A review of European low-voltage distribution networks

Rui Guo[1,2*], Simon Meunier[3,4], Christina Protopapadaki[1,2], Dirk Saelens[1,2]

[1] *KU Leuven, Department of Civil Engineering, Kasteelpark Arenberg 40, Heverlee 3001, Belgium*

[2] *EnergyVille, Thor Park 8310, Genk 3600, Belgium*

[3] *Université Paris-Saclay, CentraleSupélec, CNRS, GeePs, Gif-sur-Yvette 91192, France*

[4] *Sorbonne Université, CNRS, GeePs, Paris 75252, France*

ABSTRACT

Due to the increasing integration of low-carbon technologies (e.g., heat pumps, photovoltaic systems, electric vehicles) needed to achieve climate-neutral plans in the European Union and several other European countries, low-voltage distribution networks face new challenges regarding reliable operation and growth in operation and investment costs. Increased knowledge and analysis of low-voltage distribution networks is a fundamental step toward addressing the challenges related to the deployment of low-carbon technologies, which require data on relevant grid parameters to support simulations. Although there were some data available on existing local European low-voltage grids and a few generic ones, the low-voltage network techno-economic data were still scattered and not compared between each other. This study provides a first-of-a-kind structured literature review of low-voltage grids in Europe from 26 open access grids and 29 scientific articles or reports, with a special emphasis on technical and economic parameters. Moreover, representative values for the technical and economic parameters of low-voltage grids in corresponding European countries or regions are recommended based on the collected data. This work can help academics and distribution system operators select the appropriate technical and economic grid parameters to comprehensively quantify the impacts of low-carbon technology integration into European low-voltage grids and to investigate options (e.g., grid reinforcements) to mitigate these impacts.

HIGHLIGHTS

- A structured review of European low-voltage grids.
- Topology and techno-economic data related to grids are collected.
- Data from 26 open access grids and 29 articles/reports are gathered and discussed.
- Typical values of technical and economic parameters are suggested for European grids.
- Helps academics and grid operators to study low-carbon technology integration.

KEYWORDS

Low-voltage distribution network, Low-carbon technologies, Europe, Techno-economic data, Grid reinforcements.

(Word count: 8125)

Nomenclature

Acronyms

AR	Article/report
DSO	Distribution system operator
EU	European Union
LCT	Low-carbon technology
LV	Low-voltage
OG	Open access grids
OH	Overhead
UG	Underground

Indices

k	Position in the feeder
y	Year

[*] *Corresponding author email address: rui.guo@kuleuven.be*

τ	Transformer

Variables

C_y	Cost at year y (€)
r	Inflation rate

Parameters

$C(\tau)$	Transformer investment cost, i.e., cost of the newly installed transformer (€)
$C_l(dl)$	Linear cost of replacing the current one-phase consumer link by a three-phase cable (€/m)
$C_l(f)$	Linear cost of installing the new feeder cables (€/m)
$C_l(\text{UG}, zone)$	Linear cost of underground cable replacement in the zone (€/m)
$C_l(\text{OH}, zone)$	Linear cost of overhead cable replacement in the zone (€/m)
D_f	Number of consumers in the detailed feeder
D_i	Number of consumers in the island
$l_t(f)$	Feeder length (m)
$S_{nom}(\tau)$	Transformer nominal power (kVA)
$\%\text{OH}(zone)$	Percentage of the low-voltage cable length which is overhead in the zone
$\%\text{UG}(zone)$	Percentage of the low-voltage cable length which is underground in the zone

1 Introduction

Europe accounted for 14.2% of the world's CO_2 emissions in 2020 [1]. To combat climate change, the European Union (EU) [2] and other European countries like Norway [3] and Switzerland [4] have set their own net-zero emissions targets for the next decades. To achieve this goal, ambitious policies and legislation are proposed to boost energy efficiency and renewable energy, and promote electrification and low-carbon technologies (LCTs) [5]. Numerous innovative projects, such as sEEnergies [6] and TANGO [7], were funded by the EU and other European countries to investigate the potential of LCTs for decarbonizing the economy [8]. In the building sector, LCTs range from electricity production with renewable energy sources to energy storage technologies, such as heat pumps and electric vehicles, which will be interconnected and interact in the power system [9][10]. However, the integration of LCTs can significantly impact traditional load patterns at the national and local distribution grid levels, especially in low-voltage (LV) grids [12][13]. The reason is that the LV grids were historically designed for smaller loads rather than integrating new highly-consuming loads (e.g., heat pumps) or accommodating distributed generation (e.g., rooftop photovoltaic systems).

Model-derived energy-economy pathways are usually leveraged to inform policymakers and ensure that the national policy and investment decisions are aligned with long-term climate goals [14] for the whole globe [15], Europe [16], China [17], and the U.S. [18]. However, the high-level assessments by the global integrated assessment models and bottom-up national-scale approaches usually ignore or simplify the potential issues of LCTs integration in the electric network [19]. As a result, policymakers may overestimate the potential penetration of LCTs by ignoring technical constraints related to the LV grid [20].

LV grid models are typically used for power system analysis by integrating the load/generation profiles of LCTs [21][22]. In order to evaluate the impact of LCTs robustly, a number of studies have adopted simulation methods to investigate the integration and smart control of LCTs on LV grids in European countries like Belgium [12][13], Switzerland [24][25], Italy [11], the UK [27][28], Spain [29], Ireland [30], Sweden [31], Denmark [32][33], the Netherlands [32][34][35], and Germany [32][36]. Except for Gupta et al. [24], who conducted a relevant study for Switzerland based on the whole Swiss distribution network, other studies selected local/representative LV test feeders or reference network models for the case study. The LV test feeders or reference network models can be regarded as a theoretical network that can serve as a proxy for realistic grids, which have been developed to support conducting power flow analyses. For the theoretical network, power grid modelling methods and tools have been thoroughly reviewed in the literature [38][39]. The modelling methods can be generally categorised into four types: single-node model [40], transshipment model [41], direct current model [42], and alternating current power flow model [42]. Simulation tools include, amongst other, OpenDSS [43], GridLAB-D [44], and Modelica [45]. Those tools provide detailed modelling of the power system, including power flow, grid stability analysis, harmonics, and short-circuit analysis. Apart from the studied LV test feeders in the European countries, several generic European LV test feeders [46][47] were released for research. However, unlike in the U.S., where there are some institutions like the IEEE, the Pacific Northwest National Laboratory, the Electric Power Research Institute, the Pacific Gas and Electric Company and the Test Feeder Working Group that have developed a lot of LV test feeders [48][49] (which were notably used for grid stability analysis [50][51]), the typical LV grid models for the whole of Europe are relatively few as a large amount of grid data are confidential [52].

Since the European distribution grids differ greatly from the North American grid in design approaches, topology and installation common practices [48], the IEEE European LV test feeder was first developed [53], which sought to fill a benchmark gap by presenting some common LV configurations and was used in research on LCT integration in Europe (e.g., [54]). However, this test feeder was based on a radial UK feeder [49]. Thus, there may be some differences in other parts of Europe. In addition, this feeder was not representative of the actual European system, as only a single feeder for a single distribution transformer was proposed [55]. In response to the limitations of the IEEE European LV test feeder, Koirala et al. [47] modified the IEEE European test feeder and took data from a real distribution network while respecting privacy to develop a real (non-synthetic) typical European town's distribution test network. This real test feeder was a 4-wire system with isolated neutral from consumer ground. However, it only represented a LV grid in a town, which neglected the LV grids in semi-urban and rural zones. Mateo et al. [46] proposed a methodology to build synthetic European representative LV feeder-level distribution networks by gathering data from 79 large European distribution system operators (DSOs). The grid-related indicators of the developed representative networks were close to the DSOs real indicators. Nevertheless, these feeder-level distribution networks only contained three-phase balanced urban and semi-urban LV networks, which failed to solve the problem of the unbalanced networks. The Conseil International des Grands Réseaux Electriques also released a set of benchmark networks that included a European LV distribution benchmark network [56]. This network was of radial topology and was inherently unbalanced due to the connection of single-phase consumers. However, the data source for the European LV benchmark network model was unspecified, which limits its scope of application.

The literature review reveals different LV grids in those investigated European countries and even multiple LV grids in one country, making it difficult to select the appropriate one for carrying out analyses. Moreover, no paper collects and compares the technical parameters of LV grids that originated from different references. Therefore, the first novel contribution of this study is to review, compare and analyse the technical parameters of those European LV grids. The authors believe a comprehensive review of the LV grids across Europe will start from the perspective of the grid technical parameters needed for the power system modelling, which can help facilitate the relevant research on the impact of LCTs on the European LV grids as a whole. Indeed, a structured knowledge of LV grids is key to defining representative case studies and thus generating meaningful results.

The integration of LCTs in LV grids causes grid stability problems, such as transformer and cable overloading, harmonic distortion, voltage unbalance and variation [57]. To tackle these problems, grid reinforcements [58][59] are often adopted by replacing transformers and feeder cables, among others. Other solutions such as grid optimization measures (e.g., reactive power control) can also be considered to stabilize LV grids [60]. Nevertheless, the latter solutions require appropriate communication infrastructure and controls, and the associated economic and regulatory challenges remain [61][62]. In addition to adopting technical measures for grid reinforcements, relevant economic analysis is necessary to identify the most cost-effective grid reinforcement option. More importantly, quantifying the potential grid reinforcement costs corresponding to different integration levels of LCTs into LV grids can facilitate the identification of better measures and the development of strategies and policies related to LCTs. The economic parameters of LV grid components (e.g., cost of transformer and cable replacements) are required to support these economic analyses. Although the relevant research (e.g., [13][35][63]) in some European countries contained data on economic parameters, these costs were spilt into various references that were not compared to each other and were not updated for inflation. To the authors' best knowledge, no prior study reviews those economic parameters in Europe, which hinders the quantification of grid reinforcement costs due to LCTs integration in Europe. Therefore, the second novel contribution of this work is that economic parameters related to European LV grids are reviewed and centralised, updated and harmonised to the current prices. These parameters can notably be used to estimate the cost of reinforcing LV grids across Europe.

Given the identified limitations of the current literature, this paper reviews the topology, technical and economic parameters of LV grids in Europe, discusses and recommends representative values of technical and economic parameters for LV grids in Europe. The collected data and recommended representative values will support the research about LCTs integration into LV networks across Europe or specific European countries, which is in line with the following United Nations sustainable development goals: affordable and clean energy (goal 7) and climate action (goal 13) [64]. The remainder of this paper is organised as follows. Section 2 introduces the methodological analysis framework. Sections 3, 4, and 5 present detailed analyses of the topology, technical parameters, and economic parameters of European LV grids, respectively. Finally, Section 6 concludes the paper.

2 Methodological analysis framework

This study focuses on the topology, technical and economic parameters related to European LV grids, based on the literature review, European databases and expert knowledge. Two complementary types of literature sources were used to collect data on the grid architecture and characteristic technical parameters: open access grids and scientific articles/reports. For the literature search, Web of Science and Google search engines with keywords "low-voltage grids", "grid reinforcements", and "European distribution system" were used. It is worth noting that the scope of "Europe" in this study corresponds to the geographical definition of Europe [65], and the search is based on this scope. A total of 26 open grids and 29 relevant scientific articles/reports were found for data collection. Open access grids offer a wide range of technical parameters and detailed values for these parameters, such as the resistance of each feeder segment. Scientific articles and reports provide some information about technical parameters but rarely the values of all the required technical parameters. However, they cover a wider range of European countries than open access grids. Data on the economic parameters are only available from scientific articles/reports. Since LV grids may vary considerably in different European countries, the method comprises three steps, which are shown in Figure 1:

Step 1: analysis of grid topologies. This step involves the documentation and analysis of the topologies of European LV grids, which is further elaborated in Section 3.

Step 2: review of technical grid parameters of LV grids. The investigated technical parameters consist of nine aspects divided into parameters related to the island configuration and transformer, the feeder segments, and the consumer links. These aspects are further elaborated in Section 4, where the technical parameters are also discussed, and representative values are furthermore recommended for the European LV grids based on the collected data.

Step 3: review of economic parameters. The economic parameters include the cost of new transformer investment, feeder cable replacement, and consumer link replacement, among others, as further elaborated in Section 5. The costs obtained for years earlier than 2020 were updated with an average EU yearly inflation rate of 1% [66]. These costs were therefore named "2020 equivalent cost". Moreover, the typical planning horizon (years) and discount rates were also reviewed to support the related life-cycle economic analysis. The economic parameters are discussed, and corresponding representative values are recommended based on the collected data for the whole of Europe as a first estimate.

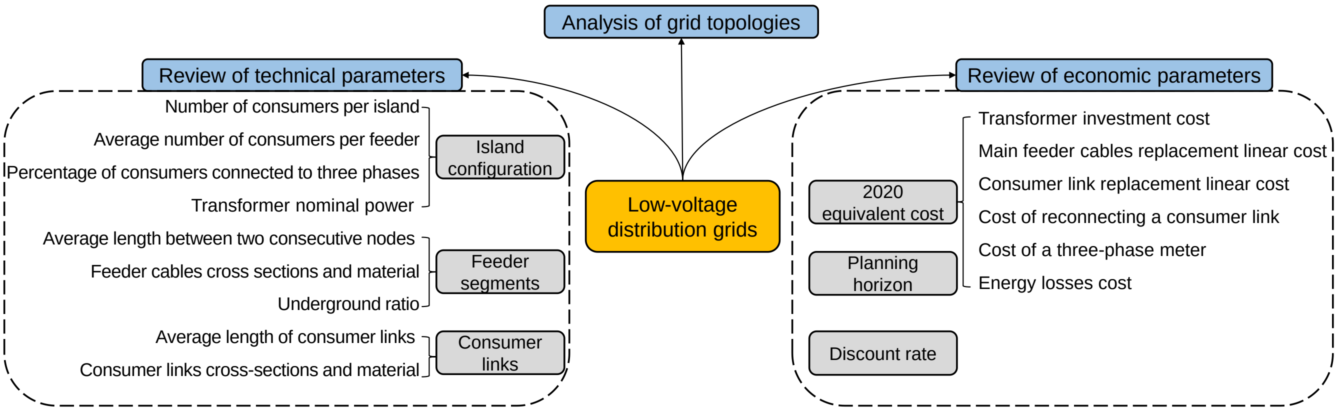

Figure 1 – Analytical framework.

3 Grid topology and modelling method

According to the European standard EN 50160:2010 [67], a LV distribution grid refers to an electrical system with a nominal frequency of 50 Hz and a nominal voltage of 230 V between each phase and the neutral. Through the review of the European LV grids, it can be concluded that the typical European LV grid is a radial network that consists of one MV/LV transformer and several feeders. A feeder starts at the secondary of the transformer and ends at the final consumer of the feeder. Besides, the typical European LV networks can be treated as three-phase four-wire systems [47][56]. Figure 2 shows two examples of radial European LV networks in urban [46] and rural [68] zones, which are commonly considered zones in the literature. The urban one is a generic European LV network, while the rural one is an example from a German network.

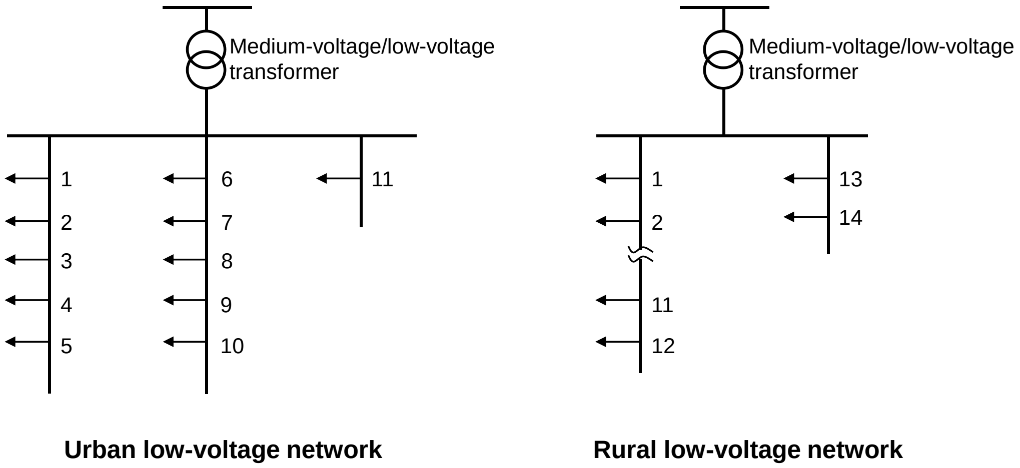

Figure 2 – Examples of radial European LV networks. Adapted from [46][68].

The entire LV networks can be modelled explicitly (i.e., all feeders in a distribution island are modelled). However, the full LV island modelling approach can become computationally expensive [69]. To face this issue, Protopapadaki and Saelens [69] adopted a dummy island approach that focuses on a specific feeder while also accounting for loads on the rest of the island. Figure 3 shows the dummy island approach for a LV grid. This topology models the feeder of interest in detail, while an aggregated balanced load represents the rest of the LV island. This allows considering loads and distributed generation sources in the rest of the island and notably assessing the transformer loading and the voltage drop at the transformer caused by those. Compared to the full island approach, the dummy island approach could reduce the calculation time by a factor of about 10 in the used modelling tool while triggering errors less than 0.03, 0.01 and 0.01 pu on extreme voltage [69]. Figure 3 shows the LV grid topology with a dummy island approach [69].

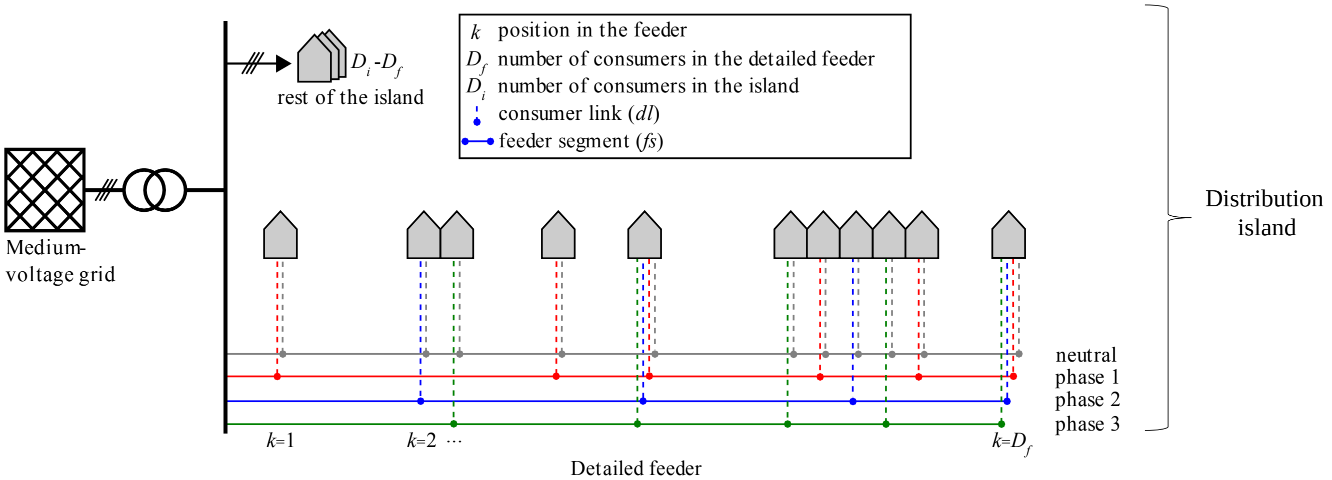

Figure 3 – A typical European LV grid topology with the dummy island approach [69].

Since the dummy island approach mainly focuses on one detailed feeder, this approach requires less data on the technical parameters than the full island approach. This paper only focuses on the necessary technical parameters for the dummy island approach, but these data and the corresponding references can be used as a basis for full island modelling and simulations.

4 Technical parameters

4.1 Parameter description

Since the typical European LV grid topology is a radial network with one MV/LV transformer, the technical parameters to define a LV grid in Europe are classified into three types: parameters related to the (1) island configuration and transformer, (2) feeder segments, and (3) consumer links (i.e., electricity connections between the consumers or prosumers and the main feeder in Figure 3). These parameters allow the power flow analysis to calculate the voltage and current for all nodes, branches and phases of the transformer [45]. Table 1 presents key technical parameters to define a LV grid. Depending on the LV grid model granularity, these parameters can be either directly used in the model (e.g., nominal transformer capacity) or used to deduce the parameters necessary for the grid model through some assumptions. For example, the average length of consumer links can be used to determine the length of each consumer link by assuming that the length of each consumer link is equal to this average. Note that the possible values for some characteristic parameters in Table 1 are from the collected data listed in Table 2.

Table 1 – Description of grid technical parameters.

Characteristic parameter	Description	Possible values
Parameters related to the island configuration and transformer		
Number of consumers per island	The number of consumers in the whole LV distribution island.	Integer
Average number of consumers per feeder	This parameter is calculated by dividing the number of consumers per island D_i by the number of feeders on this island.	Integer
Percentage of consumers connected to three phases	Consumers can be connected to one (e.g., consumer in position $k = 1$ in Figure 3) or three phases (e.g., consumer in position $k = 5$ in Figure 3). This parameter represents the share of the island consumers connected to three phases.	Continuous
Transformer nominal power $S_{nom}(\tau)$ (kVA)	The no-load losses, the phase resistance and reactance of the transformer can be deduced from the transformer nominal power $S_{nom}(\tau)$ (see Appendix A).	75, 100, 150, 160, 250, 300, 400, 630, 800
Parameters related to feeder segments		
Average length between two consecutive nodes (m)	This parameter is calculated by dividing the total length of the feeder cable by the number of consecutive nodes (e.g., nodes in positions $k = 1$ and $k = 2$ in Figure 3).	Continuous
Feeder cables cross-section (mm^2) and material	The feeder cables cross-section and material influence their linear resistance, linear reactance and ampacity (see Appendix A).	16, 25, 35, 50, 55, 70, 95, 120, 150, 185, 240, 300, 400, 500; Aluminium, copper
Underground ratio (%)	The percentage of feeder cables that are undergrounded. This parameter influences the cable linear reactance and ampacity (see Appendix A) as well as the cable replacement costs (see Section 5.2).	Continuous
Parameters related to consumer links		
Average length of consumer links (m)	This parameter is calculated by dividing the total length of consumer links by the number of consumers.	Continuous

Consumer links cross-section (mm^2) and material	The consumer links material and cross-section influence their linear resistance, linear reactance and ampacity (see Appendix A).	16, 25, 35, 50, 55, 70, 95, 120; Aluminium, copper

4.2 Collected data

Table 2 presents the values of the technical parameters of LV grids collected through open access grids and scientific articles. Each line corresponds to one grid. The origin of each grid is specified through the source reference and a label pointing out whether this reference is an open access grid repository (OG) or a scientific article/report (AR). Most of the references are based on existing grids. The grids are presented per country and zone. Some grids are designated as generic European grids and labelled 'Europe' in Table 2. Since some zones had similar names (e.g., rural and village), in order to present the data clearly, two zones (i.e., rural and urban) were defined, as the LV feeders could often be catalogued under these two zones [13]. The LV grids in other zones were grouped into the corresponding two zones. 'Semi-rural' and 'village' were included into the 'rural' zones, while 'town', 'semi-urban' and 'suburban' were considered as 'urban' zones. Meanwhile, the original type of LV grid other than 'urban' and 'rural' is shown in column 1 of Table 2. Besides, it should be noticed that some grids did not specify the zone (labelled as 'unspecified zone in Table 2).

Note that some LV grids had multiple rated nominal powers of transformers from the DSOs, which meant that the transformers were all available for the corresponding grid. Besides, it was unclear for some LV grids whether the consumer links were considered and/or the difference was not made between the consumer links and the main feeder cables (which contributes to the 'length between two consecutive nodes'). In such cases, since the length between two consecutive nodes was usually higher than the one of the consumer links, and to be on the conservative side for grid stability analyses, the entire reported cable length was allocated to the main feeder cables.

Table 2 – Data collected on the values of grid technical parameters.

Grid origin	Number of consumers per island	Average number of consumers per feeder	Percentage of consumers connected to three phases	Transformer nominal power $S_{nom}(\tau)$ (kVA)	Average length between two consecutive nodes (m)	Feeder cross-section (mm^2) and material	Underground ratio (%)	Average length of consumer links (m)	Consumer links cross-section (mm^2) and material
Notations. OG: open access grid, AR: scientific articles and reports, al (aluminium), co (copper) Example of notation explained: 3×95 + 1×50 (40%), 4×150 (60%) al: for 40% of feeder segments, the cross-section of phases 1, 2 and 3 is 95 mm^2 and the one of the neutral is 50 mm^2. For the remaining 60% of feeder segments, the cross-section is 150 mm^2 for all phases and the neutral. All feeder segments are in aluminium. Note that the cross-section of the neutral is not always specified (e.g., 3×185 al).									
Europe (EUR), rural									
1 AR [70]	39	13	0	630	48		0		
2 AR [70]	24	6	0	250	190		0		
3 AR [70]	21	7	0	75	70		0		
4 AR [70]	27	9	0	100	21		100		
5 AR [70]	14	5	0	100	62		41		
6 AR [46]	51		0	100/250/400	27		4		
7 AR [70] (semi-rural)	233	47	0	630	8		100		
8 AR [70] (semi-rural)	214	31	0	800	10		100		
Europe (EUR), urban									
1 AR [71]	107	36		400	2		100		
2 AR [46]	101		0	400/630/1000	4		86		
3 AR [47] (town)	270	50	0	100 (3%)/250 (3%)/630 (93%)	3	3×240 + 1×150 al	54		
4 AR [71] (semi-urban)	108			400	11		100		
5 AR [46] (semi-urban)	87		0	100/250/400/ 630/1000	8		42		
Europe (EUR), unspecified zone									
1 OG [53]	55	55	0	800	26				
2 AR/OG [72][56]	6	6	0	500	63	3×240 (53%), 3×50 (47%) al	100		
3 AR/OG [72]	1	1	0	150	200	3×150 al	100		
4 AR/OG [72]	8	8	0	300	30	3×70 (42%), 3×25 (21%),	0		

Grid origin	Number of consumers per island	Average number of consumers per feeder	Percentage of consumers connected to three phases	Transformer nominal power $S_{nom}(\tau)$ (kVA)	Average length between two consecutive nodes (m)	Feeder cross-section (mm^2) and material	Underground ratio (%)	Average length of consumer links (m)	Consumer links cross-section (mm^2) and material
Notations. OG: open access grid, AR: scientific articles and reports, al (aluminium), co (copper)									
Example of notation explained: 3×95 + 1×50 (40%), 4×150 (60%) al: for 40% of feeder segments, the cross-section of phases 1, 2 and 3 is 95 mm^2 and the one of the neutral is 50 mm^2. For the remaining 60% of feeder segments, the cross-section is 150 mm^2 for all phases and the neutral. All feeder segments are in aluminium. Note that the cross-section of the neutral is not always specified (e.g., 3×185 al).									
						3×16 (39%) al			
Belgium (BE), rural									
1 AR [69]	79	28	0		23	al	100	8	
2 AR [13]	64	16		250	23	4×70 (25%), 4×120 (75%) al	100		
3 AR [73]	20	7	0		44		100		
4 AR [58]	73	15	0	160	22	4×70		8	1×16
Belgium (BE), urban									
1 AR [69]	114	28	0		8	al		3	
2 AR [13]	85	17		400	8	3×95 + 1×50 (40%), 4×150 (60%) al	100		
3 AR [73]	42	14	0		12		100		
4 AR [73]	55	18	0		8		100		
5 AR [74]	39	39	100	160	9	3×70 + 1×50 co	100		4×16 co (87%), 4×35 co (13%)
6 AR [58]	108	15	0	160	7	4×70		3	1×16
7 AR [73] (semi-urban)	63	9	0		26		100		
Denmark (DK), unspecified zone									
1 AR [32]	141	35							
Germany (DE), rural									
1 OG [75]	12	4	100	160	106	4×150 al	100	29	4×50
2 OG [75]	8	3	100	250	67	4×70 al	0	4	4×35
3 OG [75] (village)	39	10	100	250	46	4×150 al	100	21	4×50
4 OG [75] (village)	36	9	100	400	34	4×50 (50%), 4×70 (50%) al	50	17	4×35
3 OG [68]	13	13		160	21	4×70 al	0		
4 OG [68]	8	4		100	49	4×70 al	0		
5 OG [68]	8	4	100	100	105	4×150 al	100	26	4×50 al
6 OG [68]	14	7	100	160	70	4×150 al	100	26	4×50 al
7 OG [68]	26	26	100	250	12	4×70 al	0	18	4×50 al
9 OG [68]	26	26	100	250	26	4×150 al	100	26	4×50 al
8 OG [68]	27	14	100	100	13	4×70 al	0		4×50 al
10 OG [68]	27	14	100	100	29	4×150 al	100	25	4×50 al
11 OG [68] (village)	57	10	100	400	37	4×150 al		23	4×50 al
12 OG [68] (village)	58	12	100	400	31	4×150 al	100	23	4×50 al
13 OG [68] (village)	117	13	100	250	29	4×150 al	100	23	4×50 al
Germany (DE), urban									
1 OG [68] (suburban)	146	15	100	630	20	4×150 al	100	11	4×50 al (50%), 4×35 al (50%)
2 OG [68] (suburban)	144	16	100	630	22	4×185 al	100	11	4×50 al (50%), 4×35 al (50%)
3 OG [68] (suburban)	145	24	100	630	12	4×150 al	100	11	4×50 al (50%), 4×35 co (50%)
4 OG [68]	145	21	100	630	17	4×185 al	100	11	4×50 al

Grid origin	Number of consumers per island	Average number of consumers per feeder	Percentage of consumers connected to three phases	Transformer nominal power $S_{nom}(\tau)$ (kVA)	Average length between two consecutive nodes (m)	Feeder cross-section (mm²) and material	Underground ratio (%)	Average length of consumer links (m)	Consumer links cross-section (mm²) and material
Notations. OG: open access grid, AR: scientific articles and reports, al (aluminium), co (copper)									
Example of notation explained: 3×95 + 1×50 (40%), 4×150 (60%) al: for 40% of feeder segments, the cross-section of phases 1, 2 and 3 is 95 mm² and the one of the neutral is 50 mm². For the remaining 60% of feeder segments, the cross-section is 150 mm² for all phases and the neutral. All feeder segments are in aluminium. Note that the cross-section of the neutral is not always specified (e.g., 3×185 al).									
(suburban)									(50%), 4×35 co (50%)
5 OG [68] (suburban)	191	21	100	250	17	4×150 al	100	11	4×50 al (50%), 4×35 co (50%)
6 OG [68] (suburban)	192	21	100	250	17	4×185 al	100	11	4×50 al (50%),4×35 co (50%)
7 OG [75] (suburban)	101	9	100	400	31	4×95 (7%), 4×120 (16%), 4×150 (77%) al	100	18	4×35
8 AR [63] (suburban)	122	20	100	250					
Germany (DE), unspecified zone									
1 AR [37]	80	40			30	4×150 al			
Ireland (IE), urban									
1 AR [30] (semi-urban)	78	78	0				100		
Italy (IT), unspecified zone									
1 AR [11]	23	8	9	250	109	3×150 + 1×95 (7%) co, 4×25 (31%) co, 3×70 + 1×55 (11%) al, 4×16 (51%) co			
Netherlands (NL), unspecified zone									
1 AR [35]	340	18		400		co			
Switzerland (CH), urban									
1 AR [25]	111								
UK, rural									
1 AR [76] (village)		4			32				
UK, urban									
1 AR [77] (semi-urban)	400	100		630	12	3×185 al			1×25
2 AR [76] (town)		19			15				
3 AR [76]		39			12				
UK, unspecified zone									
1 AR [78]	265	66	9	500					
2 AR [79]	351	59	0		26				
3 AR [80]	636	91	0	750	29		100		
5 AR [81]	428	86	0	800			100		
6 AR [82]	200	50	0	800	29		100		
7 AR [82]	567	113	0	800	27		100		
8 AR [82]	370	62	0	800	28		100		
9 AR [82]	186	31	0	800	36		100		
10 AR [82]	335	42	0	800	28		100		
11 AR [82]	171	86	0	800	26		100		
12 AR [82]	471	67	0	800	22		100		
13 AR [82]	354	177	0	800	36		100		
14 AR [82]	293	49	0	800	25		100		
15 AR [82]	64	11	0	800	64		100		
16 AR [82]	214	43	0	800	35		100		

Grid origin	Number of consumers per island	Average number of consumers per feeder	Percentage of consumers connected to three phases	Transformer nominal power $S_{nom}(\tau)$ (kVA)	Average length between two consecutive nodes (m)	Feeder cross-section (mm^2) and material	Underground ratio (%)	Average length of consumer links (m)	Consumer links cross-section (mm^2) and material
Notations. OG: open access grid, AR: scientific articles and reports, al (aluminium), co (copper)									
Example of notation explained: 3×95 + 1×50 (40%), 4×150 (60%) al: for 40% of feeder segments, the cross-section of phases 1, 2 and 3 is 95 mm^2 and the one of the neutral is 50 mm^2. For the remaining 60% of feeder segments, the cross-section is 150 mm^2 for all phases and the neutral. All feeder segments are in aluminium. Note that the cross-section of the neutral is not always specified (e.g., 3×185 al).									
17 AR [82]	330	110	0	800	25		100		
18 AR [82]	258	65	0	800	30		100		
19 AR [82]	317	53	0	800	29		100		
20 AR [82]	636	91	0	800	29		100		
21 AR [82]	238	60	0	800	29		100		
22 AR [82]	883	126	0	800	26		100		
23 AR [82]	328	36	0	800	29		100		
24 AR [82]	353	71	0	800	30		100		
25 AR [82]	162	32	0	800	16		100		

In Table 2, the UK has many recorded LV grids, but most are located in an unspecified zone. The generic European, Belgian and German grids have at least one grid in the rural and urban zones. The German LV grids are the best documented and most numerous, containing almost all types of technical parameters collected here.

To demonstrate the dispersion of the data for each technical parameter, box-and-whisker plots for the parameters are shown in Figure 4. Since the cross-sections of phase cables and neutral cables of a feeder cable might differ, the cross-sections of phase cables and neutral cables are depicted in Figure 4f and Figure 4g separately. Note that for parameters in one grid that had multiple data (e.g., 4×50 mm^2 (50%), 4×70 mm^2 (50%)), only the arithmetic mean for that parameter in that grid was calculated and plotted in Figure 4. The cable materials for feeder cables and consumer links are not represented in Figure 4. However, it is observed in Table 2 that aluminium is more widely used in the main feeder and consumer links cables than copper.

It is noticed that the number of consumers in the island and feeder (Figure 4a, b) are the parameters included most often in the collected LV grids, followed by the length between two consecutive nodes (Figure 4e) and transformer nominal power (Figure 4d). In contrast, only a few collected LV grids contain the parameters relevant to consumer links (Figure 4i, j). The remaining parameters are mainly available for the generic European, Belgian and German rural and urban grids. Thus, the technical parameters of those three grids and other grids with multiple data were primarily analysed.

Regarding the number of consumers per island and the average number of consumers per feeder shown in Figure 4a and 4b, the grid data in UK unspecified zones have the largest discrepancy (i.e., standard deviation). The data on the average number of consumers per feeder for UK urban grids also varies a lot. For generic Europe, Belgium and Germany, the arithmetic mean of these two latter parameters is larger in the respective urban grids than in the rural grids. Their standard deviation is similar for the three countries' respective urban and rural grids. For the percentage of consumers connected to the three phases, most grids have zero or fairly low values for this parameter. This compares to 100% for German rural and urban grids. For the transformer nominal power of generic European, Belgian and German grids, the arithmetic mean is also greater in urban ones than in rural ones. In the UK unspecified zones, most of those grids have a transformer nominal power of 800 kVA and an average length between two consecutive nodes of about 30 m. For generic Europe, Belgium and Germany, the rural grids in the respective countries/region usually have a longer average length between two consecutive nodes than the urban ones.

As shown in Figure 4f and 4g, the cross-sections of the feeder phase and neutral wires of German rural and urban grids are the same. The feeder cables cross-sections of German rural grids are generally smaller than that of German urban grids. For Belgian grids, the arithmetic mean of cross-sections in Belgian rural and urban feeders are close. However, the urban feeder cross-sections have a larger standard deviation than the rural ones. The feeders of collected grids in generic European unspecified zones are a three-wire system with a large range of phase wire cross-sections from 40 mm^2 to 150 mm^2. The underground ratios of collected Belgian, German urban, Italian urban, and UK unspecified zone grids are 100%. In comparison, the underground ratios of other grids vary a lot, ranging from 0 to 100%. The arithmetic means of underground ratios of generic European and German rural grids are smaller than those of corresponding urban grids, indicating that the feeder cables in urban grids are more likely to be underground. The collected Belgian and German grids record the most detailed data on parameters related to consumer links (Figure 4i, j). It can be seen that, in these two countries, the average length of consumer links is larger in rural grids than in urban grids. In comparison, the average consumer links cross-sections of rural and urban grids within each of those two countries are the same.

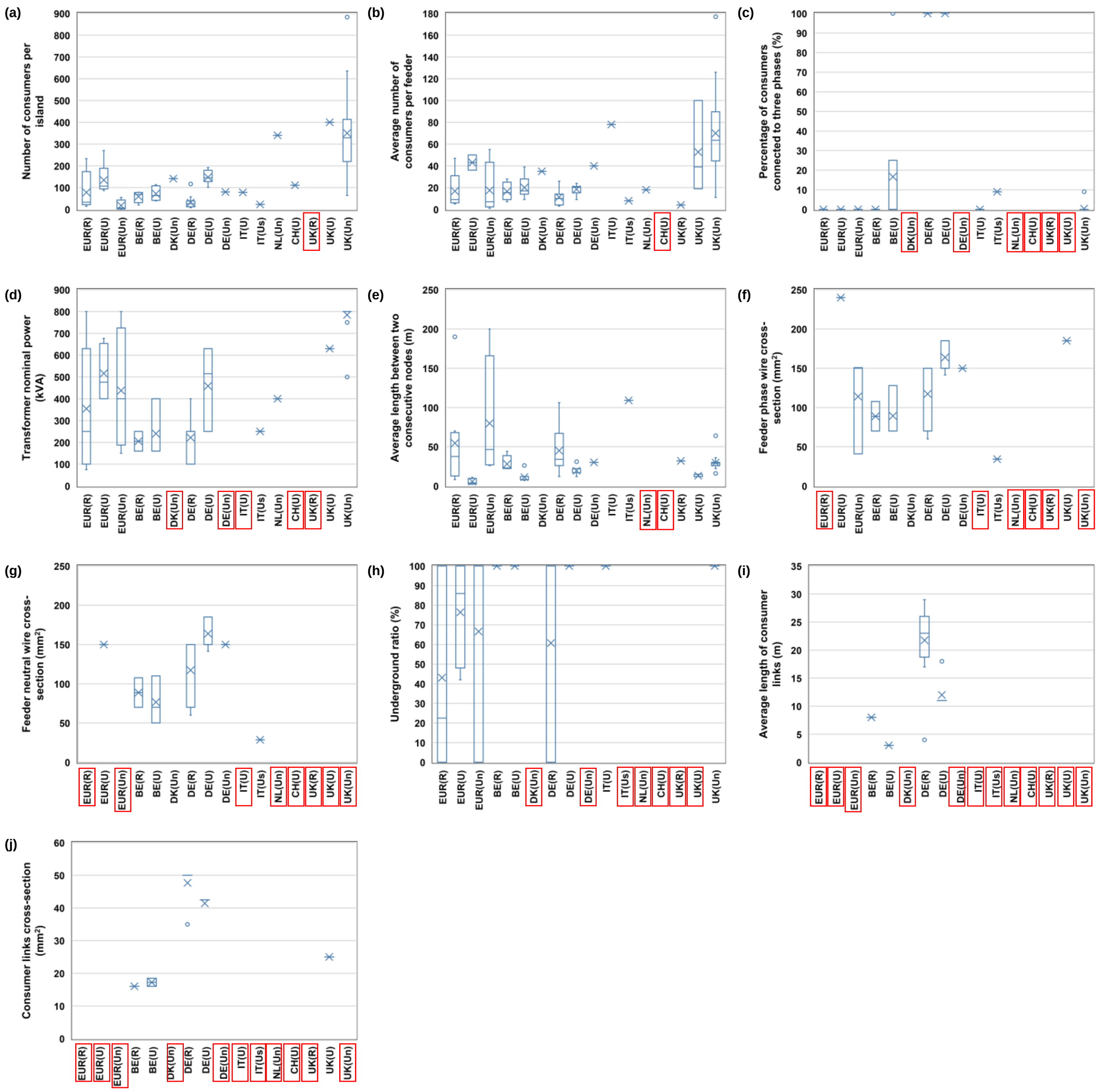

Figure 4 – Box-and-whisker plots of grid technical parameters in different countries and zones. The countries or region are indicated by the corresponding abbreviations, while the letters "R", "U", and "Un" in parentheses stand for rural, urban and unspecified zones, respectively. A red box covers the country/region without data for the corresponding technical parameter in each subfigure.

4.3 Discussion and recommendation of representative values for LV grid technical parameters

Academics and DSOs can select the appropriate LV grid and associated technical parameters they need from Table 2 and corresponding references for their analyses. However, as there are multiple LV grids in some countries/regions, it may be useful and more straightforward for certain studies to use a single grid for the corresponding country/region based on the collected data. According to Table 2, the generic European, Belgian, and German LV grids have at least one grid in the rural and urban zones. Thus, the representative values for technical parameters are recommended for these rural and urban LV grids.

The generic European LV grids can be used for all European countries or the remaining countries after the exclusion of Belgium and Germany. It is important to note that, in most cases, the recorded European LV grids were obtained from aggregating data from several countries, which are usually unspecified. Thus, it cannot be concluded, for instance, that Norwegian LV grids have the same technical parameters as Spanish ones. Additionally, there is no guarantee that the grid parameters from the literature are representative of the grids in the considered European countries. It is believed that these issues highlight the general lack of open access initiatives on LV grids. If DSOs could provide more data in open access, this would allow more country-specific trends to be considered and the representativeness of these trends would be improved. Nevertheless, it is recommended to use the generic European LV grids for the relevant research as a first estimate when grid data for one specific European country is unavailable.

For the sake of conciseness, the ‘average’ method based on the collected LV grid data was primarily used to recommend values for one grid per country and zone (rural/urban). However, academics can also develop a grid using their own methods based on the data in Table 2. For German LV grids, the values of the collected technical parameters in the corresponding country and zone in Table 2 were averaged. For the transformer nominal power, feeder cables cross-section and consumer links cross-section, the corresponding values were averaged and then rounded to the closest possible discrete value listed in Table 1. Since the consumer loads can be one- or three-phase connected, only the consumer link cross-section value is shown. Moreover, regarding the materials of feeder cable and consumer links, the most frequent occurrence of the material, aluminium, is recommended.

The same method was adopted for the Belgian LV and generic European grids. Besides, some assumptions for the generic European LV grids were proposed due to the lack of relevant data. For the consumer links, the corresponding values for the Belgian and German LV grids in urban and rural zones were averaged. Notably, the average values for the consumer links cross-sections of the generic European grids were then rounded to the closest possible discrete value (i.e., 35 mm^2) listed in Table 1. Moreover, the feeder cables cross-section and material for the generic European rural grids were assumed to be the same as for the European urban grid. Table 3 shows the representative values of technical parameters recommended for the generic European, Belgian and German LV grids. The values obtained from these assumptions are marked in green and can be updated if more data become available in the future. The standard deviation for each technical parameter of different grids is also listed in parenthesis to demonstrate the variation of collected values.

The reliability and efficiency of LV distribution networks operation are facing new challenges due to the increasing penetration of local renewable energy sources and new loads. When new loads (e.g., heat pumps) are integrated into LV grids, grids may suffer instability problems (e.g. under voltages, cables overloading) [83]. Whereas, when distributed generation (e.g., photovoltaic panels) is integrated into LV grids, it may destabilize or, on the opposite, stabilize the grid by allowing loads to consume locally produced energy [84].

Certain grid parameters that we have collected are the most likely to affect the emergence of grid stability problems when LCTs are integrated. The higher the percentage of consumers connected to three phases, the greater the possibility that LCTs can be three-phase connected without additional investment, which reduces voltage deviation and unbalance problems [58]. If the transformer nominal power is oversized in comparison to the consumption, then the transformer is less likely to be overloaded, and the possibility of voltage deviations is reduced [85]. Moreover, a shorter average feeder length between two consecutive nodes and a shorter average length of consumer links can contribute to smaller voltage variations, reducing voltage deviation and unbalance between the phases. Increasing the cross-section of the main feeder cables and consumer links also tends to decrease voltage variations by reducing cable resistance. The underground ratio slightly affects the cable ampacity [86] (see Appendix A), so it has a relatively small effect on grid stability. It is worth noting that general trends are given here, and the exact magnitude of the impact of each parameter on grid stability depends on the considered specific grid.

In general, more grid stability problems are encountered in rural grids than in urban grids [23][26][58]. Indeed, as shown in Table 3, urban grids tend to have a shorter average feeder length between two consecutive dwellings and a shorter average length of consumer links, as well as a higher percentage of three-phase connected consumers compared to rural grids. This suggests that if LCTs are integrated homogeneously into urban and rural grids, rural grids will likely require more reinforcements in the future. The knowledge of the trends presented in this paragraph and the previous one combined with the collected technical parameters (see Table 2) may help policymakers to identify areas where LCTs are unlikely to pose grid stability issues and thus help them to orientate their policy.

Table 3 – Representative values recommended for the European LV grids' technical parameters.

Number of consumers per island	Average number of consumers per feeder	Percentage of consumers connected to three phases	Transformer nominal power $S_{nom}(\tau)$ (kVA)	Average length between two consecutive nodes (m)	Feeder cross-section (mm^2) and material	Underground ratio (%)	Average length of consumer links (m)	Consumer links cross-section (mm^2) and material
Europe, rural								
78 (91)	17 (16)	0 (0)	400 (288)	55 (59)	3×240 + 1×150 al	43 (49)	15	35 al
Europe, urban								
135 (76)	43 (10)	0 (0)	630 (130)	6 (4)	3×240 (0) + 1×150 (0) al	76 (27)	8	35 al
Belgium, rural								
59 (27)	17 (9)	0 (0)	250 (64)	28 (11)	3×95 (27) + 1×95 (27) al	100 (0)	8 (0)	16 (0) al
Belgium, urban								
72 (31)	20 (10)	17 (41)	250 (139)	11 (7)	3×95 (33) + 1×95 (31) al	100 (0)	3 (0)	16 (0) al
Germany, rural								
32 (29)	11 (7)	100 (0)	250 (110)	45 (30)	3×120 (41) + 1×120 (41) al	61 (49)	22 (7)	50 (0) al
Germany, urban								
148 (31)	18 (5)	100 (0)	400 (190)	19 (6)	3×185 (20) + 1×185 (20) al	100 (0)	12 (3)	50 (3) al

5 Economic parameters

5.1 Parameter description and collected data

To investigate the economic potential and influence of LCTs integration into LV grids, the economic parameters related to LV grid components are also necessary. Table 4 shows the description and price ranges of the collected economic parameters from the literature study, as well as the European country abbreviations of the corresponding data sources. Studies in Germany (DE), Belgium (BE) and the UK provided the most data regarding recorded economic parameters. As the prices of goods and services progressively increase over time, the costs collected from scientific articles and reports were updated with Eq. (1) to calculate the corresponding "2020 equivalent cost". Thus, the values listed in Table 4 are prices in the year 2020.

$$C_{2020} = C_y \cdot (1 + r)^{(2020-y)} \quad (1)$$

where C_{2020} and C_y are the "2020 equivalent cost" and the "cost at year y" (provided in the article/report), respectively. r is the inflation rate, taken to be equal to the average EU yearly inflation rate of 1% from 2016 to 2020 [66]. Note that the cost can also be updated to express the equivalent cost in future years using the same method as in Eq. (1).

Using the values of economic parameters, the life-cycle cost method is usually leveraged to investigate the potential grid reinforcement cost caused by LCTs [35][58]. Note that apart from the collected economic parameters, some LV grid technical parameters (see Section 4) are also usually needed in the economic analysis.

Table 4 – Description and price ranges of economic parameters.

Parameter	Description	Values from the literature
Transformer investment cost $C(\tau)$	Cost of the newly installed transformer.	**150 kVA**: 6.7 k€ (UK [87])* **250 kVA**: 7.5 k€ (BE [13]), 7.6 k€ (DE [63]), 18.6 k€ (UK [87])* **400 kVA**: 10.2 k€ (BE [13]), 8.9 k€ (DE [63]), 8.5 k€ (DE [88]), 30.5 k€ (UK [87])* **630 kVA**: 14.1 k€ (BE [13]), 10.9 k€ (DE [63]), 11.7 k€ (DE [88]), 15.0 k€ (NL [35]), 21.6 k€ (CH [89]) **800 kVA**: 14.3 k€ (DE [88]) **1000 kVA**: 28.3 k€ (ES [90])
Main feeder cables replacement linear cost $C_l(f)$ Consumer link replacement linear cost $C_l(cl)$	Linear cost of replacing feeder cables. Linear cost of replacing consumer link cables.	**Overall costs** Underground (UG) & urban: 77 €/m, UG & semi-urban: 19 €/m, Overhead (OH) & rural: 18 €/m (UK [87])* UG & roadway ground: 72 €/m, UG & sidewalk ground: 48 €/m, UG & meadow ground: 24 €/m (BE [13]) UG & semi-urban: 71-78 €/m, OH & semi-urban: 11-15 €/m (ES [90]) Urban: 82 €/m (CH [89]) Urban: 93-163 €/m (UK [79])* **Cost breakdown** Cables ○ 3×150 mm^2: 19 €/m (DE [63]) ○ 3×150 mm^2 & aluminium: 14 €/m (DE [88]) ○ 3×240 mm^2 & aluminium: 20 €/m (DE [88]) Laying cable: 27 €/m (DE [63]) Surface restoration: 58 €/m (DE [88])
Cost of reconnecting a consumer link to the feeder	This cost applies to the case where the consumers are initially connected to one phase. When connecting LCTs to three phases, the newly installed three-phase consumer link must be connected to the feeder.	453 € (BE [13])
Cost of a three-phase meter	When connecting LCTs to three phases, a new three-phase meter is required.	149 € (BE [91])
Energy losses cost	Cost per kWh of energy losses for the DSO.	0.046 €/kWh (BE [92]), 0.085 €/kWh (DE [63]), 0.074 €/kWh (DE [88])
Planning horizon	This parameter is for the life-cycle cost analysis.	Overall project planning horizon: 33 years (BE [93]) Transformer lifetime: 40 years (NL [35])(DE [88]) Cables lifetime: 40 years (NL [35])(DE [88])
Discount rate	This parameter is for the life-cycle cost analysis.	3% (NL [35]), 4% (CH [89]), 5% (UK [87])(BE [94]), 8% (DE [88])

Note. *: Values were converted from £ to € with the conversion rate of 1.11 €/£ from 3 August 2020 [95].
The value-added tax was not considered for the listed prices.

5.2 Discussion and recommendation of representative values for the economic parameters

Table 4 lists the economic parameters, some of which have multiple values. Stakeholders can select the appropriate values based on their needs. Note that the lack of available data on the cost of grid reinforcement options in all European countries is also a problem for the economic analysis in specific countries. In particular, differences in economic levels between countries may result in different costs for the same grid reinforcement option. Nevertheless, recommendations are also given for representative values for the economic parameters, which can be used for all European countries as a first estimate.

Transformer investment cost. Figure 5 shows the values of the transformer investment cost as a function of the corresponding nominal power from the different references. It is observed that the transformer cost might strongly vary from one reference to another for a given transformer nominal power. Several fit functions based on the data were considered, and the one that best fitted the data was retained ($C(\tau) = 7.13 \cdot \exp\left(0.0012 \cdot S_{nom}(\tau)\right), R^2 = 0.33$). Despite its low R^2, it is observed that the fit function follows the general trend. This function can also be leveraged to estimate the cost of a transformer with unusual nominal power. Recommended representative transformer costs were then obtained from the considered fit function and listed in Table 5.

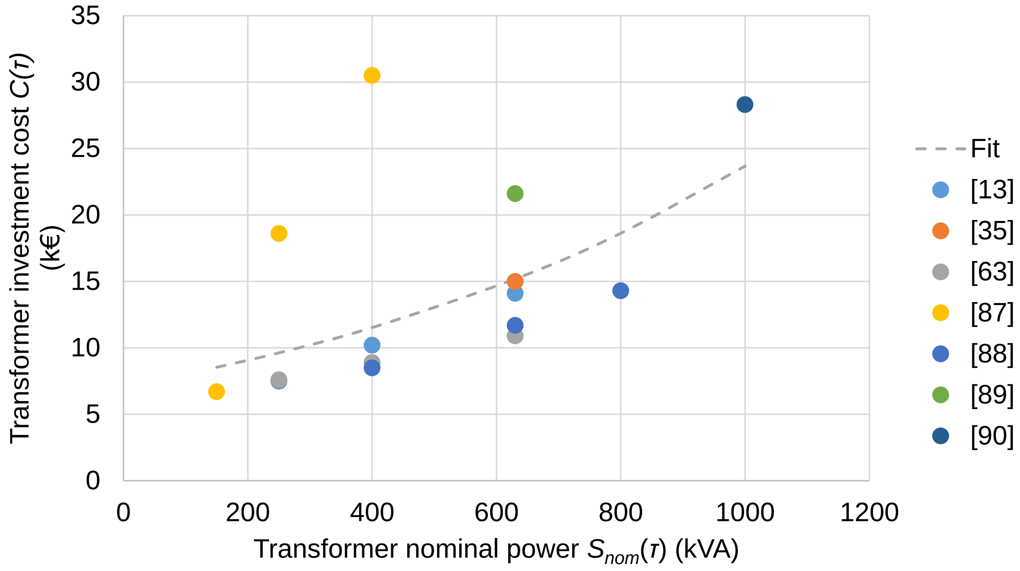

Figure 5 – Transformer investment cost as a function of its nominal power in the literature.

Cable replacement cost. As seen in Table 4, most of the cable replacement cost comes from the cable installation (e.g., laying the cable, surface restoration) and not from the cable itself. Besides, the variation of the cable cost as a function of its cross-section has a small influence on the overall cable replacement cost [58][88]. Consequently, the replacement cost for the main feeder cables and the consumer links can be regarded as the same (i.e., $C_l(f) = C_l(cl)$).

The overall costs in Table 4 indicate that the cable replacement cost strongly varies depending on the zone (rural/urban) and on the cable position (underground-UG/overhead-OH). Besides, despite certain local initiatives for undergrounding cables [13], a clear trend toward cable undergrounding at the EU scale was not identified [71]. It is therefore assumed that UG cables are replaced by UG cables and OH cables by OH cables. The following formula for the cable replacement cost is thus proposed and listed in Table 5:

$$C_l(f)(\text{zone}) = C_l(cl)(\text{zone}) = \%\text{UG}(\text{zone}) \cdot C_l(\text{UG}, \text{zone}) + \%\text{OH}(\text{zone}) \cdot C_l(\text{OH}, \text{zone}) \quad (2)$$

where $\%\text{UG}(\text{zone})$ and $\%\text{OH}(\text{zone})$ are the percentages of the LV cable length which are underground and overhead in the considered zones. These percentages are listed in Table 3.

$C_l(\text{UG}, \text{zone})$ and $C_l(\text{OH}, \text{zone})$ are the linear costs of underground and overhead cable replacement in the considered zone, respectively. $C_l(\text{UG}, \text{zone})$ strongly varies depending on the zone as the work required to open and close a trench depends on the type of ground [13]. In urban zones, the average between the values for urban [87], semi-urban [87][90], sidewalk and roadway ground [13] was considered. This gives $C_l(\text{UG}, \text{urban})$ = 58 €/m. In rural zones, the average between the values for sidewalk and meadow grounds from [13] was considered, which yields to 36 €/m. $C_l(\text{OH}, \text{zone})$ is expected not to vary significantly depending on the zone. For instance, the cost for rural zones, 18 €/m [87], is similar to the cost for semi-urban zones, 11-15 €/m [90]. Consequently, the cost for rural and urban zones can be considered equal to the average between 18 €/m and 11-15 €/m, which yields to 16 €/m. The difference between $C_l(\text{UG})$ and $C_l(\text{OH})$ indicates that the cable replacement cost $C_l(f)$ is higher in areas with a high underground ratio. However, it is important to keep in mind that, in comparison to overhead cables, underground cables are not visible in the landscape, they cause less interference with other facilities and have a lower probability of faults [96].

Regarding the energy losses cost and discount rate, the average values were calculated from the corresponding collected values from Table 4, and these average values are listed in Table 5. The planning horizon from [62] (i.e., 33 years) is recommended and listed in Table 5 as it refers to the overall project planning horizon.

Table 5 – Recommended values for the economic parameters.

Parameter	Values chosen
Transformer investment cost $C(\tau)$	150 kVA: 8.5 k€ 250 kVA: 9.6 k€ 400 kVA: 11.5 k€ 630 kVA: 15.2 k€ 800 kVA: 18.6 k€ 1000 kVA: 23.7 k€
Main feeder cables replacement linear cost $C_l(f)$ Consumer link replacement linear cost $C_l(cl)$	$C_l(f)(\text{zone}) = C_l(cl)(\text{zone}) = \%\text{UG}(\text{zone}) \cdot C_l(\text{UG}, \text{zone}) + \%\text{OH}(\text{zone}) \cdot C_l(\text{OH}, \text{zone})$ where $\%\text{UG}(\text{urban}), \%\text{UG}(\text{rural}), \%\text{OH}(\text{urban}), \%\text{OH}(\text{rural})$ are provided in Table 3, and $C_l(\text{UG}, \text{urban})$ = 58 €/m, $C_l(\text{UG}, \text{rural})$ = 36 €/m, $C_l(\text{OH}, \text{urban})$ = 16 €/m, $C_l(\text{OH}, \text{rural})$ = 16 €/m
Cost of reconnecting a consumer link to the feeder	453 €
Cost of a three-phase meter	149 €
Energy losses cost	0.068 €/kWh
Planning horizon	33 years
Discount rate	5.5 %

6 Conclusions and outlook

This paper gathers and shows the topology, technical and economic parameters of European LV distribution networks through a literature review, examination of European databases, and expert knowledge.

The topology of the typical European LV grid is a three-phase four-wire radial network with one transformer and several feeders. The collected technical parameters (e.g., average number of consumers per feeder, transformer nominal power) of LV grids provide the foundation to build European LV grid models for research. It is observed that the generic European, Belgian and German grids have at least one grid in the rural and urban zones. The German LV grids are the best documented, containing almost all types of technical parameters collected in this study. Representative values for technical parameters for German, Belgian and generic European LV grids are recommended based on the collected resources.

The economic parameters (e.g., transformer replacement cost, energy losses cost) related to the operation of European LV grids and grid reinforcements were also reviewed. Moreover, representative values for the economic parameters in Europe are recommended based on the collected resources.

In addition to collecting raw data and recommending representative values of technical and economic parameters, this work gathers the data resources and references, which allows users (e.g., academics, DSOs) to select appropriate LV grids or develop their own set of technical and economic parameters of LV grids for their purposes. Given the inherent limitations of the relative lack of available data on the grid technical and economic parameters, the results of this study must be treated with caution. A strong effort from DSOs to provide even more open access data would help to improve the accuracy of grid techno-economic analyses. In addition, compiling and comparing grid data from future case studies will keep increasing knowledge on LV grids and their evolution.LV distribution networks are undergoing significant changes with the integration of LCTs, the introduction of new power equipment (e.g., smart meters on consumer premises) and the modification of the substations. The future LV networks should be more supply-driven than the current demand-driven system and more controllable. For stakeholders (e.g., DSOs, microgrids development companies) to play an even more active role in power system balancing, algorithms should be developed and tested in a realistic environment, which prompts the need to understand, master and even develop the corresponding LV test feeders. The reviewed LV grid topology and collected/recommended values for the grid technical parameters can support the research activities on future LV grids (e.g., smart grid technologies) by reducing the resources devoted to building case studies. The collected and recommended values for grid-related economic parameters can further be used to quantify the grid reinforcement costs due to the LCTs integration and evaluate carbon abatement costs (accounting for grid costs). This can inform and help stakeholders to develop the optimal LCTs deployment strategies to reach climate-neutral goals and be the basis for estimating whether smart grid technologies (e.g., demand-side management) are required depending on the context. The findings may also allow academics and consultants to carry out LV grids related analyses at the European scale as a first estimate, which can be of great interest to policymakers.

Acknowledgements

This work is part of the H2020 "sEEnergies" project (https://www.seenergies.eu/). This project has received funding from the European Union's Horizon 2020 Research and Innovation Action under Grant Agreement No 846463.

Appendix A. Specifications of cables and transformer

Cables: applies to feeder segments and consumer links.

These specifications were based on the data from Ref. [97] on cables used in LV grids. The literature review (see Section 4.2) shows that aluminium cables are the most common for feeder segments and consumer links. Therefore, four core cables with an aluminium conductor are considered, which are XLPE-insulated and PVC-sheathed. In addition, according to the specifications of Ref. [97], the cable ampacity slightly depends on its position (overhead or underground) due to the variation of thermal resistance of the medium in which the cable is [86]. Table A-1 shows the specifications of four core cables with an aluminium conductor. The average ampacities in the urban and rural zones for generic European, Belgian, and German LV grids can be deduced through an equation similar to Eq. (2) and the underground ratios listed in Table 3.

Table A-1 – Specifications of four core cables with the aluminium conductor.

Cross-section (mm^2)	Linear resistance (Ω/m)	Ampacity - underground (A)	Ampacity – overhead (A)
16	2.45×10^{-3}	71	61
25	1.54×10^{-3}	93	81
35	1.11×10^{-3}	113	97
50	0.82×10^{-3}	136	118
70	0.57×10^{-3}	166	148
95	0.41×10^{-3}	199	182
120	0.33×10^{-3}	227	211
150	0.27×10^{-3}	254	241
185	0.21×10^{-3}	288	278
240	0.16×10^{-3}	331	330
300	0.13×10^{-3}	377	380
400	0.10×10^{-3}	431	446
500	0.082×10^{-3}	487	515

The linear reactance of feeder segments and consumer links can be considered constant and equal to 0.089×10^{-3} Ω/m [47].

Transformer.

The values provided in the following table were obtained from [98].

Table A-2 – Specifications of transformers.

Nominal power $S_{nom}(\tau)$ (kVA)	No-load losses (W)	Phase resistance (Ω)	Phase reactance (Ω)
100	190	0.033	0.106
150	251	0.022	0.072
250	355	0.012	0.045
400	511	0.007	0.029
630	750	0.004	0.019
800	927	0.003	0.016
1000	1135	0.003	0.013

References

[1] Our World in Data. CO2 emissions by region 2020. https://ourworldindata.org/co2-emissions (accessed August 31, 2022).

[2] European Commission. 2050 long-term strategy. https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en (accessed April 21, 2022).

[3] Nordic Energy Research. Carbon-neutral as soon as 2030 – Nordic Energy Research 2015. https://www.nordicenergy.org/figure/ambitious-climate-targets-and-visions-for-all-nordic-countries/carbon-neutral-as-soon-as-2030/ (accessed August 31, 2022).

[4] Swiss Federal Council. Long-term climate strategy to 2050 2021.

https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/emission-reduction/reduction-targets/2050-target/climate-strategy-2050.html (accessed August 31, 2022).

[5] Sovacool BK, Griffiths S. The cultural barriers to a low-carbon future: A review of six mobility and energy transitions across 28 countries. Renew Sustain Energy Rev 2020;119:109569. https://doi.org/10.1016/j.rser.2019.109569.

[6] European Commission. Quantification of synergies between Energy Efficiency first principle and renewable energy systems. https://cordis.europa.eu/project/id/846463 (accessed September 13, 2022).

[7] The TANGO story: Towards the largest solar factory in Europe. https://ec.europa.eu/clima/news-your-voice/news/tango-story-towards-largest-solar-factory-europe-2022-07-11_en (accessed September 13, 2022).

[8] European Union invests €122 million to decarbonise the economy. Eur Comm 2021. https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3842 (accessed March 28, 2022).

[9] European Commission. Low-carbon solutions integration in power systems 2022. https://ses.jrc.ec.europa.eu/low-carbon-solutions-integration-power-systems.

[10] Koirala A, Van Acker T, D'hulst R, Van Hertem D. Hosting capacity of photovoltaic systems in low voltage distribution systems: A benchmark of deterministic and stochastic approaches. Renew Sustain Energy Rev 2022;155. https://doi.org/10.1016/j.rser.2021.111899.

[11] Carpinelli G, Mottola F, Proto D, Varilone P. Minimizing unbalances in low-voltage microgrids: Optimal scheduling of distributed resources. Appl Energy 2017;191:170–82. https://doi.org/10.1016/j.apenergy.2017.01.057.

[12] Protopapadaki C, Saelens D. Heat pump and PV impact on residential low-voltage distribution grids as a function of building and district properties. Appl Energy 2017;192:268–81. https://doi.org/10.1016/j.apenergy.2016.11.103.

[13] Baetens R. On Externalities of Heat Pump-Based Low-Energy Dwellings at the Low-Voltage Distribution Grid. KU Leuven PhD dissertation, 2015. https://lirias.kuleuven.be/1729314?limo=0.

[14] Sachs JD, Schmidt-Traub G, Williams J. Pathways to zero emissions. Nat Geosci 2016;9:799–801. https://doi.org/10.1038/ngeo2826.

[15] McCollum DL, Zhou W, Bertram C, De Boer HS, Bosetti V, Busch S, et al. Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. Nat Energy 2018;3:589–99. https://doi.org/10.1038/s41560-018-0179-z.

[16] Fragkos P, Tasios N, Paroussos L, Capros P, Tsani S. Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. Energy Policy 2017;100:216–26. https://doi.org/10.1016/j.enpol.2016.10.023.

[17] Liu J, Yin M, Xia-Hou Q, Wang K, Zou J. Comparison of sectoral low-carbon transition pathways in China under the nationally determined contribution and 2 °C targets. Renew Sustain Energy Rev 2021;149:111336. https://doi.org/10.1016/j.rser.2021.111336.

[18] Hodson EL, Brown M, Cohen S, Showalter S, Wise M, Wood F, et al. U.S. energy sector impacts of technology innovation, fuel price, and electric sector CO2 policy: Results from the EMF 32 model intercomparison study. Energy Econ 2018;73:352–70. https://doi.org/10.1016/j.eneco.2018.03.027.

[19] Fragkos P, Laura van Soest H, Schaeffer R, Reedman L, Köberle AC, Macaluso N, et al. Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States. Energy 2021;216. https://doi.org/10.1016/j.energy.2020.119385.

[20] Connolly D, Lund H, Mathiesen B V, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. https://doi.org/10.1016/j.apenergy.2009.09.026.

[21] Haque MM, Wolfs P. A review of high PV penetrations in LV distribution networks: Present status, impacts and mitigation measures. Renew Sustain Energy Rev 2016;62:1195–208. https://doi.org/10.1016/J.RSER.2016.04.025.

[22] Kharrazi A, Sreeram V, Mishra Y. Assessment techniques of the impact of grid-tied rooftop photovoltaic generation on the power quality of low voltage distribution network - A review. Renew Sustain Energy Rev 2020;120:109643. https://doi.org/10.1016/J.RSER.2019.109643.

[23] Venegas FG, Meunier S, Protopapadaki C, Perez Y, Saelens D, Petit M. Impact of distributed energy resources and electric vehicle smart charging on low voltage grid stability. Congr. Int. des Réseaux Electriques Distrib. 2021 Conf., 2021.

[24] Gupta R, Pena-bello A, Nino K, Roduner C. Spatial analysis of distribution grid capacity and costs to enable massive deployment of PV , electric mobility and electric heating. Appl Energy 2021;287:116504. https://doi.org/10.1016/j.apenergy.2021.116504.

[25] Segundo Sevilla FR, Parra D, Wyrsch N, Patel MK, Kienzle F, Korba P. Techno-economic analysis of battery storage and curtailment in a distribution grid with high PV penetration. J Energy Storage 2018;17:73–83. https://doi.org/10.1016/j.est.2018.02.001.

[26] McKenna R, Djapic P, Weinand J, Fichtner W, Strbac G. Assessing the implications of socioeconomic diversity for low carbon technology uptake in electrical distribution networks. Appl Energy 2018;210:856–69. https://doi.org/10.1016/j.apenergy.2017.07.089.

[27] Mancarella P, Gan CK, Strbac G. Evaluation of the impact of electric heat pumps and distributed CHP on LV networks. 2011 IEEE Power Energy Soc. Trondheim PowerTech, 2011. https://doi.org/10.1109/PTC.2011.6019297.

[28] Pudjianto D, Djapic P, Aunedi M, Gan CK, Strbac G, Huang S, et al. Smart control for minimizing distribution network reinforcement cost due to electrification. Energy Policy 2013;52:76–84. https://doi.org/10.1016/j.enpol.2012.05.021.

[29] Talavera DL, Muñoz-Cerón E, Ferrer-Rodríguez JP, Nofuentes G. Evolution of the cost and economic profitability of grid-connected PV investments in Spain: Long-term review according to the different regulatory frameworks approved. Renew Sustain Energy Rev 2016;66:233–47. https://doi.org/10.1016/j.rser.2016.08.012.

[30] Richardson P, Moran M, Taylor J, Maitra A, Keane A. Impact of electric vehicle charging on residential distribution networks: An Irish demonstration initiative. IET Conf. Publ., 2013. https://doi.org/10.1049/cp.2013.0873.

[31] Luthander R, Shepero M, Munkhammar J, Widén J. Photovoltaics and opportunistic electric vehicle charging in the power system – A case study on a Swedish distribution grid. IET Renew Power Gener 2019;13:710–6. https://doi.org/10.1049/iet-rpg.2018.5082.

[32] Van Der Burgt J, Vera SP, Wille-Haussmann B, Andersen AN, Tambjerg LH. Grid impact of charging electric vehicles; Study cases in Denmark, Germany and the Netherlands. 2015 IEEE Eindhoven PowerTech, PowerTech 2015, Institute of Electrical and Electronics Engineers Inc.; 2015. https://doi.org/10.1109/PTC.2015.7232234.

[33] Pillai JR, Thogersen P, Moller J, Bak-Jensen B. Integration of Electric Vehicles in low voltage Danish distribution grids. IEEE Power Energy Soc. Gen. Meet., 2012. https://doi.org/10.1109/PESGM.2012.6343948.

[34] Brinkel NBG (Nico., Gerritsma MK (Marte., AlSkaif TA (Tarek., Lampropoulos I (Ioannis), van Voorden AM (Arjan., Fidder HA (Henk., et al. Impact of rapid PV fluctuations on power quality in the low-voltage grid and mitigation strategies using electric vehicles. Int J Electr Power Energy Syst 2020;118:105741. https://doi.org/10.1016/j.ijepes.2019.105741.

[35] Brinkel NBG, Schram WL, AlSkaif TA, Lampropoulos I, van Sark WGJHM. Should we reinforce the grid? Cost and emission optimization of electric vehicle charging under different transformer limits. Appl Energy 2020;276:115285. https://doi.org/10.1016/j.apenergy.2020.115285.

[36] Ruf H. Limitations for the feed-in power of residential photovoltaic systems in Germany – An overview of the regulatory framework. Sol Energy 2018;159:588–600. https://doi.org/10.1016/j.solener.2017.10.072.

[37] Biener W, Dallmer-Zerbe K, Krug B, Gust G, Wille-Haussmann B. Automated distribution grid planning considering Smart Grid and conventional grid reinforcement technologies. Int. Power Eng. Soc. Congr. 2015; Die Energiewende - Blueprints New Energy Age, 2015.

[38] Medjroubi W, Müller UP, Scharf M, Matke C, Kleinhans D. Open Data in Power Grid Modelling: New Approaches Towards Transparent Grid Models. Energy Reports 2017;3:14–21. https://doi.org/10.1016/j.egyr.2016.12.001.

[39] Ringkjøb HK, Haugan PM, Solbrekke IM. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew Sustain Energy Rev 2018;96:440–59. https://doi.org/10.1016/j.rser.2018.08.002.

[40] Tang H, McMillin B. Security of information flow in the electric power grid. Int. Conf. Crit. Infrastruct. Prot., vol. 253, 2007, p. 43–56.

[41] Nygard KE, Ghosn SB, Chowdhury MM, Loegering D, McCulloch R, Ranganathan P. Optimization models for energy reallocation in a smart grid. 2011 IEEE Conf. Comput. Commun. Work., 2011, p. 186–90.

[42] Schavemaker P, der Sluis L. Electrical power system essentials. John Wiley & Sons; 2017. https://books.google.dk/books?hl=en&lr=&id=Kz_CDgAAQBAJ&oi=fnd&pg=PR13&dq=Electrical+power+system+essentials&ots=pAjTB9ayiq&sig=ZRotwcqA9OBQ4VuPc-OlC_AwgHY&redir_esc=y#v=onepage&q=Electrical power system essentials&f=false.

[43] OpenDSS 2021. https://www.epri.com/pages/sa/opendss (accessed October 15, 2021).

[44] Pacific Northwest National Laboratory. GridLAB-D Simulation Software 2021. https://www.gridlabd.org/.

[45] Roy J Van, Salenbien R, Driesen J. Modelica Library for Building and Low-Voltage Electrical AC and DC Grid Modeling. Proc. 10th Int. Model. Conf. March 10-12, 2014, Lund, Sweden, vol. 96, 2014, p. 301–9. https://doi.org/10.3384/ecp14096301.

[46] Mateo C, Prettico G, Gómez T, Cossent R, Gangale F, Frías P, et al. European representative electricity distribution networks. Int J Electr Power Energy Syst 2018;99:273–80. https://doi.org/10.1016/j.ijepes.2018.01.027.

[47] Koirala A, Suárez-Ramón L, Mohamed B, Arboleya P. Non-synthetic European low voltage test system. Int J Electr Power Energy Syst 2020;118. https://doi.org/10.1016/j.ijepes.2019.105712.

[48] Marcos FEP, Domingo CM, Román TGS, Palmintier B, Hodge BM, Krishnan V, et al. A review of power distribution test feeders in the United States and the need for synthetic representative networks. Energies 2017;10:1896. https://doi.org/10.3390/en10111896.

[49] Schneider KP, Mather BA, Pal BC, Ten CW, Shirek GJ, Zhu H, et al. Analytic Considerations and Design Basis for the IEEE Distribution Test Feeders. IEEE Trans Power Syst 2018;33:3181–8. https://doi.org/10.1109/TPWRS.2017.2760011.

[50] Green RC, Wang L, Alam M. The impact of plug-in hybrid electric vehicles on distribution networks: A review and outlook. Renew Sustain Energy Rev 2011;15:544–53. https://doi.org/10.1016/J.RSER.2010.08.015.

[51] Rahman S, Khan IA, Khan AA, Mallik A, Nadeem MF. Comprehensive review & impact analysis of integrating projected electric vehicle charging load to the existing low voltage distribution system. Renew Sustain Energy Rev 2022;153:111756. https://doi.org/10.1016/j.rser.2021.111756.

[52] Gupta R, Sossan F, Paolone M. Countrywide PV hosting capacity and energy storage requirements for distribution networks: The case of Switzerland. Appl Energy 2021;281:116010. https://doi.org/10.1016/j.apenergy.2020.116010.

[53] IEEE. IEEE power and energy society test feeder 2017. https://site.ieee.org/pes-testfeeders/resources/ (accessed July 25, 2021).

[54] González-Morán C, Arboleya P, Pilli V. Photovoltaic self consumption analysis in a European low voltage feeder. Electr Power Syst Res 2021;194:107087. https://doi.org/10.1016/j.epsr.2021.107087.

[55] Koirala A. Real European Low Voltage Test Network for Smart Grid Applications. Universidad de Oviedo, 2018. https://digibuo.uniovi.es/dspace/handle/10651/48501.

[56] Strunz K, Abbey C, Andrieu C, Campbell RC, Fletcher R. Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources. 2014.

[57] Petinrin JO, Shaabanb M. Impact of renewable generation on voltage control in distribution systems. Renew Sustain Energy Rev 2016;65:770–83. https://doi.org/10.1016/j.rser.2016.06.073.

[58] Meunier S, Protopapadaki C, Baetens R, Saelens D. Impact of residential low-carbon technologies on low-voltage grid reinforcements. Appl Energy 2021;297:117057. https://doi.org/10.1016/j.apenergy.2021.117057.

[59] Resch M. Impact of operation strategies of large scale battery systems on distribution grid planning in Germany. Renew Sustain Energy Rev 2017;74:1042–63. https://doi.org/10.1016/j.rser.2017.02.075.

[60] Bayer B, Matschoss P, Thomas H, Marian A. The German experience with integrating photovoltaic systems into the low-voltage grids. Renew Energy 2018;119:129–41. https://doi.org/10.1016/j.renene.2017.11.045.

[61] Pereira GI, Specht JM, Silva PP, Madlener R. Technology, business model, and market design adaptation toward smart electricity distribution: Insights for policy making. Energy Policy 2018;121:426–40. https://doi.org/10.1016/j.enpol.2018.06.018.

[62] Kohlhepp P, Harb H, Wolisz H, Waczowicz S, Müller D, Hagenmeyer V. Large-scale grid integration of residential thermal energy storages as demand-side flexibility resource: A review of international field studies. Renew Sustain Energy Rev 2019;101:527–47. https://doi.org/10.1016/j.rser.2018.09.045.

[63] Stetz T, Marten F, Braun M. Improved low voltage grid-integration of photovoltaic systems in Germany. IEEE Trans Sustain Energy 2013;4:534–42. https://doi.org/10.1109/TSTE.2012.2198925.

[64] United Nations Development Programme. Sustainable Development Goals. United Nations Dev Program 2021. https://www.undp.org/seoul-policy-centre/sustainable-development-goals?utm_source=EN&utm_medium=GSR&utm_content=US_UNDP_PaidSearch_Brand_English&utm_campaign=CENTRAL&c_src=CENTRAL&c_src2=GSR&gclid=Cj0KCQjwqc6aBhC4ARIsAN06NmOU2E4q0mTp-0jSc0ESQ_gSGEcN6_mJQ_ (accessed October 22, 2022).

[65] How Many Countries Are There In Europe? 2021. https://www.worldatlas.com/articles/how-many-countries-are-in-europe.html (accessed September 5, 2022).

[66] Statistica. Inflation rate in the European Union and the Euro area from 2009 to 2021 2020. https://www.statista.com/statistics/267908/inflation-rate-in-eu-and-euro-area/ (accessed July 25, 2021).

[67] EN 50160:2010 Voltage characteristics of electricity supplied by public electricity networks 2011:38.

[68] Kerber Networks — pandapower 2.6.0 documentation. https://pandapower.readthedocs.io/en/v2.6.0/networks/kerber.html (accessed September 10, 2021).

[69] Protopapadaki C. A probabilistic framework towards metamodeling the impact of residential heat pumps and PV on low-voltage grids. KU Leuven PhD dissertation, 2018. https://lirias.kuleuven.be/2328633.

[70] Rodriguez-Calvo A, Cossent R, Frías P. Integration of PV and EVs in unbalanced residential LV networks and implications for the smart grid and advanced metering infrastructure deployment. Int J Electr Power Energy Syst 2017;91:121–34. https://doi.org/10.1016/j.ijepes.2017.03.008.

[71] Prettico G, Gangale F, Mengolini A, Lucas A, Fulli G. Distribution system operators observatory: from European electricity distribution systems to representative distribution networks. 2016. https://doi.org/10.2790/471701.

[72] International Council on Large Electric Systems Networks — pandapower 2.6.0 documentation. https://pandapower.readthedocs.io/en/v2.6.0/networks/cigre.html (accessed November 1, 2021).

[73] Gonzalez C, Geuns J, Weckx S, Wijnhoven T, Vingerhoets P, De Rybel T, et al. LV distribution network feeders in Belgium and power quality issues due to increasing PV penetration levels. IEEE Power Energy Soc Innov Smart Grid Technol Conf Eur 2012. https://doi.org/10.1109/ISGTEurope.2012.6465624.

[74] Roy J Van. Electric vehicle charging integration in buildings: Local charging coordination and DC grids. KU Leuven, 2015. https://lirias.kuleuven.be/1731293?limo=0.

[75] Synthetic Voltage Control LV Networks — pandapower 2.6.0 documentation. https://pandapower.readthedocs.io/en/v1.6.1/networks/synthetic_voltage_control_lv_networks.html (accessed July 24, 2021).

[76] Few S, Djapic P, Strbac G, Nelson J, Candelise C. Assessing local costs and impacts of distributed solar PV using high resolution data from across Great Britain. Renew Energy 2020;162:1140–50. https://doi.org/10.1016/j.renene.2020.08.025.

[77] Navarro-Espinosa A, Mancarella P. Probabilistic modeling and assessment of the impact of electric heat pumps on low voltage distribution networks. Appl Energy 2014;127:249–66. https://doi.org/10.1016/j.apenergy.2014.04.026.

[78] Vegunta SC, Twomey P, Randles D. Impact of PV and load penetration on LV network voltages and unbalance and potential solutions. 22nd Int. Conf. Exhib. Electr. Distrib., 2013. https://doi.org/10.1049/cp.2013.1256.

[79] Navarro-Espinosa A, Ochoa LF. Increasing the PV hosting capacity of LV networks: OLTC-fitted transformers vs. reinforcements. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf., 2015. https://doi.org/10.1109/ISGT.2015.7131856.

[80] Navarro-Espinosa A, Ochoa LF. Probabilistic Impact Assessment of Low Carbon Technologies in LV Distribution Systems. IEEE Trans Power Syst 2016;31:2192–203. https://doi.org/10.1109/TPWRS.2015.2448663.

[81] Quirós- Tortós J, Ochoa LF. Multi- year planning of LV networks with EVs accounting for customers, emissions and techno- economics aspects: A practical and scalable approach. IET Gener Transm Distrib 2021;15:468–79. https://doi.org/10.1049/gtd2.12034.

[82] Navarro-Espinosa A. Low Carbon Technologies in Low Voltage Distribution Networks : Probabilistic Assessment of Impacts and Solutions. The University of Manchester, 2015. https://www.escholar.manchester.ac.uk/item/?pid=uk-ac-man-scw:278470.

[83] Azibek B, Abukhan A, Nunna HSVSK, Mukatov B, Kamalasadan S, Doolla S. Hosting Capacity Enhancement in Low Voltage Distribution Networks: Challenges and Solutions. IEEE Int. Conf. Power Electron. Smart Grid Renew. Energy, Institute of Electrical and Electronics Engineers Inc.; 2020. https://doi.org/10.1109/PESGRE45664.2020.9070466.

[84] Pearce JM, Sommerfeldt N. Economics of grid-tied solar photovoltaic systems coupled to heat pumps: The case of northern climates of the U.S. and Canada. Energies 2021;14:834. https://doi.org/10.3390/en14040834.

[85] Protopapadaki C, Saelens D. Towards metamodeling the neighborhood-level grid impact of low-carbon technologies. Energy Build 2019;194:273–88. https://doi.org/10.1016/j.enbuild.2019.04.031.

[86] Meyers RA. Encyclopedia of physical science and technology. vol. 39. 3rd ed. Academic; 2002. https://doi.org/10.5860/choice.39-3718.

[87] Ma K, Li R, Li F. Quantification of Additional Asset Reinforcement Cost from 3-Phase Imbalance. IEEE Trans Power Syst 2016;31:2885–91. https://doi.org/10.1109/TPWRS.2015.2481078.

[88] Stetz T, Diwold K, Kraiczy M, Geibel D, Schmidt S, Braun M. Techno-economic assessment of voltage control strategies in low voltage grids. IEEE Trans Smart Grid 2014;5:2125–32. https://doi.org/10.1109/TSG.2014.2320813.

[89] Morvaj B, Evins R, Carmeliet J. Decarbonizing the electricity grid: The impact on urban energy systems, distribution grids and district heating potential. Appl Energy 2017;191:125–40. https://doi.org/10.1016/j.apenergy.2017.01.058.

[90] Cossent R, Olmos L, Gómez T, Mateo C, Frías P. Distribution network costs under different penetration levels of distributed generation. Eur Trans Electr Power 2010;21:1869–88. https://doi.org/10.1002/ETEP.503.

[91] Fluvius. Elektriciteit tariefbladen finaal 2020. https://www.fluvius.be/sites/fluvius/files/2019-12/fluvius-aansluittarieven-elektriciteit-2020.pdf (accessed June 30, 2021).

[92] Elexys. Ice Endex Power BE. MyElexysBe 2020. https://my.elexys.be/MarketInformation/IceEndexPowerBE.aspx (accessed July 25, 2021).

[93] Vlaamse Regulator van de Elektriciteits-en Gasmarkt. Tariefmethodologie voor distributie elektriciteit en aardgas gedurende de reguleringsperiode 2017-2020 2019. https://www.vreg.be/nl/tariefmethodologie-2017-2020 (accessed

October 1, 2021).

[94] Baetens R. Aansluiting met flexibele toegang in Vlaanderen 2017. https://www.vreg.be/sites/default/files/simulatiestudie_aansluiting_met_flexibele_toegang_externe_publicatie.pdf (accessed August 8, 2021).

[95] 1 GBP to EUR - British Pounds to Euros Exchange Rate 2021. https://www.xe.com/currencyconverter/convert/?Amount=1&From=GBP&To=EUR (accessed July 25, 2021).

[96] Aras F, Oysu C, Yilmaz G. An assessment of the methods for calculating ampacity of underground power cables. Electr Power Components Syst 2005;33:1385–402. https://doi.org/10.1080/15325000590964425.

[97] Bahra Cables Company. Low Voltage Power Cables 2008. https://www.bahra-electric.com/Downloads/Low_Voltage.pdf (accessed July 24, 2021).

[98] Baetens R, De Coninck R, Jorissen F, Picard D, Helsen L, Saelens D. Openideas - An open framework for integrated district energy simulations. 14th Build. Simul. Conf., 2015, p. 347–54.