energies

MDPI

Article

Determination, Evaluation, and Validation of Representative Low-Voltage Distribution Grid Clusters

Andreas Weiß [1,2,*,†], Elisabeth Wendlinger [1,3,*,†], Maximilian Hecker [1] and Aaron Praktiknjo [3]

[1] Forschungsstelle für Energiewirtschaft e.V. (FfE), Am Blütenanger 71, 80995 Munich, Germany
[2] TUM School of Engineering and Design, Technical University of Munich, Arcisst. 21, 80333 Munich, Germany
[3] Chair for Energy System Economics, RWTH Aachen University, Mathieustr. 10, 52074 Aachen, Germany
* Correspondence: aweiss@ffe.de (A.W.); ewendlinger@ffe.de (E.W.);
Tel.: +49-(0)89-158121-64 (A.W.); +49-(0)89-158121-28 (E.W.)
† These authors contributed equally to this work.

Abstract: Decarbonizing the mobility and heating sector involves increasing connected components in low-voltage grids. The simulation of distribution grids and the incorporation of an energy system are relevant instruments for evaluating the effects of these developments. However, grids are highly diversified, and with over 900,000 low-voltage grids in Germany, the simulation would require significant data management and computing capacity. A solution already applied in the literature is the simulation of representative grids. Here, we show the compatibility of clusters and representatives for grid topologies from the literature and further extend and validate them by applying accurate grid data. Our analysis indicates that clusters from the literature unify well across three key parameters but also reveals that the clusters still exclude a relevant amount of grids. Extension, reclassification, and validation using about 1200 real grids establish meta-clusters covering the spectrum of grids from rural to urban regions, focusing on residential to commercial supply tasks. We anticipate our assay to be a further relevant step toward typifying low-voltage distribution grids in Germany.

Keywords: low-voltage distribution grid; grid clustering; grid representatives

check for updates

Citation: Weiß, A.; Wendlinger, E.; Hecker, M.; Praktiknjo, A. Determination, Evaluation, and Validation of Representative Low-Voltage Distribution Grid Clusters. *Energies* **2024**, *17*, 4433. https://doi.org/10.3390/en17174433

Academic Editor: Gian Giuseppe Soma

Received: 10 July 2024
Revised: 20 August 2024
Accepted: 21 August 2024
Published: 4 September 2024

1. Introduction

In the coalition agreement, the German government has set itself the goal of covering 80% of electricity demand with renewable energies by 2030 [1]. To achieve this goal, renewable energy plants have to be significantly expanded. In contrast to conventional power plants, a significant share of renewable energy plants, especially photovoltaic system (PV) plants, are connected at lower voltage levels [2]. Another goal of the German energy transition is the electrification of the mobility and heating sector. The impact on the low-voltage (LV) grid caused by additional load and generation has been the subject of several previous studies [3–5]. One research focus is the integration of a heat pump (HP), either as a large-scale approach to heating whole districts or as a more decentralized approach to integrating HP into buildings, as investigated, e.g., by [6]. The number of HP, in combination with heat storage systems, is increasing significantly, which results in additional load on the grid. Furthermore, grids are also impacted due to changes in the mobility sector. The transition from vehicles with combustion engines to electric motors results in an additional load and new challenges for the energy system. For example, increasing the load and simultaneity of charging behavior can lead to grid bottlenecks [3]. To integrate all new energy feeders and loads into the LV grid, there is a need for a cross-sectoral integration from flexibilities like electric vehicle (EV), HP, heat storage, and small battery storage. Otherwise, the increasing load and expected simultaneity due to synchronous consumption behavior would require significant distribution grid expansion. Although these developments generally affect all voltage levels, LV grids face significant challenges, as the systematic optimization of these grids is much more difficult due to their more complex, small-scale structure. Determining the expansion requirements, therefore, demands a high degree of expertise on the current structures of grids, consumers, generators, and scenarios for their future characteristics.

1.1. Research Context

In Germany, there are about 900,000 LV grids with a total length of 1.2 million kilometers. Modeling and simulations significantly evaluate the energy transition's effects in distribution grids by analyzing different scenarios. However, the simulation of each grid to determine the future load and possible expansion requires enormous effort and computing capacity. Accordingly, scenario analyses at a national level and policy settings simplifying assumptions must be adopted in system studies. This is complicated due to the large distribution system operator (DSO) number: there are 866 DSOs in Germany [7]. It is difficult to obtain distribution grid data due to their security classification. Generally, the dimensioning of the central power distribution systems in Germany's low-voltage grid is based on the Technical Connection Conditions (VDE-AR-N 4100). To ensure compliance with the maximum permissible voltage drop, main lines in the low-voltage system must be installed in the shortest possible path and routed through generally easily accessible areas. Central power systems are installed as radial grids. The central power distribution system for residential buildings must be dimensioned in accordance with DIN 18015-1. All other central power distribution systems must be dimensioned according to their power requirements [8]. The evaluation of a small selection of LV grids is of limited value due to topological diversity, which results in conflicting objectives regarding expansion. Simplifications are required for holistic predictions regarding LV grids in Germany. One possibility is the evaluation of representative distribution grids. This paper analyzes and combines clustering methods from the literature into representative clusters. These different clusters are evaluated by assigning real LV grids and comparing their characteristics. The following research questions are addressed:

- Which technical and/or geographic–topological parameters are suitable for characterizing LV grids?
- What are the literature's different approaches defining grid representatives?
- Can the literature's grid clusters be merged, and how are they distinguished from each other?
- How applicable are merged clusters when considering a distribution system operator's real LV grid topologies?

To answer these research questions, the paper follows the scheme in Figure 1.

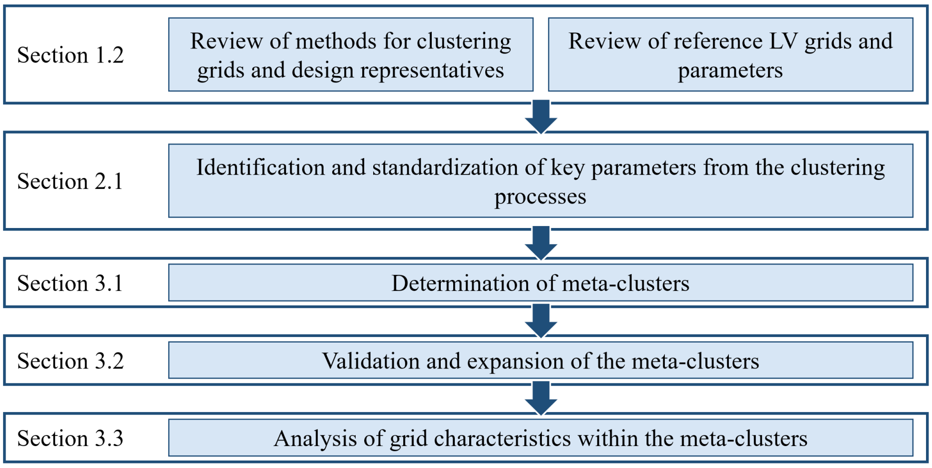

Figure 1. Schematic overview.

As a first step, LV grid representatives and respective clusters from the literature are reviewed and analyzed regarding the applied methods and the grid parameters used for clustering. In the next step, all reference grids are standardized in a comparable structure by merging and norming parameters. As a result, three key parameters used in most studies are obtained. Using the key parameters, meta-clusters are derived from the clusters in the literature. In the next step, real LV grids are categorized into the defined meta-clusters to verify the meta-clusters. After consideration of the result, five further clusters are added to cover most LV grids with the defined clusters. Finally, the characteristics of the grids within the clusters are analyzed to verify the cluster definitions.

1.2. Contributions of This Paper

In this paper, starting from the methods identified in the literature, as well as the identified LV grid topologies (see Section 1.3), a synthesis and assessment of the compatibility of these grids from the literature are conducted. The objective is to combine the characteristic parameters from different studies and define their ranges for potential clusters, assign real grid topologies to the clusters, and, as far as possible, validate the suitability of the clusters as comprehensive categories. The validation includes both the analysis of the topology and the inclusion of the energy supply as the primary purpose of the grids. With about 1200 real LV grid topologies and the real encompassing energy system, this validation is intended to set the foundation for the definition of representative LV grid topologies for the representation of the entire German LV grid. Studies from the literature mostly have specific foci. This work brings together the different approaches from various contexts and superimposes them such that the emerging representative LV grid clusters can be used in any application case.

1.3. Literature Review

The literature is split into two datasets of LV grids. First, it contains data sets of LV grids representing a specific group. For example, ref. [9] uses three different LV grids to describe rural LV grids. These representative grids are often designed specifically for a region, like [10] for the Continental United States, [11,12] for Italy, or [13–15] for Germany. These LV grids are called representative grids. Second, there are test feeders that do not represent a group. However, they are very similar to an average or typical grid. They can be used for research, such as new power-flow solution methods, or to analyze intelligent grid technologies [16]. Many of the test feeders are specifically designed for the US distribution network, like the IEEE distribution test feeders [16–18]. However, in the last ten years, several European test feeders were developed [19–21]. The critical difference between the two data sets is that the results of the analysis using distribution test feeders cannot be inferred back to real grids. This paper examines studies that create representative grids for Germany, primarily based on clustering.

The literature contains various approaches to clustering LV grids and forming synthetic grids based on greenfield approaches to create representative topologies. Depending on the available data, different methods are applied to develop clusters, which results in other challenges. The literature describes the procurement of grid data as a particularly relevant issue. It highlights that input data for appropriate clustering requires high diversity, e.g., to classify the differences between rural, suburban, and urban grids. In the following, seven selected projects are evaluated and discussed. The analysis includes the applied clustering methods, clustering parameters, and methods to derive a representative/reference grid for a cluster. These studies commonly create benchmark grids that represent specific parts of the German LV grid. However, there is a lack of international studies that generate representative and publicly available benchmarking grids.

1.3.1. Clustering Methods

The reviewed studies can be divided into four different clustering approaches listed in Table 1. The selection of the method for clustering LV grids in these studies mainly depends on the availability of data and the superordinate objective. Most studies applied k-means or hierarchical clustering algorithms to characterize and summarize LV grids. Hierarchical clustering was applied in [22] as well as [23], and it comprises algorithms that combine grids into clusters. In the first step, each grid is considered a cluster of its own, followed by the iterative combination of the most similar clusters. For the combination, the distance between the parameters of the clusters is used: the two clusters with the smallest distance to each other are merged into one cluster. When multiple grids belong to one cluster, the most minor, most significant, or the average distance to the different clusters can be used as an indicator [24]. This process is executed iteratively until a defined similarity threshold is reached. For example, ref. [22] evaluated several electrical parameters to cluster 271 LV grids with hierarchical classification. Ref. [23] focused on analyzing the impact of rising decentral PV generation on distribution grids, whereas [22] focused on the determination of resulting loads for the year 2030 using representative grid topologies.

The k-means algorithm was applied in [4,13,14], which aimed to derivate new planning and operation principles in distribution grids. The k-means algorithm is an iterative process, too. It divides grids into clusters by separating them according to selected characteristic parameters. Initially, the number of clusters has to be defined (k). Then, the algorithm randomly chooses centroids, which serve as beginning points for the clusters. In the following iterations, the positions of the centroids are optimized such that the range of values within a cluster is minimized, which results in them having as similar characteristics as possible. The algorithm halts its optimization when there is no more change in the position of centroids or after a defined number of iterations is reached.

Table 1. Overview of methods and resulting clusters employed in the analyzed literature.

Name of Method	Reference in Literature	Number of Analyzed Grids	Number of Clusters	Number of Reference Grids
k-means	[4]	7370	10	20
	[13]	0	6	6
Optical classification	[9]	86	3	7
	[25]	203	5	20
Hierarchical clustering	[22]	271	20	9
	[23]	331	6	12
Literature	[26]	0	9	5

The optical classification in [9,25] was applied with a focus on electrical and geographical characteristics. This method analyzes clusters according to their topological or geographical structure and assigns them to a cluster based on these characteristics. For example, ref. [9] evaluated electrical and topological parameters to categorize 86 real LV grids into three clusters with optical classification to analyze how each representative grid could accommodate PV while avoiding grid expansion.

Another way to identify clusters is to base them on the literature, e.g., principles of settlement structure design or grid planning. For example, in [26], the characteristic grid properties were based on the planning and operation of settlement structures. Ref. [26] also analyzed the effects of the PV ramp-up on LV grids, whereas the objective of [25] was the determination of the required grid expansion. As Table 1 highlights, there is a significant difference regarding the grid topologies serving as the data basis in these studies. Five studies considered real grid topologies of DSOs as a basis, whereby the number and types of grids differed greatly. Also, the diversity of the grids differed significantly according to their focus areas (e.g., rural, suburban, or urban areas). In addition to the number of grids, the number of parameters describing a grid differed between the studies.

1.3.2. Clustering Parameters

All four methods described in Section 1.3.1 have in common that they either characterize different clusters from a large set of grid parameters [4,13,22,23] or first identify important grid parameters according to the strategic selection from which clusters are subsequently derived [9,25,26]. The parameters considered in the studies were compared and analyzed to examine the key parameters that can reasonably describe and cluster LV grids. Table 2 lists the most relevant parameters/categories used for clustering in the individual studies.

Table 2. Parameters used for clustering in the reviewed literature.

Parameter/Category	Literature
Transformer rating	[9,23,25,26]
Line parameters	[22,23,26]
Number of GCP	[22,25]
Number of appartments per GCP	[4,26]
Distance to neighbor	[4,9,25,26]
Population density	[13,25,26]
Other	[9,13,23,25,26]

The literature shows no definite consensus across studies, as almost all consider "other" parameters for clustering grids. This results from the differences in the underlying databases of the respective studies (e.g., raster or topological data), the primary focuses of research, or the weighting of various clustering parameters. Despite the differences, the most common parameters across studies are the transformer rating and the distance to a neighbor.

The parameters/categories used in the literature to characterize clusters are described as follows:

- Transformer rating: the power level in kilovolt-amperes of the transformer connecting the LV and the medium voltage (MV) grid.
- Line parameters: topological parameters as the number of feeders connected to the transformer, maximum line length, average impedance, number of GCP per line, and average line length (all of these parameters are related to the structure of the grid).
- Number of GCPs: the number of GCPs connected to the transformer within the grid area.
- Number of apartments per GCP: the average number of apartments per GCP or the number of respective electric meters per GCP.
- Distance to a neighbor: the average distance between neighboring GCPs, the distance to the next four neighboring buildings, the distance to the fourth nearest neighboring building, or the number of GCPs per kilometer of grid lines.
- Population density: the density of the population per square km in the LV grid area.
- Other: other parameters, for example, the load boundary of the transformer, region of supply or the municipality, types of buildings, PV potential, degree of underground cables, total consumer resistance, maximum resistance, and cable material.

1.3.3. Methods to Design Reference LV Grids

In addition to defining and characterizing the clusters, the literature also pursues the selection or modeling of representative grid topologies. Different methods are applied to determine these characteristic grids, similar to the individual cluster approaches (compare Section 1.3.1). Within the reviewed literature, three techniques are employed to determine a representative LV grid for the clusters strongly oriented toward the respective input data. The most straightforward method for selecting a representative grid for clusters based on real grid topologies is to choose the grid of the input data that best represents the cluster. The representativeness is determined from the parameters underlying the cluster method, which are selected and weighted. For example, ref. [4] used "apartments per GCP" and "distance to a neighbor" as parameters to cluster grids and then chose the grid with the minimal distance of these parameters to the cluster centroid as a representative LV grid. Refs. [22,25] also used this method. With this approach, the results can vary, depending on which parameters are used for clustering. The more parameters are considered in the clustering process, the more conclusive the determined representative is. Similarly, other methods rely on real grid topologies but aim to create synthetic grids. Instead of considering the most average grid, these methods utilize average relevant parameters to create representative grids. This method was applied by [9,26]. It is essential to involve many grids because, otherwise, single extreme values can influence the result significantly. The third method used to build representative LV grids is expressed as the "green field approach". Synthetic topologies are approximated using suitable tools based on real operating and planning principles. An advantage of this method is that no real LV grids are required. For instance, ref. [13] uses open street maps as a data basis. According to ref. [27], however, when applying this method without accurate grid data, verifying the result's actual representativeness is impossible.

1.3.4. Key Results in the Literature

When analyzing the different clustering methods from the literature, the specific objective of the studies should be considered. Refs. [9,23,26] focused on the effects of a rising PV feed-in and their integration into the existing LV grids. The results show that the violation of the voltage bandwidth is the most occurring problem through the rise of PV plants in LV grids. The studies all proposed the use of reactive power control. Grid overloads due to high PV generation were only identified by [9] in about 50% of rural grids. Ref. [23] suggested further research regarding the impact of a grid-friendly operation of storage and generation plants. The study [4] intended to derive planning and operation principles. In addition to that, the focus of [4] was on urban grids, which are especially facing changes in load behavior through EVs and HPs. The authors suggested further research to analyze details of the effects of charging infrastructure for EVs and HPs, as well as the synergies between loads and decentral generation [4]. The study's [13] objective was also to derive planning and operation principles. The resulting grids do not represent the whole set of grids in Germany [13]. The objective of [25] was the identification of Swiss LV grid expansion requirements through reference grids. One of the results is a tool that allows a quick evaluation of the load limits, shape, and environment parameters of many grids by analyzing grid parameters. For an improved result, the author suggested using more grids. In [22], grid loads were to be determined based on representative grid topologies for a scenario in 2030. As the focus of the scenario was the integration of renewable energies, the authors suggested a further analysis of the load behavior, especially the charging infrastructure for EVs, uni- as well as bidirectional, with their effects on grid loads. Concerning the clustering of LV grids and the identification of representative LV grids, the literature is summarized in the following critical statements:

- Clustering methods: Different techniques can be applied, depending on the data basis and the objective of the clustering. The most common methods are hierarchical classification, optical classification, and k-means algorithms.
- Clustering parameters: The parameters used to describe LV grids vary a lot in the literature. The clustering process can focus on different parameters, whereby the choice significantly influences the resulting topologies.
- Methods to design reference grids: three different methods are applied to determine reference grids, whereby the choice of method primarily depends on the data basis.

These studies identified 59 clusters and 63 reference grids, from which 58 were published with their parameters (compare Table 1). Based on the study results and the identified research demands, this paper intends to synthesize and systematically enhance methods for clustering LV distribution grids.

2. Methods to Cluster and Analyze LV Grids

In the following, a method for the identification of meta-clusters based on the clusters from the literature is described. In this paper, a manual cluster approach was chosen. As the representative clusters in the referenced literature are correspondingly inhomogeneous in their descriptions of the respective clusters, an automated clustering of the studies classified as relevant was not possible due to the different approaches and databases. For example, the study [4] published numbers of the representative grids, ref. [9] published the average values of the cluster, and [23] described the typical range of the parameter from the cluster. The studies specified different parameters, some of which can only be compared to a limited extent. Subsequently, the procedure for validating the meta-clusters with accurate grid data and the following refitting and extension of the meta-clusters were specified. As the third step, the method for analyzing characteristics apart from the three key parameters was explained.

2.1. Identification of Meta-Clusters

In the reviewed literature (Section 1.3), a total of 79 LV reference grids were identified, of which 58 were selected for further analysis. The remaining grids were discarded because they either represented extreme grids or only a limited number of characteristics were available, preventing further processing. Furthermore, 18 technical and five geographical parameters were identified, of which the two most applied parameters were the "transformer rating" and the "distance to a neighbor". The transformer rating is strongly related to the amount and type of buildings connected to the grid. The number of inhabitants supplied via one transformer is also a decisive factor; e.g., an LV grid with many apartment buildings has a higher transformer rating than a grid with single-family houses. The transformer rating is scaled to analyze differences between clusters independent of the amount of GCP. The transformer rating per GCP was considered in six of the seven studies and published for 39 out of 58 reference LV grids. The other most applied parameter was the "distance of the buildings to a neighbor", which indicates the compactness of a settlement structure. The average grid distance (combined length of all lines divided by the number of GCP) was identified as a very similar parameter. In most cases, this enabled the calculation of the distance to the nearest neighbor, even without specific information in the published grids. Therefore, the average distance between GCPs could be calculated in 46 out of 58 representative LV grids. The literature highlights that these two parameters enable us to distinguish particular differences between rural LV grids. However, another parameter is necessary to allow for diversification to and between urban structures. The study [4] was the only analyzed project focusing on urban grids. This study applied the number of GCPs per line kilometer and the number of electricity meters per GCP to cluster grids. This indicates how many apartments and, thus, how many inhabitants live in each building, which enables a distinction between single-family houses and large apartment buildings. In combination with the distance to a neighbor, this parameter indicates the population density in an area. Thus, the amount of residential units per GCP provides a valuable indication regarding the degree of urbanization. The number of residential units per GCP was published in three of the seven studies with 38 reference grids. To deduct meta-clusters out of the 58 reference grids and cluster categories from the literature, mainly these critical parameters were analyzed and defined, as follows:

- Transformer rating per GCP: the transformer rating in kVA divided by the number of GCPs connected to the line under this transformer.
- Average distance to a neighbor: the distance in meters from one GCP to the next one.
- Average amount of residential/commercial units per GCP: the number of residential or commercial units connected to one GCP.

Two of the seven studies applied and published all three critical parameters of their clusters. Hence, 23 out of 58 reference grids were described with these parameters. To further deduct meta-clusters, the reference grids from the literature were merged into groups in five steps. Figure 2 gives an overview of the steps for calculating meta-clusters.

To standardize the categories from the literature, all 58 reference grids were compared manually. The first step focused on the 23 reference grids described using all three identified key parameters. Through manual classification, grids with similarities regarding these three key parameters were joined into clusters. For example, Figure 3 shows that reference grid B from [26] (green dot) was very similar to the reference grid NS-N14 C05 from [4] (red dot), and therefore, they were merged into one cluster.

Each cluster was then described by defining the ranges of the key parameters, resulting in three-dimensional cuboids. An exception in the merging process was the cluster "scattered settlement mixed-use area": none of the other grids from the literature merged into this cluster, described by all three key parameters. Nevertheless, its explicit description made a distinct aggregation possible, and the ranges for three parameters were defined. The first step results are initial groups with ranges of three key parameters.

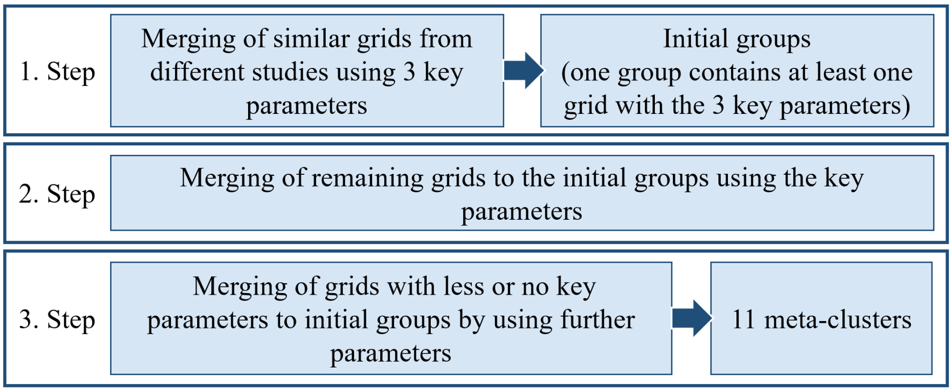

Figure 2. Steps for the deduction of meta-clusters.

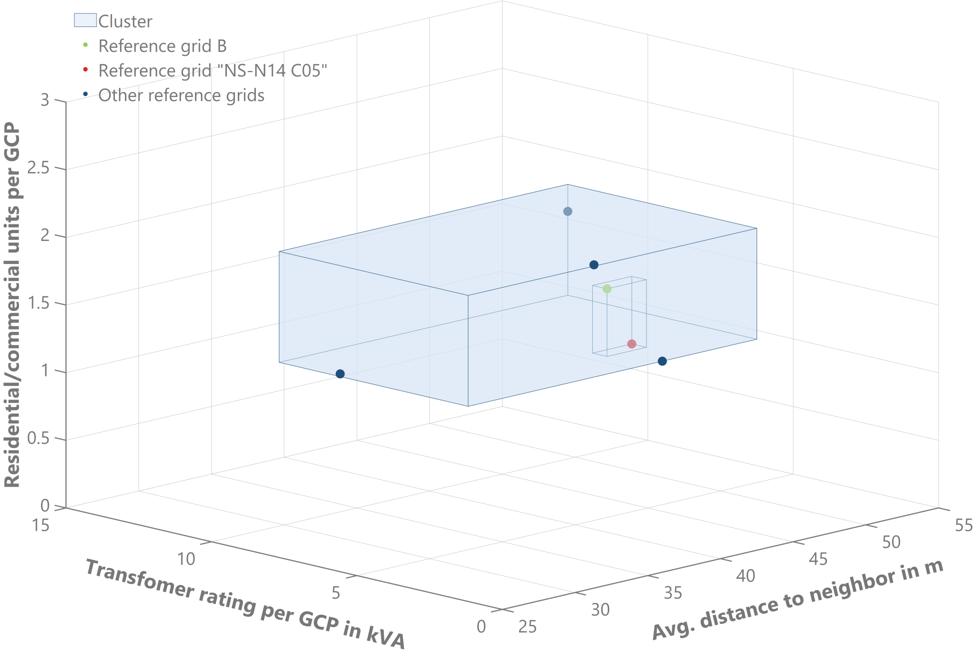

Figure 3. Assignment of reference grids from the literature to clusters through an iterative process.

In the second step, grids from the literature described by only one or two of the critical parameters were analyzed. Through a comparison of the fundamental parameter(s) with further available characteristics, these grids are assigned to the initial groups by comparing the individual parameters. In the example "village" and "hamlet" from [25], grids 4, 5, and 6 from [22], clusters 4, 5, and 6 from [23], and the "village" grid from [9] were merged with the defined meta-cluster "residential area with low-density B". Thus, the initial groups were supplemented with further grids.

Furthermore, to avoid a restriction of the characteristic diversity of the reference grids, particularly clusters with comparably wide ranges in the key parameters were re-examined. Comprehensive clusters were subdivided into individual clusters if at least one reference grid was defined by all critical parameters with a substantial deviation from the other grids in one key parameter. In the last step, the boundary values for the critical parameters of each cluster were reset under the following conditions:

- Clusters should not overlap in more than one key parameter.
- No gaps were permitted between key parameter ranges of neighboring clusters.
- Most clusters from the literature should fit into one cluster.

This process identified 11 meta-clusters and corresponding ranges for the key parameters. The exact distribution of these clusters and the step-by-step unification of the grids on which the clusters are based can be accessed in Appendix A. To validate the manually created meta-clusters and exclude an incorrect, non-representative definition of the clusters, in a fifth step, 1200 real LV grids were assigned to the meta-clusters (see Sections 2.2 and 3.2). An analysis of the result allowed seven further clusters to be defined. The grids within the resulting clusters were then analyzed and compared concerning their characteristics (see Sections 2.3 and 3.3).

2.2. Fitting of Real LV Grids in the Defined Meta-Clusters

To validate the 11 meta-clusters identified in Section 2.1, about 1200 real grids provided via a rural German DSO were classified within the meta-clusters. In the first instance, only 35% of the grids fit into the meta-clusters. As shown in Figure 4, most of the grids were scattered around the centroid (red dot) at an average distance to a neighbor of 30.6 m, with 1.4 residential/commercial units per GCP and a transformer rating per GCP of 9 kVA. Around the centroid, two major regions contained about 50% of all grids, which were not part of a meta-cluster. The first region was in the range of 20–30 m for the avg. distance to a neighbor, 1–2.5 residential/commercial units per GCP, and 4–10 kVA for the transformer rating per GCP. Within this space, 208 grids were allocated, which is why a new meta-cluster was defined. The second region was above a transformer rating per GCP of 10 kVA. Here, 94% out of 531 grids were not assigned to a meta-cluster. Since reference grids from the investigated studies with a high commercial share had a transformer rating per GCP above 30 kVA, it was reasonable to assume that these regions had a high commercial load share. To verify this hypothesis, the commercial load share was investigated as a function of the transformer rating per GCP. The commercial load share was determined to rise with the transformer rating per GCP. This trend suggests that a lot of grids primarily serve commercial customers. In addition, several grids are described as "mixed-use regions", covering the demands of residential and commercial regions with a moderate transformer capacity per GCP. To split residential, mixed-use, and commercial regions, the transformer values 15 kVA and 25 kVA were selected due to the strong increase in commercial share, as well as the fact that the proportion of the commercial load share respectively exceeded 30% and 50% at these values.

A deeper analysis of the grids with a transformer rating per GCP below 15 kVA and between 15 and 25 kVA revealed that the share of the commercial load rose with the distance to the next neighbor. As a result, grids with a primarily commercial load could be identified in the regions of a distance to the neighbor above 90 m and below a transformer rating per GCP of 15 kVA, as well as in the regions of an average distance to the neighbor above 60 m and a transformer rating per GCP between 15 and 25 kVA. Therefore, two further commercial meta-clusters were defined (commercial areas B and C). Furthermore, three meta-clusters with moderate commercial loads were identified, similar to the meta-cluster with lower transformer ratings per GCP (residential area with high-, medium-, and low-density). However, these had higher transformer ratings per GCP between 15 and 25 kVA. Table 3 lists the parameters of the resulting meta-cluster.

Figure 4. Representation of meta-clusters from the literature and the position of the about 1200 real grids in the three-dimensional parameter space.

Table 3. Meta-cluster from literature with white, redefined clusters and gray background.

ID	Cluster Name	Transformer Rating per GCP in kVA	Avg. Distance to Neighbor in m	Residential/ com. Units per GCP
1	Low-density residential area A	2–4	30–50	1–2.5
2	Low-density residential area B	4–10	30–50	1–2.5
3	Medium-density residential area A	2–4	20–30	1–2.5
4	Medium-density residential area B	4–10	20–30	1–2.5
5	High-density residential area	4–7	<20	1–2.5
6	Low-density multi-family residential area	8–18	35–70	5–9
7	Multifamily residential area A	2–10	30–50	2.5–5
8	Multifamily residential area B	>10	30–50	2.5–5
9	High-density multi-family residential area	8–18	15–35	5–9
10	Urban multifamily residential area	15–35	30–100	9–26
11	High-rise area	>35	>50	26–50
12	Scattered settlement mixed-use area	10–15	40–90	1–1.5
13	Low-density mixed-use area	10–25	30–50	1–2.5
14	Medium-density mixed-use area	10–25	20–30	1–2.5
15	High-density mixed-use area	10–25	<20	1–2.5
16	Commercial area A	>25	>0	0–5
17	Commercial area B	15–25	>60	0–5
18	Commercial area C	0–15	>90	0–5

2.3. Analysis of the Assigned Grids' Characteristics

To assess the quality of the defined meta-clusters, further parameters of the 1200 real LV grid topologies, which were assigned to the defined meta-clusters, were evaluated. This included the comparison of topological parameters, as well as the analysis of generation and consumption units connected to these grids. The grid topologies were prepared, plausibilized, and matched with real consumers and power generation units as part of a grid load analysis within [28] using the electric grid and energy system model for distribution grids "GridSim" [29]. This step included the processing and topographic intersection of GIS data and associated databases and their plausibility check. In this process, grids with several transformers, as their switching status could not be assigned, and grids without available apparent power were excluded. This also applied to grids with lines and grid connection points isolated from the busbar, which resulted in a significant decimation. Ref. [28] shows that the simulation results for the current state and future scenarios [3] were used to quantify and evaluate the meta-clusters.

In the first analysis, the distances of the centroids of the data were compared with the centroids of the meta-clusters (cuboid centroid—due to open upper limits, a calculation was not possible for commercial clusters (A, B, and C), multifamily residential area B, and the high-rise area) in a three-dimensional space over the defined parameters. The exact coordinates of the three characteristics are listed in Table A9 for each meta-cluster and used as reference values for comparison when possible. The analysis indicated that, especially in meta-clusters with a large number of grids characterized by them, the centers of the data showed minimal deviations from the centers of the cuboids. The amount of grids classified in the meta-clusters also confirmed the regional rural focus of the DSO providing the data. Urbanized grids with many residential and commercial units per GCP were almost absent from the dataset. They, therefore, were not considered for further analysis (only meta-clusters with at least 20 grids were considered).

The analysis of the characteristics of grids in the respective meta-clusters was conducted by statistically evaluating various parameters and comparing them with each other and all available grids. This analysis aimed to identify and confirm characteristic patterns from the grid data, which substantiated the classification into the respective meta-clusters. This included the evaluation of the grid dimensioning by comparing the total grid size and the number of feeders and GCPs, as well as the generation and consumption units located therein, by comparing the energy consumption of residential/commercial units and the electric heat supply.

3. Results of the Clustering and Grid Analysis Process

This chapter describes and classifies the analysis results for clustering LV distribution grids. This includes the evaluation of the literature and the process of fitting real LV grid topologies into meta-clusters.

3.1. Results of the Meta-Cluster Development

Eleven meta-clusters were deducted using the method described in Section 2.1. The ranges of their key parameters are shown in Figure 5 as blue cuboids in the three-dimensional space of the key parameters. Overall, the transformer rating per GCP ranged from 2 to over 35 kVA. The average distance between two GCPs ranged from 15 to 35 m in the most densely covered cluster and up to 100 m in the most dispersed cluster. The number of consumers per GCP varied between 1 and 50. The meta-cluster "low-density residential area B", for example, was built upon three representative grids, all described by the three key parameters, and eight further grids that were described with one or two key parameters. The structure of the supply area of this meta-cluster can be described as suburban, with predominantly single-family houses. From the average distance between two GCPs of 30 to 50 m, it could be deduced that the settlement density was rather distributed. The share of commercial customers was meager, as the primary objective was the coverage of the energy consumption of residential units. The transformer rating per GCP for this meta-cluster was between 4 and 10 kVA and, therefore, rather low.

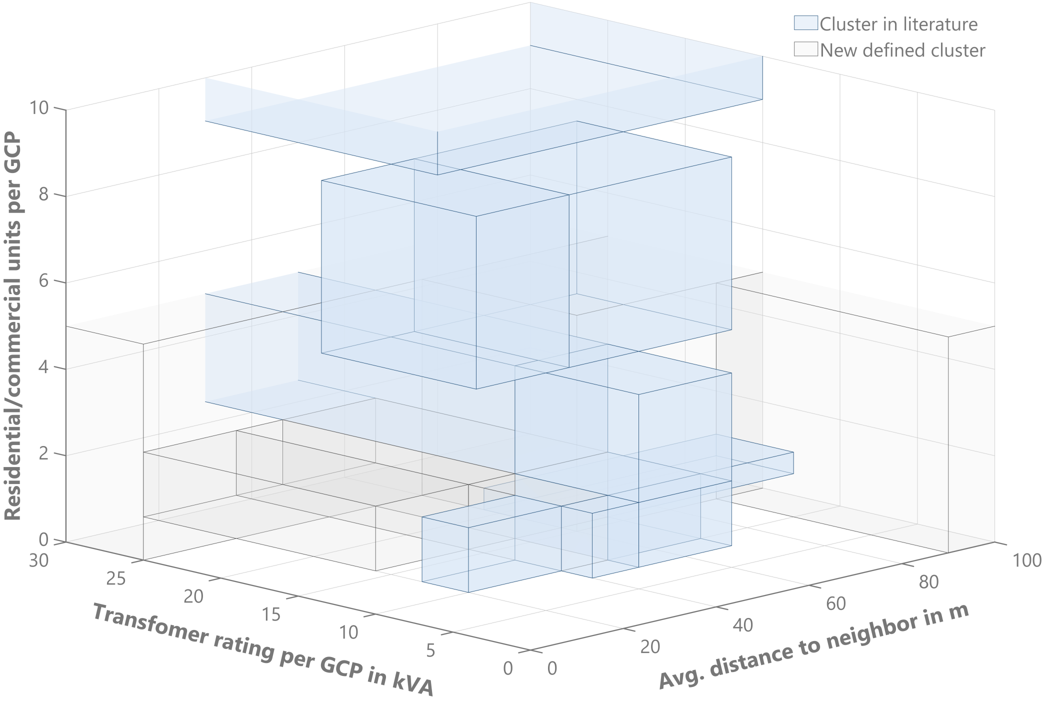

Figure 5. Excerpt of meta-clusters in three-dimensional parameter space.

3.2. Results of the Fitting of Real LV Grids into Meta-Clusters

Seven new meta-clusters were created by combining categories from the literature with the analysis of more than 1200 real LV grids. These are listed in Table 3 in gray rows. The added meta-clusters describe mixed and commercial areas in particular. Through these additional meta-clusters, over 88% of the real LV grids could be assigned to the meta-clusters. Table A9 highlights the number of real LV grids categorized by each meta-cluster. It is evident that most of the grids are classified in rural meta-clusters covering the energy demand of one-to-two-family house settlements. This matched the expected pattern, as these real grids originated from a DSO with a predominantly rural service area. This was confirmed according to the deficient number of grids in clusters containing multifamily house settlements. The meta-clusters with mixed supply functions (residential and commercial units) represent a moderate number of real grids. The extent to which the topological dimensions and energy consumption of the real grids fit this classification is analyzed in the following chapter.

3.3. Characteristics of the Grids Assigned to the Meta-Clusters

The comparison of the topological characteristics is intended to clarify the extent to which the grids assigned to the meta-clusters differ categorically. Figure 6 statistically highlights the differences in aggregate line lengths in the different meta-clusters. This first evaluation already indicates that the classification of the grids into the corresponding meta-clusters succeeded. It confirms the hypothesis that the size of the buildings and the supply task (the supply of residential and commercial units) have a considerable impact on the dimensions of the grid. Residential areas that primarily supply one- to two-family houses are significantly larger in dimension than grids that either provide more significant residential buildings or cover the energy consumption of a limited amount of commercial units. An analysis of the feeders in Figure A1 shows that, in meta-clusters whose primary objective is the coverage of residential units, a higher amount of feeders is present (ID 1–5 and 7–8), which decreases over grids of mixed-use clusters (ID 12–15) down to the commercial meta-clusters (ID 16–17). A comparable situation emerged from the analysis of the number of GCPs per grid (compare Figure A2). When taking into account the transformer rating (compare Figure A3), it is evident that grids with a low number of commercial units (ID 16) were also assigned to the appropriate meta-cluster. The small proportion of GCPs with a high transformer rating indicates that the primary consumption originated from a limited amount of commercial units and that a dedicated supply area and a dedicated transformer were explicitly installed for these units.

An analysis of the cumulative energy consumption normalized to the GCP showed a reasonably homogeneous spread across the grids of all meta-clusters (compare Figure A4). The greatest deviation was evident in small commercial grids (ID 16) and compact multi-family residential areas (ID 7–8). A closer examination of the specific energy consumption showed again that grids that were classified in meta-clusters whose primary task was to supply residential units had correspondingly higher residential unit energy consumption (compare ID1–5 and 7–8 in Figure A5). This also decreased across the mixed-use (ID 12–15) down to the commercial meta-clusters (ID 16–17), although a review of the specific commercial consumption revealed a contrary pattern (compare Figure A6). An analysis of the electrical heat supply revealed an almost homogeneous pattern with a slight tendency towards grids that have been assigned to clusters whose primary supply task is to cover the energy consumption of one- and two-family houses (ID 1–5) (compare Figure A7). This corresponds to the expected tendency but clarifies that, even in the one- and two-family houses suitable for electric heat supply, considerable potential remains, e.g., the development of HPs. An evaluation of the installed capacity of rooftop PV systems in Figure A8 also indicates the expected pattern. Grids in the clusters with primarily one- and two-family houses had an expectedly higher PV capacity than the grids in clusters with larger residential buildings (ID 7–8). This is explained by the easily accessible roof areas of one-/two-family houses, which are connected in larger numbers (compare GCPs in Figure A2) in the grids of the meta-clusters (ID 1–5).

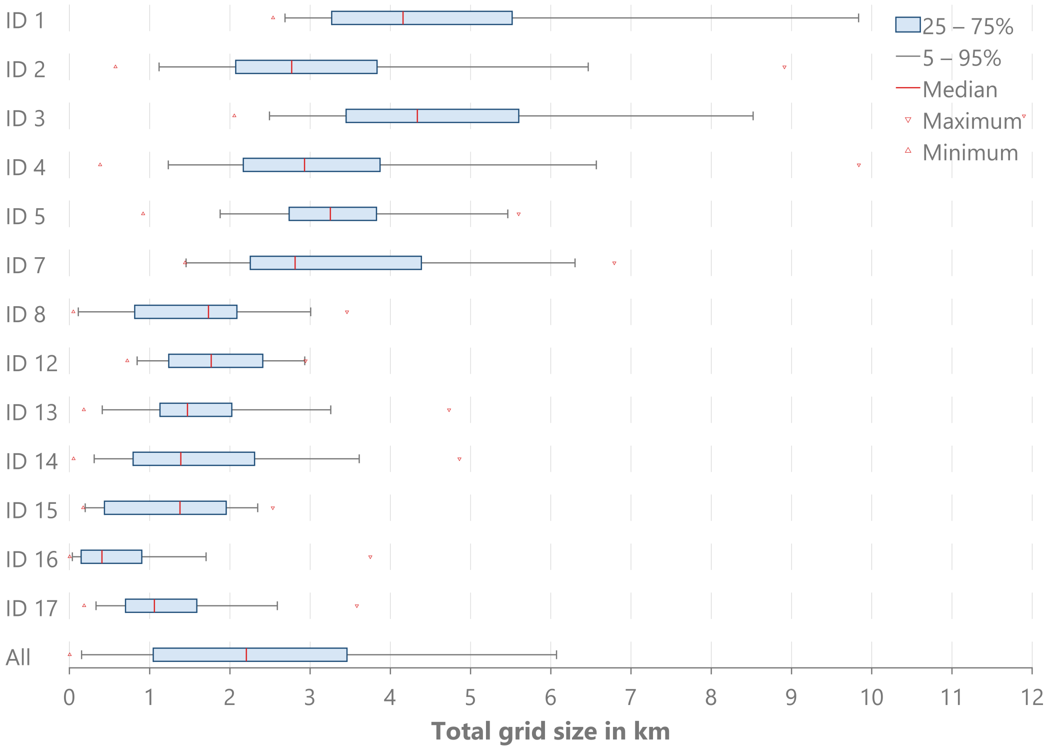

Figure 6. Statistical evaluation of the total line length of all grids in the different meta-clusters in km.

The statistical evaluation of the grids classified into the different meta-clusters confirmed the classification of the meta-clusters. The topological structure of grids in meta-clusters with the primary task of supplying one and two-family houses (ID 1–5) was verified through expected patterns in the dimensions of the grids (total line length, number of feeders and GCPs), the average residential unit consumption, and high installed PV and electric heating capacities. Grids assigned to meta-clusters with supply tasks for large residential buildings (ID 7–8) also confirmed their classification with high residential unit consumption and transformer ratings per GCP, as well as low installed PV power. Grids allocated to commercial meta-clusters (ID 16–17) showed a high transformer rating per GCP, high commercial consumption, and a low number of feeders, confirming the expected pattern. Also, almost all analyzed parameters of the statistical range of grids assigned to mixed-use meta-clusters (ID 12–15) ranged statistically between residential and commercial meta-clusters. Overall, this statistical analysis confirmed that the grids set to the meta-clusters via the three parameters corresponded to their meta-clusters’ definitions and the expected patterns.

4. Conclusions and Critical Review

In the following, the results of this paper are summarized, and the research questions are answered. Furthermore, a critical review of the results and options for improving the results, as well as an outlook on further remaining research options, is given.

4.1. Conclusions

This paper has investigated seven studies about the clustering and identification of representative LV grids, and their results were consolidated into meta-clusters. In the literature, a distinction can be made among four superordinate approaches: “hierarchical clustering”, “k-means algorithms”, “optical classification”, and “literature classification”. The key parameters “transformer rating”, “average distance to a neighbor”, and “the average amount of residential/commercial units per GCP” were identified as the most ordinary and, therefore, most suitable for a concrete description of the grid area. These key parameters were used to define 11 meta-clusters from the literature. Furthermore, the resulting meta-clusters were verified using data from over 1200 real LV grids. This led to the identification of further clusters, which bridged the gaps between the clusters from the literature, resulting in 18 meta-clusters describing LV distribution grids. These clusters covered the range of grids from rural to urban regions, focusing on residential and commercial supply tasks in different-sized building types. The seven meta-clusters defined through the analysis of real grids and their allocation to the meta-clusters from the literature represent primarily commercial and mixed areas. Thus, there seems to be a lack of research regarding these supply areas. After definition, 88% of the actual grid topologies could be assigned to the clusters. Parameters other than the three key parameters were analyzed and compared to validate the result. For example, the energy consumption normalized to the GCP, the total line length, or the PV penetration was analyzed. The results confirm the validity of the definition of the meta-clusters. In addition to the analysis of clusters, the options for the identification of a representative grid for a cluster were analyzed in the literature. However, a grid that is part of a cluster can be identified as a representative, e.g., the one closest to the centroid. Another option is to define a representative grid by using the mean values from the characteristics of all the cluster grids. The third option is to use the green-field approach, which relies on operating and planning principles to approximate the grid topology.

4.2. Critical Review

It is important to note that the quality of the results relies strongly on the quality of the input data utilized in this process. The grids were prepared and validated extensively, ensuring that they represent real grids with a high probability. Nevertheless, these grids represent only a model of reality, which is dynamically changed in real grid operation, e.g., due to different switch positions. Although the results show the validity of the definition of the clusters for LV grids, several options exist to improve the selection. For example, the 1200 real grid topologies applied to verify and extend the meta-clusters represent rural/small-town areas. This is a distinct limitation of this publication, and therefore, the validation should be extended using data from further DSOs. Another limitation regarding this dataset is that it is from only one DSO, which excludes possible differences in local grid planning principles. The diversity of LV grids resulting from different approaches to grid planning and operation was, thus, not considered. In this context, particular attention should be devoted to urban topologies where grids can be operated in a meshed configuration. In general, the categorization of grids according to the supply task based on the identified key parameters shall remain valid, but meshed grid operation results in lower voltage drops, which makes it possible to dimension the strings differently. The derivation of subcategories within the urban clusters into meshed and unmeshed grid topologies could comprehensively represent the topological diversity of LV grids. A further uncertainty is the missing consideration of the energy system, which incorporates the grids when defining the cluster categories. The electric load can differ significantly between regions, although the geographical or structural parameters are similar. Furthermore, the federal states in Germany follow different timelines, e.g., to reach carbon neutrality or the roll-out of a public charging infrastructure. The resulting local ramp-up of PV-systems and flexible consumers, such as electric vehicles or heat pumps, will also potentially impact the grid planning principles with which the various DSOs dimension their grids. Thus, when applying the reference grids according to geographical and structural parameters, local framework conditions should be considered in assigning the electric load to the grid representatives.

Generally, the clustering of LV distribution grids still has considerable potential for optimization, which is primarily limited due to the unavailability of data. The clustering approach adopted in this paper is certainly not the solution for a comprehensive, overall representation of the German low-voltage grid, but it does constitute a first attempt in this direction. The selected clustering approach cannot be directly reproduced using automated algorithms, as various auxiliary conditions are necessary for this. Complementing the methods applied in this publication with a quantitative, data-based approach represents the next logical stage in eliminating the main limitations inherent in this publication, and it will thus contribute to the verification of the clusters.

4.3. Outlook

The results of this paper provide a solid basis for further studies. After improving the validation with data from further DSOs (see Section 4.2), the subsequent step is the determination of representative grids for each identified cluster. This enables simulation results for possible scenarios and grid operation mechanisms to be applied holistically for further regions. Hence, grid expansion needs or grid operation mechanisms to prevent or delay these can be identified for each reference grid. The results indicate future improvement needs for real LV grids assigned to this representative grid's cluster. Furthermore, the distribution of the clusters across Germany is a relevant examination. The possibility of classifying all of Germany into clusters, e.g., by geographical allocation, would enable the scaling of the simulation results of representative grids. Relevant indicators such as grid expansion costs or possible savings through intelligent load management could be approximated nationally.

Author Contributions: Conceptualization, A.W., E.W. and M.H.; methodology, A.W., E.W. and M.H.; software, M.H.; validation, A.W.; formal analysis, M.H.; investigation, A.W., E.W. and M.H.; resources, A.W. and E.W.; data curation, M.H.; writing—original draft preparation, A.W., E.W. and M.H.; writing—review and editing, A.W., E.W. and M.H.; visualization, E.W. and M.H.; supervision, A.W. and A.P.; project administration, A.W. and E.W.; funding acquisition, E.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was conducted as part of the activities of the Forschungsstelle für Energiewirtschaft e.V. (FfE) in the project "unIT-e^2—living lab for integrated e-mobility" (orig. "unIT-e^2—Reallabor für verNETZte E-Mobilität"). The project is funded by the Federal Ministry of Economic Affairs and Climate Action (BMWK) (funding code: 01MV21UN11).

Data Availability Statement: As part of this publication, factsheets were created for the respective clusters, which describe the characteristics of each cluster. This additional material was published on the website of FfE: https://www.ffe.de/veroeffentlichungen/beitragsreihe-zur-charakterisierung-von-niederspannungsnetzen-identifikation-von-netzclustern/ (latest access on 22 August 2024). In addition, reference grids were developed for each cluster, and their factsheets were also published on the FfE's website: https://www.ffe.de/veroeffentlichungen/beitragsreihe-zur-charakterisierung-von-niederspannungsnetzen-und-netzrepraesentanten-identifikation-von-referenznetzen-fuer-die-cluster/ (latest access on 22 August 2024). The computable node-edge models were published through gitlab in the OpenDSS standard: https://gitlab.com/ffe-munich/reference-low-voltage-grids (latest access on 22 August 2024).

Conflicts of Interest: The authors do not have any conflicts of interest that could have impacted the content presented in this paper. The authors Andreas Weiß, Elisabeth Wendlinger and Maximilian Hecker were employed by the company Forschungsstelle für Energiewirtschaft e.V. (FfE). The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. In addition, no actions were performed that could be considered ethically problematic since the analyzed data are non-personalized.

Abbreviations

The following abbreviations are used in this manuscript:

DSO	distribution system operator
EV	electric vehicle
GCP	grid connection point
HP	heat pump
LV	low-voltage
MDPI	Multidisciplinary Digital Publishing Institute
MV	medium voltage
PV	photovoltaic system

Appendix A. Unification of Cluster-Based Grids

The step-by-step unification of the grids on which the clusters are based was performed in four major steps:

1. Merging of grids with all three key parameters.
2. The merging of grids with fewer than three key parameters.
3. Splitting clusters with wide ranges in comparison to other clusters.
4. Adjusting the ranges of key parameters (adjustments about adjacent clusters).

Table A1. Unification of cluster-based grids for clusters 1 and 2.

Step	Grids	Avg. Trans-Former Rating per GCP in kVA	Avg. Range to Neighbor per GCP in m	Residential/ com. Units per GCP
1.	[4] C05 N11 [4] C10 N13 [4] C05 N14 [4] C05 N15 [4] C05 N17 [26] Cluster B	2.8–9.3	28.3–48.1	1.3–2.1
2.	[9] “Dorf” [22] Grid 4 [22] Grid 5 [22] Grid 6 [23] C04 [23] C06 [25] “Weiler” [25] “Dorf”	2.8–10.5	28.3–49	1–2.1
3.	[4] C10 N13 [4] C05 N14 [4] C05 N15 [9] “Dorf“ [22] Grid 4 [22] Grid 5 [22] Grid 6 [23] C04 [25] “Weiler” [25] “Dorf”	4.4–10.5	28.3–48.1	1–1.9
	[4] C05 N11 [4] C05 N17 [23] C06 [26] Cluster B	2.8–3.9	37.1–49	1.3–2.1
4.	Cluster 1	4–10	30–50	1–2.5
	Cluster 2	2–4	30–50	1–2.5

Table A2. Unification of cluster-based grids for cluster 3.

Step	Grids	Avg. Trans-Former Rating per GCP in kVA	Avg. Range to Neighbor per GCP in m	Residential/ com. Units per GCP
1.	[4] C06 N06 [4] C10 N10 [4] C06 N20 [26] Cluster C	2.6–3.3	15–26.7	0.7–2.6
2.	[13] Cluster L01 [13] Cluster L02	2.5–3.4	14.8–26.7	0.7–2.6
3.	—	—	—	—
4.	Cluster 3	2–4	20–30	1–2.5

Table A3. Unification of cluster-based grids for cluster 5.

Step	Grids	Avg. Trans-Former Rating per GCP in kVA	Avg. Range to Neighbor per GCP in m	Residential/ com. Units per GCP
1.	[4] C08 N08 [26] Cluster D	4.1–6.4	15–20	1.4–2.3
2.	[9] “Vorstadt” [13] Cluster H [13] Cluster S [26] Cluster E	4.1–6.4	9.7–20	1.2–2.3
3.	—	—	—	—
4.	Cluster 5	4–7	<20	1–2.5

Table A4. Unification of cluster-based grids for clusters 7 and 8.

Step	Grids	Avg. Trans-Former Rating per GCP in kVA	Avg. Range to Neighbor per GCP in m	Residential/com. Units per GCP
1.	[4] C05 N05 [4] C05 N16 [4] C05 N18 [4] C05 N19	3.5–43.2	34.1–46.8	2.5–4.2
2.	[22] Grid 1	3.5–43.2	34.1–46.8	2.5–4.2
3.	[4] C05 N05 [4] C05 N16 [4] C05 N19	11.4–43.2	34.1–46.8	2.5–3.8
	[4] C05 N18	3.5	34.1	4.2
4.	Cluster 7	2–10	30–50	2.5–5
	Cluster 8	>10	30–50	2.5–5

Table A5. Unification of cluster-based grids for clusters 6 and 9.

Step	Grids	Avg. Trans-Former Rating per GCP in kVA	Avg. Range to Neighbor per GCP in m	Residential/com. Units per GCP
1.	[4] C01 N01 [4] C04 N04	10–15.8	30.8–51.1	6.1–8.8
2.	[26] Cluster F [25] "Kleinst."	10–15.8	25–51.1	6.1–8.8
3.	[4] C04 N04	10	51	6.1
	[4] C01 N01 [26] Cluster F [25] "Kleinst."	15–15.8	25–30.8	8.5–8.8
4.	Cluster 6	8–18	35–70	5–9
	Cluster 9	8–18	15–35	5–9

Table A6. Unification of cluster-based grids for cluster 10.

Step	Grids	Avg. Trans-Former Rating per GCP in kVA	Avg. Range to Neighbor per GCP in m	Residential/com. Units per GCP
1.	[4] C07 N07 [4] C09 N09 [4] C07 N12 [26] Cluster H	13.8–27.3	30–97.3	9.2–16.8
2.	—	—	—	—
3.	—	—	—	—
4.	Cluster 10	15–35	30–100	9–26

Table A7. Unification of cluster-based grids for cluster 11.

Step	Grids	Avg. Trans-Former Rating per GCP in kVA	Avg. Range to Neighbor per GCP in m	Residential/com. Units per GCP
1.	[4] C02 N02	40	104.2	38.2
2.	[26] Cluster H	40–67	104.2	38.2–41
3.	—	—	—	—
4.	Cluster 11	>35	>50	26–50

Table A8. Unification of cluster-based grids for cluster 12.

Step	Grids	Avg. Trans-Former Rating per GCP in kVA	Avg. Range to Neighbor per GCP in m	Residential/ com. Units per GCP
1.	—	—	—	—
2.	[9] "Land" [13] Cluster L03 [22] Grid 8 [26] Cluster A [25] "Streusied."	10–12.5	43.1–87	1.3–1.5
3.	—	—	—	—
4.	Cluster 12	10–15	40–90	1–1.5

Appendix B. Comparison of Representative to Represented Grids

Table A9. Position of the cuboid and data centroids of the meta-clusters in the three-dimensional parameter space.

ID	Grids	Centr. Type	Avg. Trans-Former Rating per GCP in kVA	Avg. Range to Neighbor per GCP in m	Residential/ com. Units per GCP
1	43	Cuboid Data	3.00 3.28	40.00 33.78	1.75 1.59
2	157	Cuboid Data	7.00 6.67	40.00 36.39	1.75 1.52
3	100	Cuboid Data	3.00 3.20	25.00 24.44	1.75 1.47
4	208	Cuboid Data	7.00 6.45	25.00 24.82	1.75 1.52
5	51	Cuboid Data	5.50 5.27	10.00 17.84	1.75 1.59
6	4	Cuboid Data	13.00 11.07	52.50 37.45	7.00 5.69
7	20	Cuboid Data	6.00 7.18	40.00 35.11	3.75 3.10
8	23	Cuboid Data	40.00 37.37	— 38.92	3.75 3.68
9	3	Cuboid Data	13.00 14.32	25.00 27.16	7.00 6.88
10	3	Cuboid Data	25.00 24.88	65.00 39.03	17.50 11.51
11	0	Cuboid Data	— —	— —	38.00 —
12	22	Cuboid Data	12.50 12.97	65.00 56.64	1.25 1.19
13	82	Cuboid Data	17.50 15.82	40.00 38.47	1.75 1.48
14	58	Cuboid Data	17.50 15.41	25.00 25.32	1.75 1.50
15	22	Cuboid Data	17.50 16.13	10.00 16.92	1.75 1.48
16	220	Cuboid Data	— 103.70	— 73.17	2.50 1.56
17	48	Cuboid Data	20.00 20.30	— 92.23	2.50 1.34
18	9	Cuboid Data	7.50 11.88	— 109.93	2.50 1.35

Appendix C. Statistical Evaluation of Key Grid Parameters

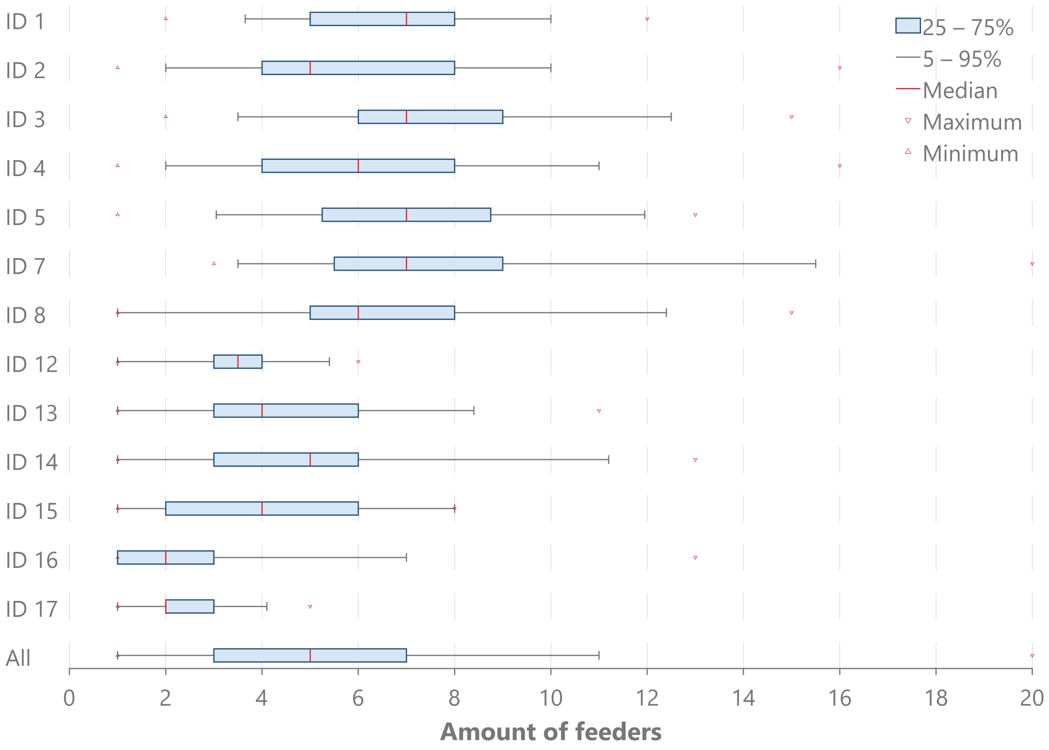

Figure A1. Statistical evaluation of the amount of feeders per grid in the different meta-clusters.

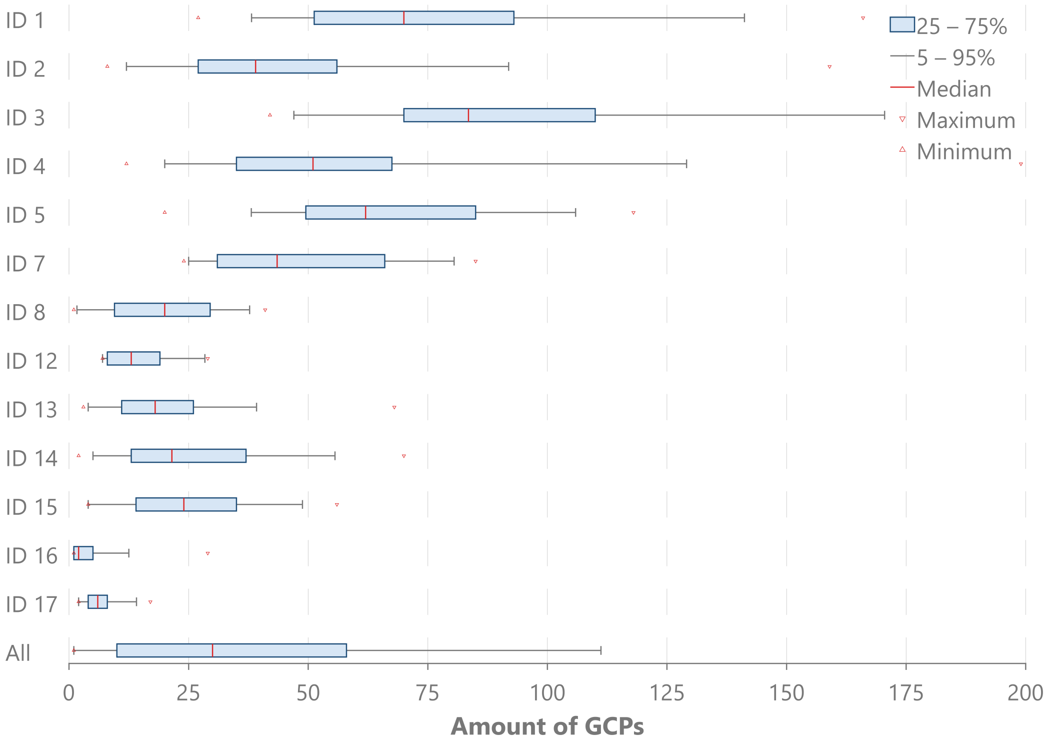

Figure A2. Statistical evaluation of the amount of GCPs per grid in the different meta-clusters.

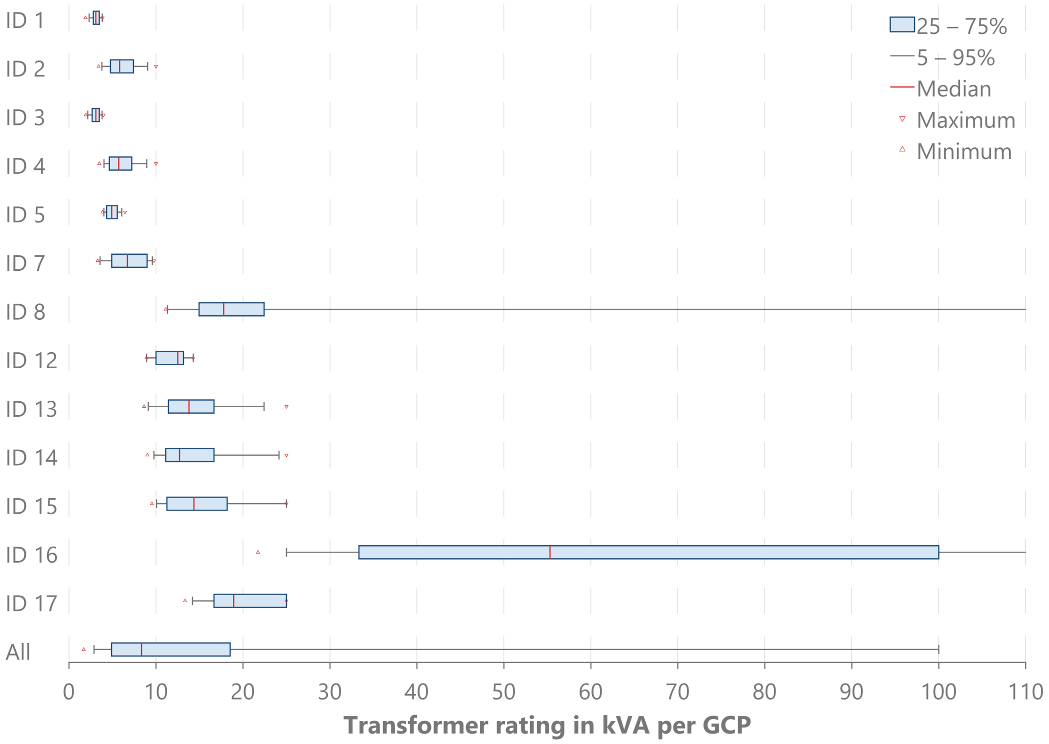

Figure A3. Statistical evaluation of the transformer rating per GCP in the different meta-clusters in kVA.

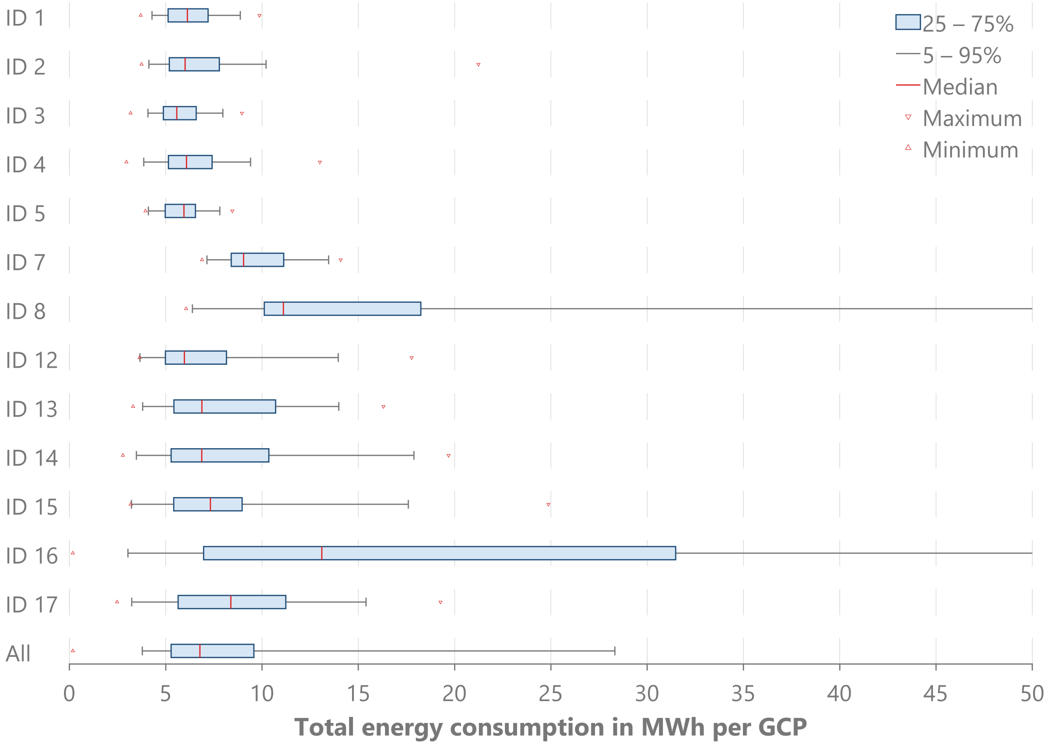

Figure A4. Statistical evaluation of the total annual energy consumption per GCP in the different meta-clusters in MWh.

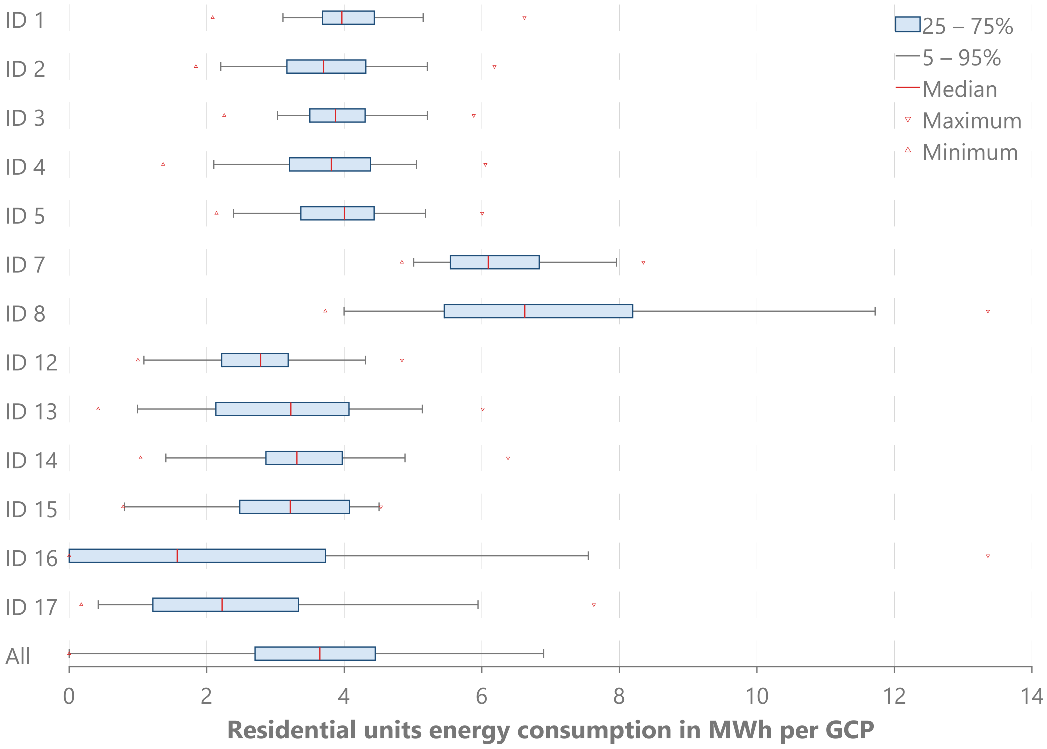

Figure A5. Statistical evaluation of the residential units' annual energy consumption per GCP in the different meta-clusters in MWh.

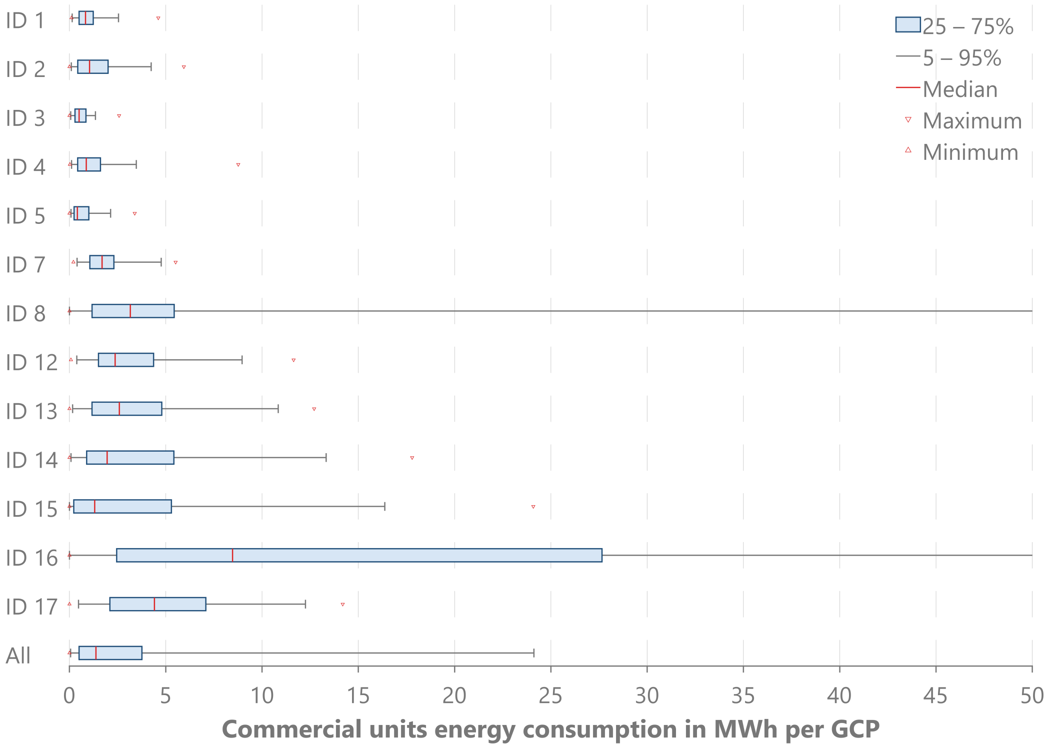

Figure A6. Statistical evaluation of the commercial units' annual energy consumption per GCP in the different meta-clusters in MWh.

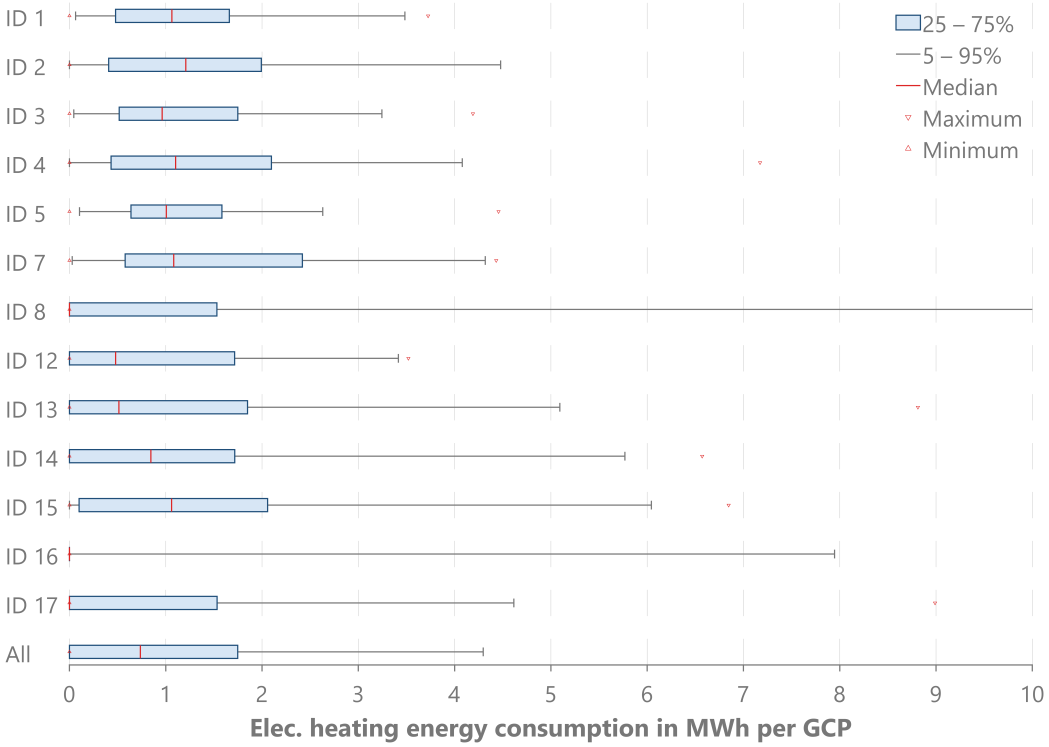

Figure A7. Statistical evaluation of the electric heating annual energy consumption per GCP in the different meta-clusters in MWh.

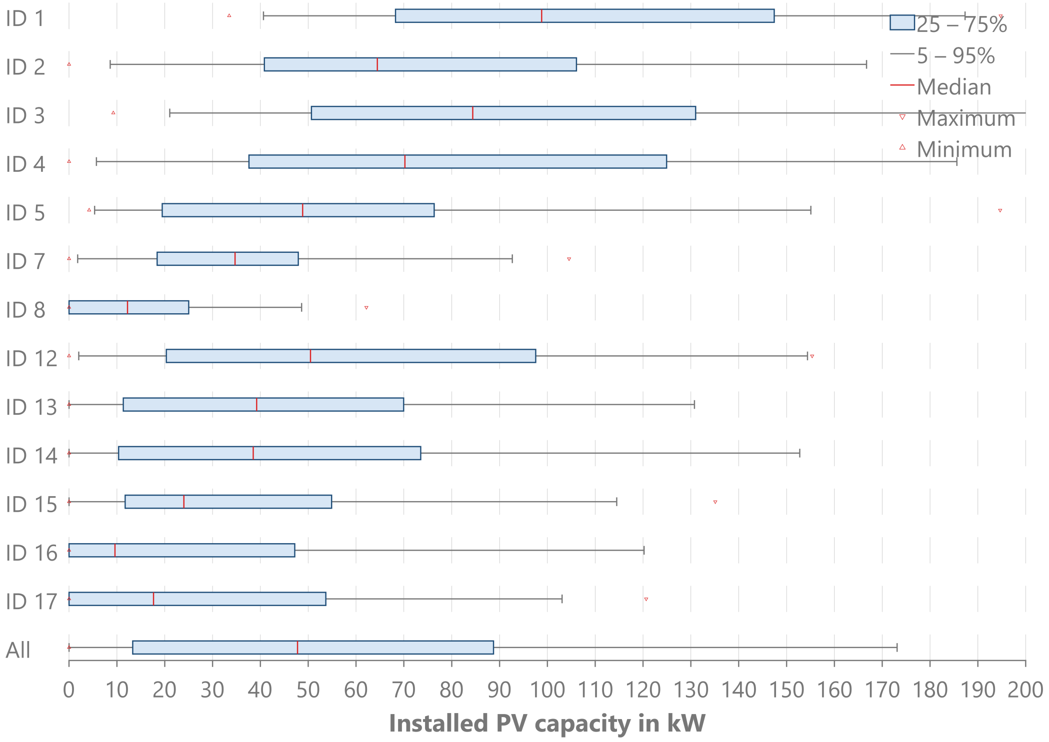

Figure A8. Statistical evaluation of the installed PV capacity per grid in the different meta-clusters in kW.

References

1. Federal Government of Germany: German Law for the Expansion of Renewable Energies (German Renewable Energy Sources Act—EEG 2023). Available online: https://leap.unep.org/en/countries/de/national-legislation/renewable-energy-sources-act-eeg-2023 (accessed on 22 August 2024).
2. Federal Network Agency of Germany (BNetzA): EEG in Zahlen. Available online: https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/ErneuerbareEnergien/EE-Statistik/start.html (accessed on 22 August 2024).
3. Müller, M. Future grid load with bidirectional electric vehicles at home. In Proceedings of the International ETG Congress, Online, Kassel, Germany, 10 June 2021.
4. Wintzek, P.; Ali, S.; Monscheidt, J.; Gemsjäger, B.; Slupinski, A.; Zdrallek, M. Planungs- und Betriebsgrundsätze für städtische Verteilnetze—Leitfaden zur Ausrichtung der Netze an ihren zukünftigen Anforderungen. In *Neue Energie aus Wuppertal, Band 35*; Zdrallek, M., Ed.; University of Wuppertal: Wuppertal, Germany, 2021.
5. Weiß, A. Simulation and analysis of future electric mobility load effects in urban distribution grids. In Proceedings of the International ETG Congress, Online, Kassel, Germany, 10 June 2021.
6. Greif, S.; Freiberger, L.; Corradini, R.; Trentmann, L.; Schenk, W. Wärmepumpen in Bestandsgebäuden—Möglichkeiten und Herausforderungen im Eigenheim. In *Wärmepumpen in Bestandsgebäuden—Möglichkeiten und Herausforderungen im Eigenheim*; Wüstenrot Stiftung: Munich, Germany, 2022; ISBN 978-3-96075-027-7.
7. Federal Network Agency of Germany (BNetzA): Monitoringbericht 2023—Marktbeobachtung. Available online: https://data.bundesnetzagentur.de/Bundesnetzagentur/SharedDocs/Mediathek/Monitoringberichte/MonitoringberichtEnergie2023.pdf (accessed on 12 August 2024).
8. *VDE-AR-N 4100*; Technische Regeln für den Anschluss von Kundenanlagen an das Niederspannungsnetz und deren Betreib (TAR Niederspannung). Ausgefertigt am 2017-04, Version vom 2017-06. VDE Verband der Elektrotechnik Elektronik Informationstechnik e. V.: Berlin, Germany, 2017.
9. Kerber, G. Aufnahmefähigkeit von Niederspannungsverteilnetzen für die Einspeisung aus Photovoltaikkleinanlagen. Doctoral Thesis, Technical University of Munich, Munich, Germany, 2011.
10. Schneider, K.P.; Chen, Y.; Engle, D.; Chassin, D. A Taxonomy of North American radial distribution feeders. In Proceedings of the 2009 IEEE Power & Energy Society General Meeting, Calgary, AB, Canada, 26–30 July 2009. [CrossRef]
11. Pilo, F.; Pisano, G.; Scalari, S.; Dal Canto, D.; Testa, A.; Langella, R.; Caldon, R.; Turri, R. ATLANTIDE—Digital archive of the Italian electric distribution reference networks. In Proceedings of the CIRED 2012 Workshop: Integration of Renewables into the Distribution Grid, Lisbon, Portugal, 29–30 May 2012. [CrossRef]
12. Bracale, A.; Caldon, R.; Celli, G.; Coppo, M.; Dal Canto, D.; Langella, R.; Petretto, G.; Pilo, F.; Pisano, G.; Proto, D.; et al. Analysis of the Italian distribution system evolution through reference networks. In Proceedings of the 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Berlin, Germany, 14–17 October 2012. [CrossRef]
13. Meinecke, S.; Drauz, S.; Bornhorst, N.; Spalthoff, C.; Lauven, L.-P.; Cronbach, D.; Menke, J.-H.; Kneiske, T.; Braun, M.; Klettke, A.; et al. *SimBench—Elektrische Benchmarkmodelle*; Universität Kassel: Kassel, Germany; Fraunhofer IEE: Kassel, Germany; RWTH Aachen University: Aachen, Germany; Technical University of Dortmund: Dortmund, Germany, 2019.
14. Weisenstein, M.; Wellßow, W.; Ma, H.; Reis, L. Synthetic LV-Grid Models for Scientific Investigations. Available online: https://nbn-resolving.de/urn:nbn:de:hbz:386-kluedo-67555 (accessed on 1 February 2023).
15. Meinecke, S.; Sarajlić, D.; Drauz, S.R.; Klettke, A.; Lauven, L.-P.; Rehtanz, C.; Moser, A.; Braun, M. SimBench—A Benchmark Dataset of Electric Power Systems to Compare Innovative Solutions Based on Power Flow Analysis. *Energies* **2020**, *13*, 3290. [CrossRef]
16. Schneider, K.P.; Mather, B.A.; Pal, B.C.; Ten, C.-W.; Shirek, G.J.; Zhu, H.; Fuller, J.C.; Pereira, J.L.R.; Ochoa, L.F.; de Araujo, L.R.; et al. Analytic Considerations and Design Basis for the IEEE Distribution Test Feeders. *IEEE Trans. Power Syst.* **2008**, *33*, 3181–3188. [CrossRef]
17. Kersting, W.H. Radial distribution test feeders. *IEEE Trans. Power Syst.* **1991**, *6*, 975–985. [CrossRef]
18. Kersting, W.H. Radial distribution test feeders. In Proceedings of the 2001 IEEE Power Engineering Society Winter Meeting, Columbus, OH, USA, 28 January–1 February 2001. [CrossRef]
19. Strunz, K. *Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources*; International Council on Large Electric Systems: Paris, France, 2014.
20. Koirala, A.; Suárez-Ramón, L.; Mohamed, B.; Arboleya, P. Non-synthetic European low voltage test system. *Int. J. Electr. Power Energy Syst.* **2020**, *118*, 3181–3188. [CrossRef]
21. Mateo, C.; Prettico, G.; Gómez, T.; Cossent, R.; Gangale, F.; Frías, P.; Fulli, G. European representative electricity distribution networks. *Int. J. Electr. Power Energy Syst.* **2018**, *99*, 273–280. [CrossRef]
22. Schmid, T.; Müller, M.; Kleinertz, B.; Böing, F.; Hinterstocker, M.; Bruckmeier, A.; Köppl, S.; Konetschny, C.; Zeiselmair, A.; Samweber, F. *Projekt MONA 2030: Grundlage für die Bewertung von Netzoptimierenden Maßnahmen—Teilbericht Basisdaten*; Forschungsstelle für Energiewirtschaft e.V. (FfE): Munich, Germany, 2017.
23. Eisenreich, M. Einbindung dezentraler Erzeuger am Beispiel von Photovoltaikanlagen ins elektrische Verteilungsnetz und die Auswirkungen auf die Netzstruktur. Doctoral Thesis, Technische Universität Darmstadt, Darmstadt, Germany, 2018.
24. Bacher, J.; Pöge, A.; Wenzig, K. *Clusteranalyse: Anwendungsorientierte Einführung in Klassifikationsverfahren*; De Gruyter: Berlin, Germany, 2011; ISBN 9783486710236.

25. Gust, G. Analyse von Niederspannungsnetzen und Entwicklung von Referenznetzen. Master's Thesis, Karlsruhe Institut of Technology, Karlsruhe, Germany, 2014.
26. Scheffler, J. Bestimmung der Maximal Zulässigen Netzanschlussleistung Photovoltaischer Energiewandlungsanlagen in Wohnsiedlungsgebieten. Ph.D. Thesis, University of Technology Chemnitz, Chemnitz, Germany, 2002.
27. Postigo Marcos, F.; Mateo Domingo, C.; Gómez San Román, T.; Palmintier, B.; Hodge, B.-M.; Krishnan, V.; De Cuadra García, F.; Mather, B. A Review of Power Distribution Test Feeders in the United States and the Need for Synthetic Representative Networks. *Energies* **2017**, *10*, 1896. ISSN 1996-1073. [CrossRef]
28. Blume, Y.; Ostermann, A.; Reinhard, J.; Müller, M. Anforderungen an aktuelle Verteilnetze und deren zukünftige Versorgungsaufgabe. In Proceedings of the IEWT—12. Internationale Energiewirtschaftstagung, Vienna, Austria, 8–10 September 2021.
29. Weiss, A.; Biedenbach, F.; Mueller, M. Analyse methodischer Modellierungsansätze im Kontext von Verteilnetzsimulationen. In Proceedings of the IEWT—12. Internationale Energiewirtschaftstagung, Vienna, Austria, 8–10 September 2021.