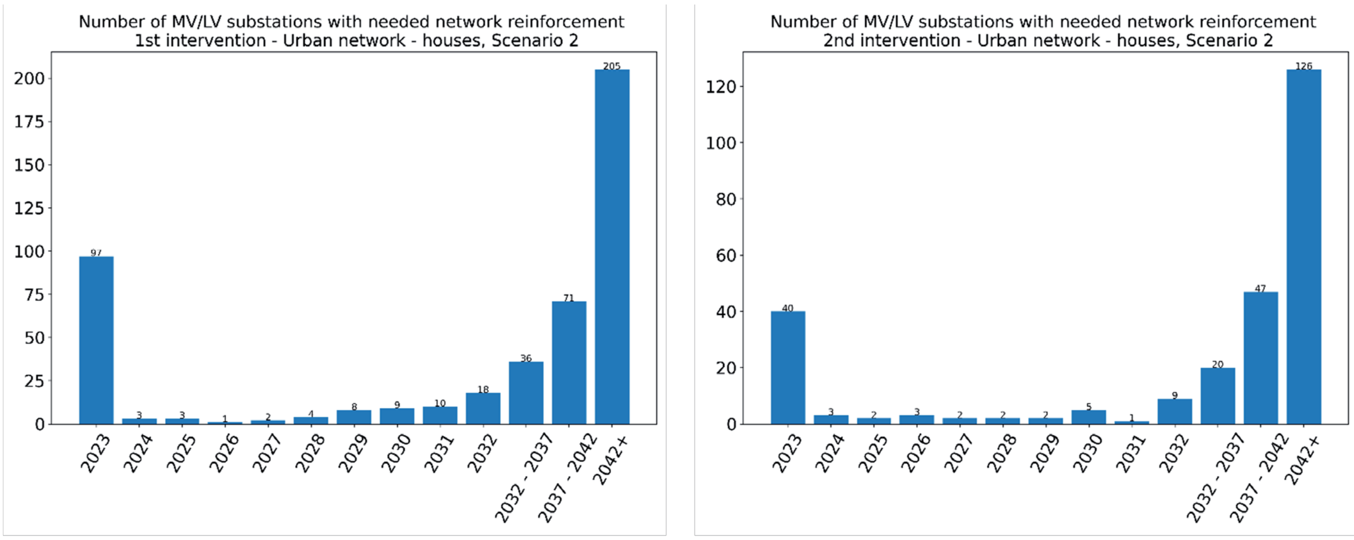

Fig. 7. Replacement of lines and cables in 20-year period: »Urban networks-houses« cluster

— 772 transformers (123%) in the »Rural networks« cluster

— 67 transformers (17%) in the »Industry/commercial« cluster

- The most unfavorable situation is in the »Rural networks« group, where multiple replacements of transformers are needed – the total number of replacements (123%) exceeds the number of existing units, indicating that some transformers must be replaced more than once, e.g., a 400 kVA transformer is first replaced with a 630 kVA transformer, and then later with a 1,000 kVA transformer. In this group, the highest number of replacements (623 transformers, i.e., 81%) is planned in the last five-year period. In the »Urban networks – houses« group, 225 transformers are planned to be replaced in the same period, which is 40% of all required replacements. In the other two groups, the situation is significantly better.
- The total length of the LV network in the Elektroistra Pula distribution area is approximately 4,500 km, of which about 2,000 km are overhead lines and 2,500 km are

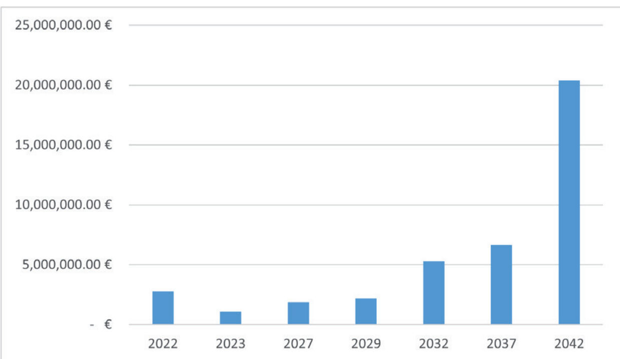

Fig. 8. Investment in MV/LV transformers in the 20-year period

cable lines. During the observed period, approximately 800 km of the network will need to be replaced, which represents 18% of the total length. The largest portion of investments concerns the »Urban networks – houses« cluster, where 564 km of the network will need to be replaced, accounting for more than 70% of all planned investments.

Furthermore, a financial analysis related to the replacement of existing MV/LV transformers was carried out, as shown in Fig. 8. The costs associated with replacing substations at the HV/MV and MV/MV levels are estimated at €52 million. Fig. 8 shows the growth of total costs for renewing MV/LV substations. By 2042, approximately €40 million will need to be invested in the renewal of these substations.

V. Methodology for Assessing the Critical Assets in MV And LV Networks

The aim of this study was not only to analyze the impact of the increasing number of EVs on current–voltage conditions in the Istria region, but also to define a unified methodology that would allow the application of the study results to other areas. The methodology for assessing the impact of EV growth on current–voltage conditions in the distribution network, i.e., the methodology for evaluating and identifying critical network assets, is described in this paper.

The results of the analysis show that the methodology can also be applied to other distribution areas if the defined steps are followed. Also, the methodology can be applied no matter the characteristics of networks in the observed area, after certain input parameters are modified to better reflect the actual state of networks. The analysis of the impact of transport electrification on the development of the distribution network is methodologically divided into the analysis of the MV network and the analysis of the LV network. These analyses can be conducted separately, independently of each other, although they are connected by certain input parameters, e.g., the projection of load growth, and documents relevant for assessing the number of EVs and the construction of the corresponding infrastructure.

Regardless of the voltage level of the distribution network, for each distribution area it is necessary, in the first step, to perform a legislative and regulatory analysis, as well as an analysis of certain demographic and economic indicators, in order to adapt the EV growth projection from the Istria region. The number of tourists in Istria significantly contributes to the expected acceleration of transport electrification, and such growth is not expected in other distribution areas. In addition, data on the initial load curve of a given distribution area are needed to enable the creation of a resultant load curve. The load curve is unique for each distribution area and serves as input data for further MV and LV network analyses.

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The MV network is analyzed in its entirety; that is, a detailed network model is used to assess the impact of transport electrification at the MV level. For this reason, the first step in the methodology is to analyze the configuration of the existing model of the MV network presented in a specialized distribution network simulation tool, e.g., NEPLAN. Network models are available in all distribution areas due to the preparation of development studies or other studies whose results are based on the MV network model.

It is to be expected that the existing model will always need to be adjusted, for example, due to the construction of new or decommissioning of existing substations, or due to adjusting peak load to actual conditions. Additionally, the existing NEPLAN model must be expanded by adding new elements that represent the load from EV charging stations, heat pumps, or solar power generation. The consumption and/or production power values are determined based on initial projections of peak load growth.

In the final step, the current–voltage conditions in the network model are analyzed for each selected year within the observed period. Based on these results, the need for investment in new transformers and lines, the need for constructing new and replacement of existing substations, and the dynamics of network investments are determined.

The analysis of the LV network is different, as presented in this paper. For numerous reasons, including the large number of LV networks in each distribution area, LV networks are not modeled in their entirety in the specified distribution network simulation tool. The simplified approach to modeling the LV network has several advantages, and for this reason, the methodology proposes such an approach also for application in not only the analyzed but also other distribution areas. In the first step of applying the methodology to LV network analysis, a clustering procedure must be carried out based on the available technical attributes. It is important to note that the number of clusters determined for the area analyzed in this paper does not necessarily have to be the same for other distribution areas. In addition to determining the optimal number of clusters, the clustering algorithm also produces a representative model of the LV network, i.e., the medoid of each cluster. A network model is created exclusively for the medoids, and the results of the analysis are generalized to all other LV networks within the same cluster. Generalizing the results, i.e., projecting the medoid results onto the other LV networks within the same cluster, is described in detail in the previous chapter. This step is also a key part of the methodology, as it enables the system operator to plan investments more effectively each year.

During the implementation of the steps in the methodology, certain conclusions were drawn that lead to recommendations for future application in other distribution areas. The quality of the analysis results largely depends on the availability and accuracy of the data, particularly data on the LV network, the determination of the necessary attributes, and the accuracy in identifying the medoid. These points are most closely related to the clustering procedure. Since this is a statistical analysis, a high-quality set of input data is a prerequisite for the accuracy of the process. In addition to input data, certain steps can further improve the accuracy of projecting the medoid results. Accuracy can be increased if clustering is performed at the branch level and if the medoid is defined as a branch rather than the entire network. Additionally, the impedance of the lines, as well as the number and average length of branches, should be taken into account. Finally, the calculation of the *kdU* factor can be modified to include the actual impedance, not just the line length. If all of these steps were implemented in the methodology, its future application would allow for even more accurate results and more precise analyses.

VI. Conclusion

This work demonstrates that the growth in electric vehicle (EV) numbers can lead to the exceedance of technical limits in the distribution network, including the need for transformer replacements and line upgrades. The results clearly identify critical sections of both medium-voltage (MV) and lowvoltage (LV) networks and the timing of required investments.

Beyond identifying potential issues, the study developed a methodology for accurately assessing the impact of transport electrification and planning necessary network investments. The methodology includes an analysis of the existing network state, demographic and economic indicators, regulatory frameworks, and projections of EV growth. MV network assessment uses a detailed full-network model, while LV network analysis employs clustering to define representative models (medoids), allowing results to be generalized across other networks within each cluster. Additional steps, such as accounting for line impedances and refining the kdU factor, enhance the precision of the analysis.

Timely and coordinated investments in both MV and LV networks can prevent adverse effects of increased electricity demand and ensure reliable network operation. The methodology can also be applied to other distribution areas, supporting a sustainable continuation of transport electrification in Croatia without compromising network reliability.

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