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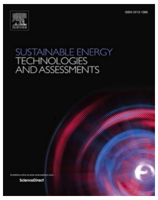

Technical evaluation of European and North American sustainable benchmark scenarios based on renewable Local energy Communities penetration

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ABSTRACT

The growing electrification and renewable energies integration, driven by global sustainability and efficiency objectives, foster future scenarios providing actors such as distributed energy resources, storage, and active consumers with a crucial role in the energy transition. The aim of this work is to assess the impact on distribution networks of the emergence and proliferation of sustainable Local Energy Communities. The methodology employed in this study uses quasi-dynamic simulations based on scenarios involving varying levels of electric demand and low voltage networks under both business-as-usual and Local Energy Communities-based conditions. This approach enables quantification of key indicators and provides insight into the technical impact of Local Energy Communities integration in distribution networks considering European and North American benchmark cases as reference systems. The results obtained allow concluding that reference systems with meshed topologies can withstand electric demand growth with less severe impacts compared to radial systems. Furthermore, the integration of sustainable Local Energy Communities provides improvements, of different level for each scenario, in voltage profiles (kept within operation limits), overloads (up to 50% reduction) and technical losses (up to 37% reduction).

Introduction

The evolution of the energy model, pursuing sustainable energy consumption produced from renewable energy sources, meeting current challenges of quality, continuity, reliability and resilience, is becoming increasingly critical in order to fulfil European and global objectives focused on alleviating energy dependence on fossil fuels and mitigating the effects of climate change.

At European level, the green pact focused on sustainable development, the "Green Deal", contemplates "*a pan-European integrated energy system that is low in carbon, secure, reliable, resistant, accessible, cost-efficient that supplies all of society and paves the way for a fully carbon neutral economy by 2050, maintaining and expanding industrial leadership in energy systems during the energy transition*" [1]. At the same time, reference areas such as North America are developing policy proposals addressing the climate crisis and subsequent sustainability issues, as well as socio-economic-related aspects. The United States Federal *Green New Deal (GND)* is a relevant example [2]. Electricity is set to become a key element of energy transition with global reach. Along with the increase of renewable generation, the electrification of society will play a critical role in achieving the emissions reduction pursued. In its report "*Net Zero by 2050. A Roadmap for the Global Energy Sector*", the International Energy Agency (IEA) forecasts that "*The global demand for electricity more than doubles between 2020 and 2050*" [3].

A relevant and cross-sectional element for upcoming scenarios is the price of electricity, whose recent increase and variability, together with the technological development experienced by renewable generation devices and storage systems, have boosted interest in sustainable self-consumption from renewable energies. In this line, according to mentioned IEA's Net Zero Emissions by 2050 Scenario, the number of households relying on solar PV is growing from 25 million in 2022 to more than 100 million by 2030 [4]. Consequently, renewable energies

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are expected to account for approximately 40 % of building electricity consumption by 2030 [5]. A further step in this context is given by Local Energy Communities (hereinafter, LEC), born with aims such as obtaining cooperative advantages from renewable generation facilities and potential scopes as energy efficiency services or consumptions aggregation. Although LEC are in emerging regulatory phases, their evolution and penetration are expected to have a significant impact [6].

Such LEC growing perspectives technically involve high increases in the penetration of elements such as dispersed generation units, storage systems (in general, distributed energy resources, DER) and manageable loads in low voltage (LV) distribution networks. Therefore, electricity networks face the challenges of feeding growing electricity demands and integrating new generation based on non-manageable primary resources, not only in large-scale renewable energy plants but also from the mentioned rising presence of embedded distributed renewable generation sources [7]. This new paradigm requires electrical networks to fulfil their backbone role for electric supply under dramatically different conditions from those under which they were originally designed; that is, evolution from systems based on unidirectional supply by large plants, based on predictable, manageable and synchronous generation sources, to bidirectional, disperse, variable and power electronics-based systems. These challenges include the participation of new actors such as aggregators, prosumers, or LEC [8].

Along with challenges, opportunities and tools for success in reaching the mentioned overarching global objectives arise, fostered by the new paradigm and its enabler: Smart Grids developments [9]. Technologies for DER integration and improvement of transmission and distribution assets operation, contribute to paving the way for electrification of society, linked to the energy transition and sustainability [10,11,12]. Moreover, solutions for coordinating the management and control of dispersed resources and loads (which includes aggregation and LEC) provide flexibility to the system, which is critical to cope with the variability of the primary resource associated with renewable generation [13]. Different research projects tackle challenges by working in the development of technology solutions aimed at enhancing the integration of LEC in energy systems.

The existing literature, as highlighted in the provided references, delves deeply into the challenges and solutions concerning the integration of DER in Power Systems. This prevalent focus centers on ensuring stable DER connections and optimizing real-time operations, often employing real-time control algorithms. However, a gap emerges when seeking quantitative assessments of the impacts of embedded connections of renewable generation sources and self-consumption installations within distribution networks.

The novelty of the present work emerges in its detailed exploration of the technical implications stemming from the growth of renewable-based LEC within electrical distribution systems. LECs are identified as potential key actors in sustainable electrification and increased renewable energy penetration. Consequently, this research elucidates both qualitative and quantitative effects, in technical indicators such as voltage levels, overloads, and technical losses, arising from LEC penetration, especially in scenarios of growing electricity demands.

Diverging from the prevailing operation-centric focus in existing studies, this work introduces a unique methodology tailored for technical scenario assessments. Building on the foundation presented in reference [14], this study contrasts two distinct benchmark systems designed for Europe and North America. These models, representing various socio-economic perspectives in terms of electric demand and DER inclusion, reflect the intricate features of two real-world representative distribution configurations. Rooted in an all-encompassing set of indicators, the presented methodology aims to highlight not only the steady-state operational aspects of the network but also its overarching energy efficiency and sustainability metrics. By drawing parallels between scenarios spanning diverse global regions, the research encompasses a variety of design paradigms, spanning from network layouts to consumption patterns and renewable energy profiles.

The methodology, complemented by the findings, seeks to provide decision-makers, system operators, and regulators with comprehensive insights, setting the stage for the development of future energy infrastructures. Moreover, this research positions itself as a potential cornerstone for more granular, subsequent network analysis studies.

This paper is organized as follows: Section 2 describes the general methodology followed in the work, including the definition of indicators, benchmark systems and study cases. In section 3 simulation tools and modelling details are presented, with focus on load and generation profiles. Section 4 presents the results obtained in terms of the impact of PV based LEC integration in the LV distribution network, considering both reference systems analyzed. Finally, Section 5 summarizes the main conclusions of the study and introduces further working lines.

Methodology

The presented methodology proposes an analytic approach oriented to provide means to understand the behaviour of power systems under different sustainability assumptions and, thus, to provide insights for improving energy scenarios technical estimations and systems development planning processes.

To quantify the technical impact of the electric demand growth and the integration of LEC, a set of simulation analyses based on the comparison of different scenarios, with and without LEC, and considering two representative systems (European and North American) has been performed. Three main KPIs (Key Performance Indicators) are used to quantify the results:

- LV voltage levels.
- Line sections load levels.
- Technical losses.

These KPIs have been selected since voltage profiles and load levels of network infrastructure are variables highly representative of the status of a power system when considering steady state conditions. In addition, technical losses impact efficiency and sustainability remarkably. Furthermore, the selected parameters are strongly affected by electric demand growth and DER penetration, both key factors of the scenarios related to the energy transition.

The calculation of the described KPIs is based on the analysis of the Power System operation by performing quasi-dynamic power flow simulations using PowerFactory DIgSILENT [15] software. In the following subsections, the building of the test cases and scenarios is described, while section 3 provides details of simulation tools and load and generation profiles modelling.

Benchmark systems

Two benchmark systems have been defined in order to be used as base where loads and PV units are integrated according to different levels of demand evolution and generation penetration, defining the sets of scenarios detailed in 2.2. With the aim of analyzing similarities and differences of representative cases, in terms of electric demand evolution perspective and with increasing interest in LEC, European and North American reference benchmark networks are analyzed. Moreover, both networks present relevant differences in LV systems topology (radial versus meshed) which enriches the comparison. Further analyses in future research works will expand the study to additional relevant areas.

European benchmark system

The European benchmark system is based on the *IEEE European Low Voltage Test Feeder* [16], a reference network developed by the IEEE working group of the Distribution System Analysis Subcommittee of the Power Systems Analysis, Computing, and Economics (PSACE) Committee, with the purpose of providing a benchmark for researching LV feeders common in Europe. Specific details of one-line scheme and test feeder parameters along with load profiles are provided by IEEE in [17].

The LV test feeder is a radial distribution feeder connected to the medium voltage (MV) system through a transformer at the substation, which steps the voltage down from 11 kV to 416 V.

The LV feeder includes the connection of loads at different nodes, with the summation of the rated power of all loads fed by the LV line being equal to 335 kW. Each individual load implements a one-minute time resolution over 24 h for time-series simulation. For scenarios considering LEC integration, PV units connected at demand nodes have been modelled, using real generation hourly p.u. profiles based on data from south Spain. In section 3 the load and generation modelling is explained. Fig. 1 shows the one-line diagram of the European benchmark.

North American benchmark system

For the sake of consistency, the North American benchmark system built for the presented work, is also based on IEEE references, specifically on the *342-Node Low Voltage Network Test System* [18], developed by the Test Feeders Working Group of the Distribution System Analysis (DSA) Subcommittee of PSACE Committee. As explained by the developers, this network is representative of LV systems deployed in urban cores in North America. Considering that the power system in such urban cores can be a combination of spot networks and grid networks, the reference LV test system includes a single 120/208 V grid system and 8 277/480 V spot networks. These LV system and spot networks are supplied by 8 13.2 kV MV distribution feeders supplied from a single High Voltage (HV) substation. Schemes, topology, network elements details and nominal load values are detailed by IEEE in [19].

Fig. 2 shows a complete one-line diagram of the system, including HV and MV elements (in red), LV network in blue, and LV spot nodes in green. The topology of this network, specifically in LV side, is more complex than the one considered for European reference case, due to its non-radial but heavily meshed configuration. For security reasons, the low voltage side of transformers are equipped with protections preventing the LV network from providing power back into the primary distribution feeders.

The North American LV System includes nominal values for the demand connected to LV nodes, with the summation of the rated power of all loads being above 40 MW. Such value is significantly higher than the total load fed by the European benchmark feeder, which is aligned with the differences in complexity between both systems (radial feeder in Europe and meshed network in North America).

Unlike the *IEEE European LV Test Feeder*, the North American LV Network Test System does not include hourly load profiles for the demand (only nominal values). Therefore, its demand characterization has been completed with p.u. hourly profiles from public reference data of North America urban areas. Section 3.1.2 explains the integration and modelling of load and generation profiles in this benchmark network.

Scenarios

The methodology followed in the present work is based on the analysis of the KPIs introduced above considering several scenarios implemented for each representative benchmark system.

The definition of the scenarios reflects the evolution of both PV-based LEC integration and electric demand growth, contemplating the link between sustainability and the electrification of society mentioned in the introduction, therefore considering an increasing evolution of electricity consumption, as explained below.

Depending on the consideration of the integration of LEC, the scenarios are classified as Business As Usual (BAU) and LEC scenarios, according to the following criteria:

BAU scenarios.

These scenarios consider a conventional system with all the demand fed by HV and MV networks. In the base case scenario the demands are based on nominal values included in the benchmark systems (profiles described in 3.1). For the subsequent scenarios, variations of the nominal demand at each node are considered, based on the global energy demand evolution forecast by IEA noted in the introduction. The defined BAU scenarios are listed below, indicating in the name of the scenario the nominal value considered for the loads, with respect to the base scenario:

- Base case.
- 120 % demand.
- 140 % demand.
- 160 % demand.
- 180 % demand.
- 190 % demand.

LEC scenarios.

These scenarios consider the integration of PV units in the demand

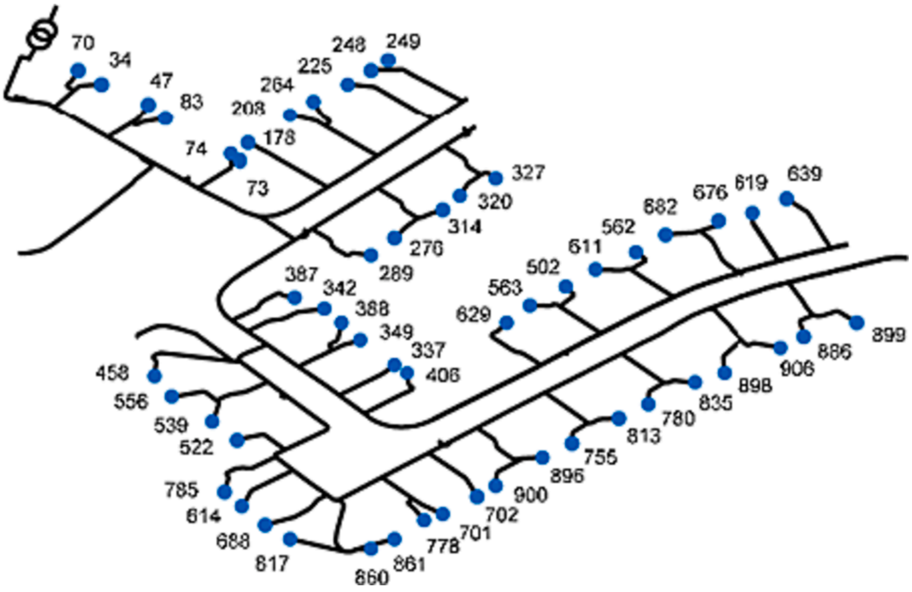

Fig. 1. One-line diagram of the European LV test feeder.

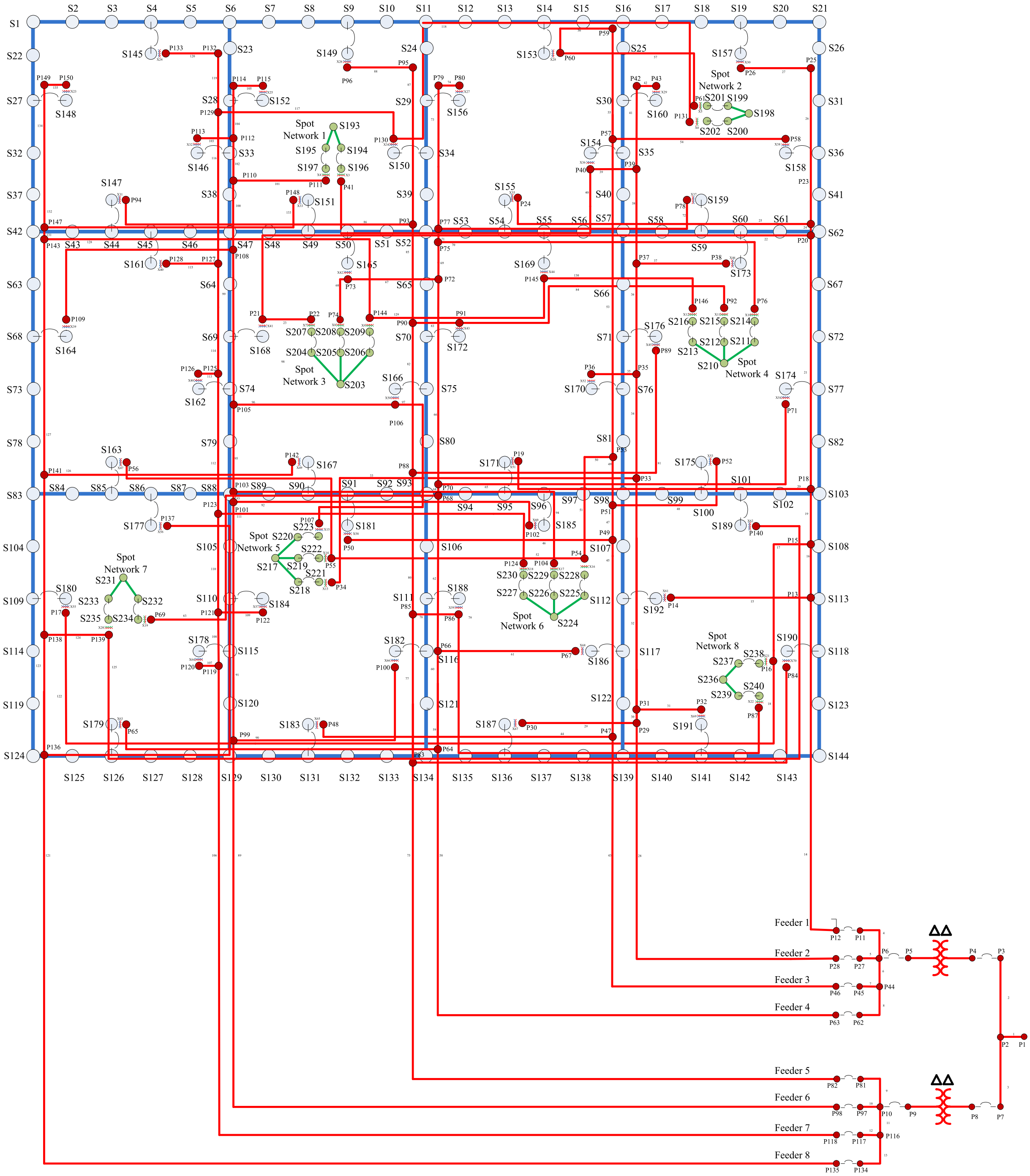

Fig. 2. One-line diagram of the North American LV Test System.

nodes, thus emulating the behaviour of sustainable LEC. Following the same criteria of BAU scenarios, and pursuing the feasibility of comparing scenarios, the same variation ratios of nominal power of PV generation is considered to define the LEC scenarios. The defined LEC scenarios, whose names indicate the ratios of nominal power values considered for loads and for PV units with respect to the base scenario, are listed below:

- Base case: Nominal loads of benchmark systems. PV units connected at each demand node, with nominal values explained in 3.1.1.2 and 3.1.2.2.
- 120 % demand & PV.
- 140 % demand & PV.
- 160 % demand & PV.
- 180 % demand & PV.
- 190 % demand & PV.

Limits of the study

As it is outlined above, the primary objective of this work is to discern the technical implications arising from different sustainability assumptions incorporated into prospective scenarios, intended to feed technically-oriented planning processes. This specific focus requires setting boundaries for the analysis, thereby excluding from the scope of the study certain aspects to be explored in subsequent works. Next, the main limitations of the present study are listed.

- The system models and simulations conducted focus on steady-state network studies, evaluating the evolution of electrical variables over a designated period (as detailed in section 3). As a result, the utilized modeling and simulation techniques are not suited for online or real-time applications, which belong to different type of analyses with objectives that diverge from those pursued in this work.
- The findings of the study, presented in section 4, seek to derive insights into the technical behaviour of the considered Power Systems, thus being an essential input for planning processes. The economic analysis of the scenarios is outside the scope of this work, as a potential continuation in future studies. A preliminary, non-exhaustive list for a cost-benefit analysis (CBA) might encompass aspects such as the implementation costs of DER, costs associated with subsequent monitoring and control elements, potential infrastructure savings in distribution networks, evolving electricity costs, regulatory framework, as well as various social and environmental considerations.
- The research concentrates on two benchmark systems that draw from IEEE reference models for Europe and North America. Utilizing benchmark systems is a standard approach both for system operators and planners, as well as for research projects. These models capture many of the characteristics of actual distribution systems, however complementary studies should be carried out to replicate the analysis in additional regions or to zoom in on a specific, real-life distribution system.
- The design of the energy communities under consideration is based on the deployment of photovoltaic solar generation units, given that solar is currently the predominant technology for distributed generation in self-consumption installations. This study does not cover other elements like storage or alternative renewable sources, such as wind, providing pathways for future research.

Models and calculation

This section explains the implementation of the benchmark systems and scenarios described, including topologies, loads and generation units modelling in simulation platform. In addition, the calculation process for the selected KPIs is included.

Simulation models

The following subsections detail the models of both benchmarks systems used as test benches to extract the results presented in 4, paying special attention to the considerations for the load and generation profiles definition and modelling.

Models for European benchmark system

The reference topology of the benchmark European network ([17], Fig. 1) has been modelled in the simulation platform PowerFactory, including the properties of the network elements briefly described in 2.1.1, as well as loads and generation profiles.

Load profiles. Each node of the IEEE European LV test feeder includes a load representing the demand fed in such point, and is modelled considering base power, power factor and load profile with a one-minute time resolution. The source data of IEEE European LV test feeder is found in [17]. Different modifications in the initial load profiles data included in the IEEE benchmark feeder were required, in order to obtain geographical consistency with real generation data considered. In previous work [14] this process is detailed.

Generation profiles. The integration of LEC is modelled through the connection of distributed PV units at the demand nodes, developed in PowerFactory taking into account nominal power and daily generation profiles (based on real data obtained from measurements in June from PV installations). Next, the quantification of the nominal power of each PV unit is undertaken, taking as reference the magnitude of the rated electric consumption at each connection node, considering consequently a fraction of the maximum demand of the affected node, being the chosen criterion 50 % of the maximum power demanded (maximum value between 13:45 h and 14:45 h). Finally, since PV connection is assumed to be mainly for self-consumption purposes, the electric connection of generation units at each node replicates the single-phase topology of the loads.

Models for North American benchmark system

The reference topology of the North American benchmark network, including its different elements introduced in section 2.1.2, has also been modelled in the simulation platform PowerFactory. The details for load and generation profiles integration in the North American network simulation model are explained next.

Load profiles. As advanced in section 2.1.2, the characterization of the demand profile for the North American reference network has been built integrating additional hourly data which complement the information of rated nominal loads provided in the *342-Node Low Voltage Network Test System*, included in [19].

Taking into account urban-based perspective of the benchmark network, hourly load profiles obtained from Texas cities reference models contained in PowerFactory DIgSILENT databases, have been considered. Data in such models are based on the works of Texas A&M University [20], which consider the methodologies on synthetic grids modelling presented in [21] and [22]. A sample set of hourly load profiles present in analyzed Texas reference models has been processed to obtain representative per unit load profiles for this area of North America, which have been applied to the specific topology and individual loads of the modelled benchmark network. In order to keep consistency with European cases, hourly data from June days have been used.

Generation profiles. Similar to the European case, DER based on PV units connected in the demand nodes characterizes the integration of LEC in North American reference network. Generation profiles have been obtained from Texas reference models, which along with load profiles also includes solar generation hourly data, considering the same references explained in section 3.1.2.1, thus seeking consistency between demand and generation hourly data.

Regarding rated power considered for each PV unit, in this case a factor of 70 % of rated demand connected at each node is considered, taking into account that values for minimum load data at PV generation hours is slightly higher in p.u. than in European case. Finally, as explained for European case, the topology of the electrical connections replicates the one of the local loads.

Simulation method

The calculation of the KPIs which will be used to quantify the effect of the evolution of electric demand and penetration of DER is based on the analysis of the Power System operation under steady-state conditions. Under such assumptions, load flow calculations are suitable for the study, analyzing load and generation profiles evolution along the day, considering time scales typically in the range of minute(s).

As introduced in previous sections, the simulations performed to conduct the described load flow analyses are executed using PowerFactory software, where both benchmark systems and all the case studies explained in the previous subsections have been modelled. Specifically, a quasi-dynamic simulation toolbox has been used, providing the capacity of performing series of load flow simulations obtaining the discrete evolution of state variables values along the considered period of time (in this work a complete day period is analyzed).

Quasi-Dynamic simulations have allowed to obtain results providing relevant data regarding voltage levels, load levels and technical losses. The obtained results have been treated focusing the analysis on the nodes and on the line sections of the networks. Thus, the variables selected for the analysis of the simulations results, presented in section 4, are the following:

- Node voltages:
  - o Umin (%): Minimum voltage magnitude, relative to nominal value, obtained at any node of the LV system for a 24 h period quasi-dynamic load flow.
  - o Umax (%): Maximum voltage magnitude, relative to nominal value, obtained at any node of the LV system for a 24 h period quasi-dynamic load flow.
  - o Uavg (%): Average voltage magnitude, relative to nominal value, obtained for a 24 h period quasi-dynamic load flow.
- Line sections power flows:
  - o Max Load (%): Maximum power flow through any LV line section, regarding nominal value, obtained for a 24 h period quasi-dynamic load flow.
  - o Total Losses (kWh): Total energy losses in the LV system considering the whole 24 h load flow simulation.

Results and discussion

The following subsections present the most relevant results obtained from the simulations, summarizing values for more than 1000 line sections and 1250 nodes per scenario analyzed.

BAU scenarios

This subsection summarizes the results of quasi-dynamic simulations performed for the BAU scenarios described in 2.2.1. Table 1 shows the results of the selected KPIs, explained in 3.2, for each BAU scenario and each benchmark system. In the table EU refers to the European benchmark network and NA denotes the North American benchmark network.

As can be observed, average voltages are similar in European and North American cases, being slightly higher in the latter. Minimum voltage values decrease with the increase of the demand in both cases. In the case of the European reference system, in the last two scenarios the voltages fall below 93 % of nominal voltage, which is commonly beyond the minimum operation voltage typically allowed by regulation. On the other hand, in the North American benchmark network, although the trend is equivalent, in none of the analyzed scenarios voltage minimum levels fall beneath 97 % of nominal voltage, thus no critical operation risk is reached.

Table 1
Node voltages and line power flows results for BAU scenarios.

Scenario		Voltages			Power flows	
		Umin (%)	Umax (%)	Uavg (%)	Max Load (%)	Total Losses (kWh)
base case	EU	98.30	103.96	102.08	99.17	21.18
	NA	101.04	103.19	102.43	85.05	1061.01
120 % demand	EU	96.96	103.95	101.67	**125.09**	31.32
	NA	100.31	102.91	101.99	**102.57**	1541.99
140 % demand	EU	95.50	103.94	101.26	**155.13**	43.91
	NA	99.56	102.63	101.56	**120.28**	2118.54
160 % demand	EU	**93.84**	103.93	100.85	**192.23**	59.34
	NA	98.81	102.36	101.11	**138.17**	2793.52
180 % demand	EU	**91.73**	103.93	100.41	**246.56**	78.42
	NA	98.04	102.07	100.67	**156.26**	3569.92
190 % demand	EU	**89.72**	103.92	100.19	**311.21**	90.79
	NA	97.65	101.93	100.44	**165.39**	3997.14

Regarding results for power flows in line sections it can be observed that in the European benchmark case load ratios increase dramatically with the demand growing scenarios, being above nominal values just from 120 % demand scenario. In the North American case, overloads are reached as well, although with lower increase ratios.

The results obtained support that meshed topologies, as the one considered for the LV network of the North American benchmark case, help both to maintain voltage levels within healthy margins and to reduce the rise of lines load levels even in scenarios with high increase of demand.

Absolute values of technical losses are remarkably higher in the North American case, which is justified given the relevant differences in the total loads fed by each system, as explained in section 2.1. On the other hand, the increase in losses with the growth of demand is faster in the European case.

Next section will show the effect of the connection of distributed PV close to the consumption points.

LEC scenarios

Table 2 presents results for each LEC scenario and each benchmark network (EU for European one and NA for North American one).

The values obtained for nodes voltages show that the connection of PV units close to demand nodes allows for keeping voltage levels within 97.75 % and 106 % of nominal values for any combination of scenario and benchmark system considered, thus avoiding violations of typical operation voltages requirements.

Concerning power flows, results show that, generally, the integration of PV based LEC helps to reduce both overloads and technical losses. Although in both cases scenarios considering a higher growth rate for demand still present overloads even with PV penetration, they are significantly less severe than in BAU scenarios, specifically in the Europe benchmark network, where the positive impact of PV penetration is more remarkable than in the North American one, mainly due to the higher correlation between hourly demand and solar profiles in the case of the considered European area.

For the sake of clarity and to assist in drawing conclusions, results for BAU and LEC scenarios are explicitly compared in the next subsection.

Comparison of scenarios

In the following subsections the presented results are compared quantitatively and graphically.

Nodes voltages

Minimum voltage values have emerged as the most relevant node results. Accordingly, Fig. 3 illustrates a graphical comparison of minimum node voltages obtained for BAU scenarios and LEC scenarios in North American (NA, presented in orange colours) and European (EU, in blue) benchmark systems.

It can be explicitly appreciated the improvement on minimum voltage levels achieved with the integration of LEC in European scenarios, allowing regular operation voltage levels even for the higher demand-growing scenarios. Indeed, the trend observed in the figure, shows that the improvement increases with the rise of the demand growth. On the other hand, although for North American case the trend is also decreasing with the increase of demand, voltage levels remain within normal operation levels in all scenarios, making the difference between BAU and LEC scenarios minimal.

Line sections power flows

Fig. 4 presents the maximum load values for each scenario comparing BAU and LEC cases in North America (NA, in orange) and Europe (EU, in blue).

Table 2
Node voltage and line power flows results for LEC scenarios.

Scenario		Voltages			Power flows	
		Umin (%)	Umax (%)	Uavg (%)	Max Load (%)	Total Losses (kWh)
base case	EU	100.00	105.04	102.96	60.72	14.69
	NA	101.08	103.32	102.55	80.01	812.22
120 % demand&PV	EU	100.00	105.24	102.74	74.77	21.44
	NA	100.37	103.01	102.10	96.48	1227.31
140 % demand&PV	EU	99.86	105.43	102.51	89.73	29.61
	NA	99.63	102.75	101.69	**113.12**	1685.37
160 % demand&PV	EU	99.23	105.61	102.29	**105.84**	39.29
	NA	98.89	102.49	101.27	**129.93**	2221.19
180 % demand&PV	EU	98.59	105.79	102.05	**123.41**	50.58
	NA	98.13	102.23	100.84	**146.92**	2836.98
190 % demand&PV	EU	98.26	105.88	101.93	**132.89**	56.88
	NA	97.75	102.10	100.63	**165.39**	3175.60

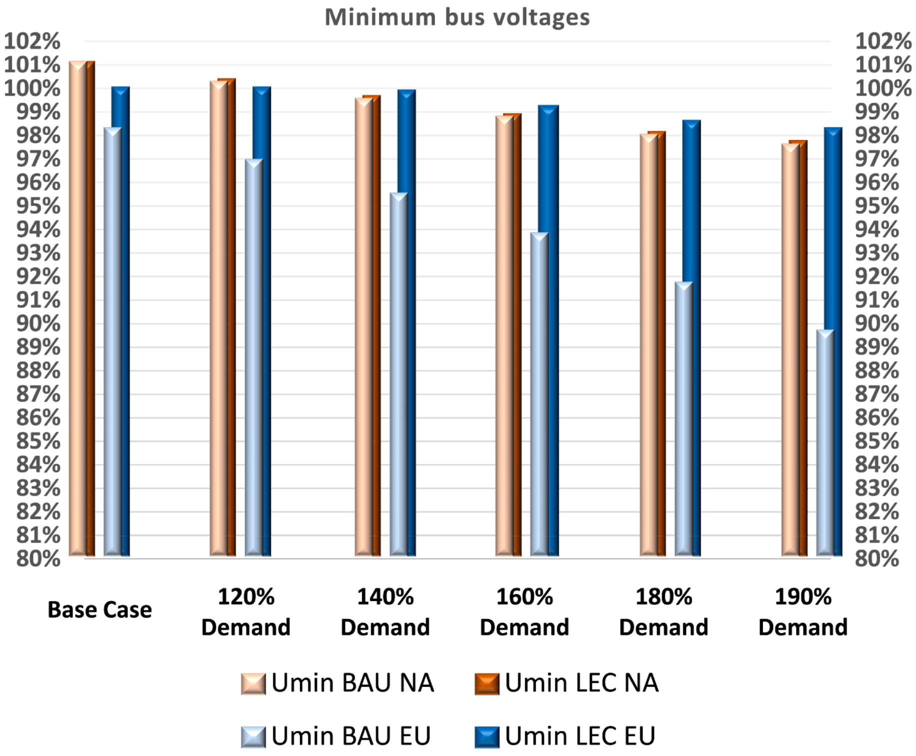

Fig. 3. Minimum bus voltages comparison.

The comparison shows explicitly how in BAU scenarios the increase of overloads in European case is notably sharper (with a total slope of 236 %) than in North American case (89 %). Another noteworthy observation is that the improvement achieved for this KPI in LEC European scenarios is particularly relevant.

On the other hand, in North American LEC scenarios, enhancements in load levels are more modest since, according to hourly profiles in the considered area, electric demand is still high in periods with low solar irradiation. A specific analysis correlating the maximum load level suffered by each LV line section with the hour when it is reached, shows that one of the effects of the integration of PV units in North American system is the displacement of the maximum load hour from early afternoon (14 h, 15 h) in BAU scenarios to evening hours (19 h) in LEC scenarios (which is useful to design further LEC configurations). The same analysis in European case shows that the correspondence between maximum load hours and maximum solar production is higher, therefore instead of an offset of peak hours, a clear reduction of maximum load is achieved. Fig. 5 graphically presents this analysis for the 140 % scenario.

Regarding technical losses, due to the relevant difference in absolute energy values between both networks explained above, results have been normalized and represented accordingly in p.u, taking as reference the BAU base case value for each system, allowing a meaningful graphical comparison, shown in Fig. 6. It can be appreciated that the increase of losses with the growth of the demand is higher in European case, as well as the relevant improvement achieved in LEC scenarios. Consistently with the analysis explained in previous sections, meshed topology of North American case, which offers a better behaviour to cope with demand rise, allows reducing losses increase rhythm. Additionally, load and generation profiles characteristics involve a lower impact of PV penetration in North American case than in European one.

Conclusion

This work analyzes the effect of the integration of sustainable PV-based Local Energy Communities into LV distribution systems, in a context of electric demand growth. Two benchmark systems based on IEEE reference models (Europe and North America) have been built to

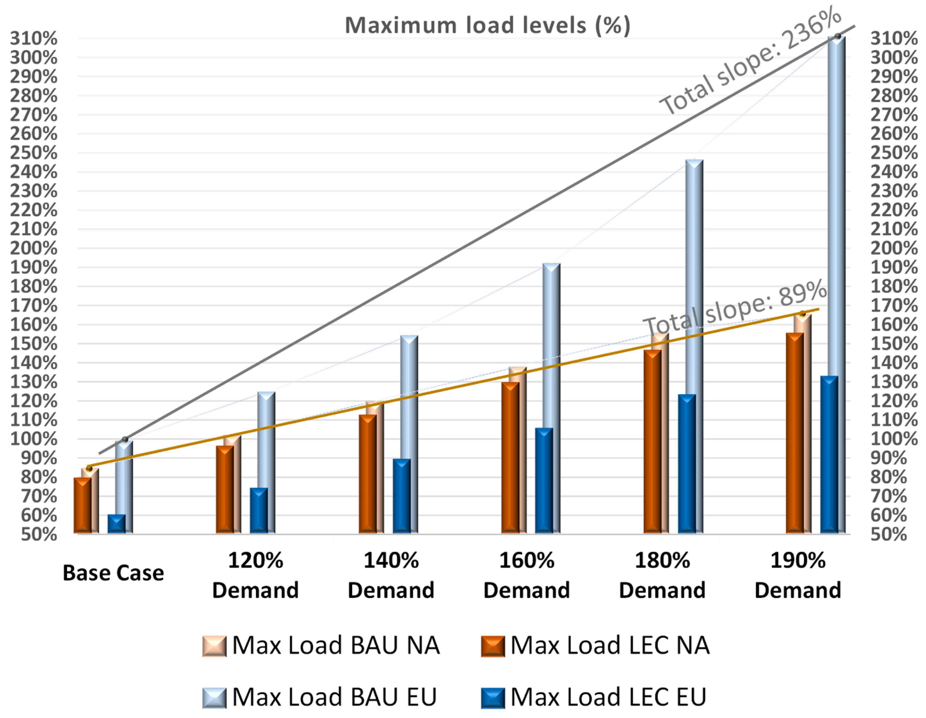

Fig. 4. Maximum load levels comparison.

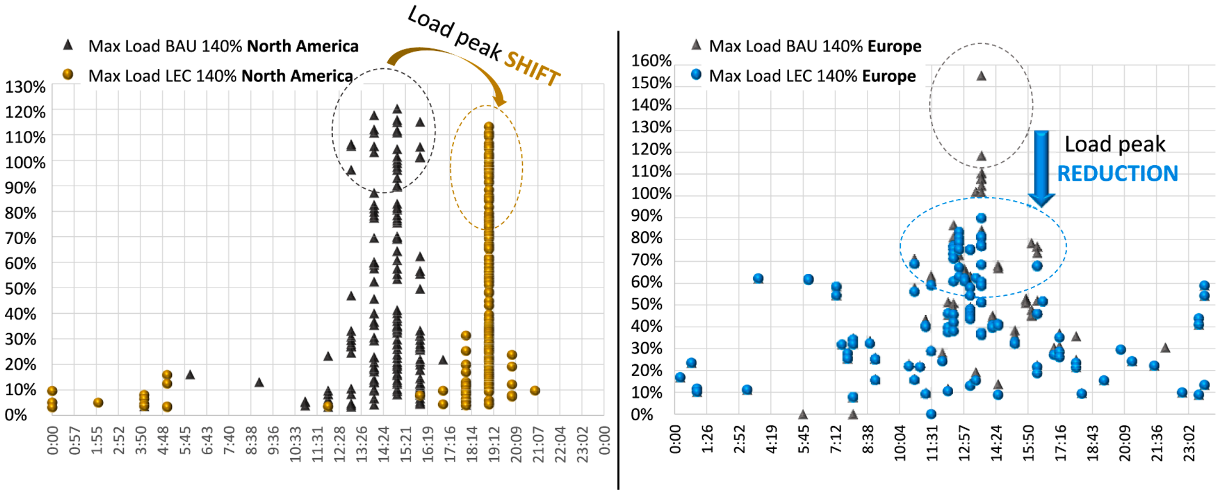

Fig. 5. Load peak hours comparison.

define and compare significant scenarios in which quasi-dynamic load flow simulations have been performed, obtaining voltage and power flow results throughout day-long power flow analyses.

The relevant variations between both benchmark systems characteristics, in terms of LV topologies (radial in Europe, meshed in North America) and hourly demand and generation profiles (high correlation in the European case, significant misalignment in the North American one) provide significant differences regarding the impact of the increase of electric demand as well as the effect of PV penetration.

In terms of voltage profiles, in the European case the growing evolution of electric demand leads to minimum voltage limits violation in BAU cases (below 0.9 p.u. in the most ambitious scenario), while the connection of PV based LEC achieves values within healthy limits in all scenarios. The enhancement in voltage profiles in European LEC scenarios compared to BAU ones reaches an improvement of over 8.5 %. The results regarding maximum load levels and technical losses show that in BAU scenarios the increase of demand can involve high levels of overloads in both reference systems, being significantly more severe in the European case (more than 300 % compared to rated values, being up to 165 % of rated values in the North American case), while in LEC scenarios the maximum load values decrease dramatically, particularly in European cases, where the reduction in maximum power flowing through LV line sections ranges from 39 % to 57 % with the connection of PV units. In North American cases, rather than a reduction in the maximum load levels, PV integration results in a notable shift in the peak load hour from early afternoon (14 h, 15 h) in BAU scenarios to evening hours (19 h) in LEC scenarios. This analysis serves as a valuable tool for refining LEC configurations, potentially emphasizing the need for integrated storage solutions.

It is also remarkable, precisely considering sustainability purposes, the reduction in technical losses achieved through the connection of LEC, both in North American and European scenarios (maximum

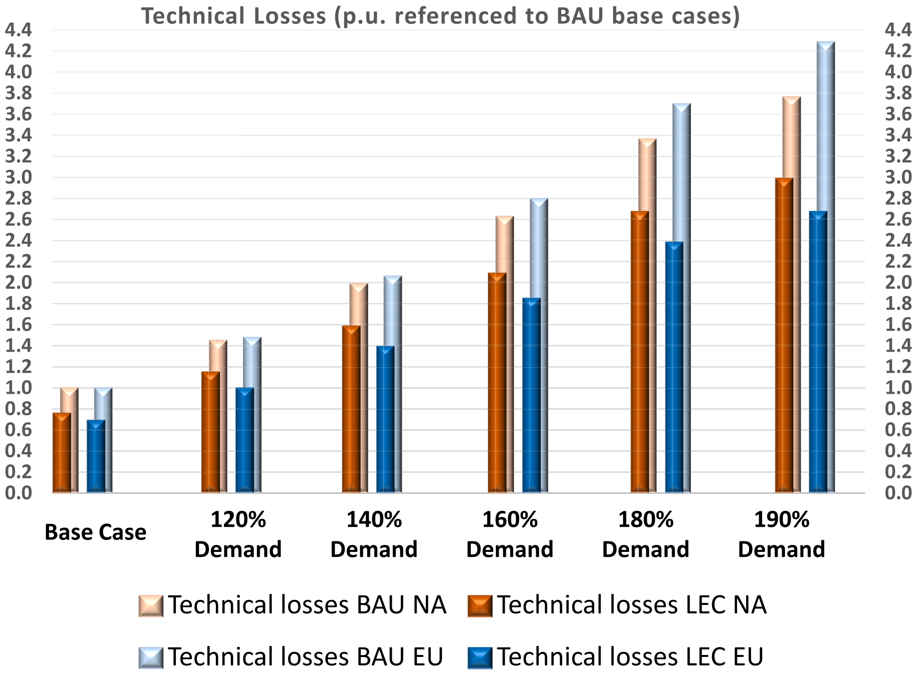

Fig. 6. Technical losses comparison.

reduction of 23 % in the North American case and 37 % in the European case).

In light of the quantitative results obtained in this study, the main high-level general outcomes drawn from the systems comparison are that meshed topologies (North American case) are better prepared to cope with electric demand growth, and that in the European case, the integration of PV-based LEC provides relevant enhancements for all the KPIs evaluated, therefore showing potential to play a key role in meeting sustainability objectives, facilitating the electrification of society and the penetration of renewable energies. Regarding North American case, a higher alignment between electric demand and sustainable energy availability periods arises as the main challenge to maximize the advantages of LEC integration.

Further analyses in this field will explore the maximization of the positive impacts of the integration of LEC considering more complex structures of sustainable LEC integrating additional elements aligned with the Smart Grids paradigm, such as storage systems, diverse renewable generation sources or electric vehicles with V2G capabilities.

CRediT authorship contribution statement

Samuel Borroy Vicente: Methodology, Investigation, Validation, Formal analysis, Writing – original draft. **Daniel Marquina Cordero:** Software, Methodology, Investigation. **Andres Llombart Estopiñán:** Conceptualization, Writing – review & editing, Supervision. **Ángel Zorita Lamadrid:** Writing – review & editing. **Luis Hernandez-Callejo:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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