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# Is it feasible a massive deployment of low voltage direct current microgrids renewable-based? A technical and social sight

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## ABSTRACT

The popularity of renewable energy systems has contributed significantly in the last years to the utility of low voltage direct current microgrids. However, these systems come with new challenges. This survey focuses on introducing a state-of-the-art low voltage direct current distribution system and sheds light on the challenges that must be faced in order to complete energy transition. This literature review was systematically carried out using the two largest scientific databases (SCOPUS and WOS) where the query (low voltage direct current microgrid) resulted in 198 articles. The purpose of this paper is not to reiterate the comparison of direct current with alternating current systems, which has already been discussed extensively. Instead, the objective of this survey is to assess the feasibility of the low voltage direct current distribution system and its impact on social development. To this end, this work provides valuable information for renewable energy planners, giving some insights or solutions to bridge the gap between the current energy network and the future DC energy microgrids. In particular, this article focuses on parameters such as grid topologies, distribution and voltage standardization efforts. The three major findings are: (i) the off-grid solutions enhance the efficiency rate in energy facilities (from 15% to 30%), and the vast majority of them are supported with energy storage systems to increase their reliability. However, in economic terms the most suitable systems still are the grid-connected solutions. Another finding is that (ii) the bus configurations are most used as well as the best in terms of their effectiveness to distribute low voltage and direct current energy within the microgrid. Lastly, (iii) the voltage value standardization around 48 V and 380 V, and even though there seems to be a clear convergence between them, the lack of agreement is delaying the massive implementation of these solutions worldwide. Finally, a novel assessment of social impacts and reflections on low voltage direct current microgrids is also included.

## 1. Introduction

Following the Covid-19 outbreak, the global recuperation process made it imperative to build greener electrification systems, thus prompting a massive growth in the renewable energy sector [1]. The European Union (EU) reinforced this trend through the Green Deal [2] and the *Fit for 55* policy packages [3] stating that decarbonization of energy systems is critical to reaching set climate objectives. Moreover, the United Nations are paving ways to reach these targets on a global stage through the Sustainable Development Goals (SDG), particularly goals 7 and 11 [4].

The goals stated by both the SDG and Green Deal lie in the development as well as the deployment of renewable energy technologies, such as solar photovoltaic (PV), solar thermal, wind, geothermal, biomass, and hydropower [5,6]. Distributed energy resources (DER) based on renewable sources are becoming a promising technology that will help curb climate change and also ensure universal access to electricity, even in the poorest regions of the planet [7–9]. Currently, the share of renewable energy in the electrification sector has increased. Indeed, world leaders are working to improve the energy produced through renewable sources there-by reducing greenhouse emissions by 40% according to 1990 data [10,11]. In addition, the European Union has plans of at least a 40% growth in renewable energy share by 2030 [3].

Following the Green Deal, the European Union favours self-powered homes using DER and energy storage systems (ESS) [12]. The massive deployment of such renewable energy in buildings, aided by the Renovation Wave fund [13] and other initiatives like zero carbon

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**Nomenclature**

| | |
|---|---|
| $AC$ | Alternating current |
| $CHP$ | Combined heat and power |
| $DC$ | Direct current |
| $DER$ | Distributed energy resources |
| $DRER$ | Distributed renewable energy resource |
| $DSO$ | Distribution system operators |
| $ESS$ | Energy storage system |
| $ETIP$ | European Technology and Innovation Platform |
| $EV$ | Electric vehicle |
| $HV$ | High voltage |
| $KPI$ | Key Performance Indicator |
| $LCOE$ | Levelized cost of electricity |
| $LV$ | Low voltage |
| $LVDC$ | Low voltage direct current |
| $MG$ | Microgrid |
| $MV$ | Medium voltage |
| $NPV$ | Net present value |
| $POE$ | Power over ethernet |
| $PV$ | Photovoltaic |
| $RENE$ | Renewable energy |
| $ROI$ | Return over investment |
| $SDG$ | Sustainable development goals |
| $UPS$ | Uninterrupted power system |
| $ZCB$ | Zero-carbon buildings |
| $ZEB$ | Zero-emission building |
| $ZEZ$ | Zero-emission zones |
| SAE | Society of Automotive Engineers |

buildings (ZCB) for all, is equally fostered by the European Commission [14]. Both initiatives are expected to increase the penetration of renewable energy technology [15] and substantially increase energy efficiency [16] in buildings connected to low voltage grids.

The deployment of self-power buildings carries the following advantages: modularity, scalability, flexibility, reliability, and resilience [17–20]. However, considering the vast majority of household loads (e.g. LED lighting, TV sets, PCs, electric vehicles, electronic devices, etc.) projected to be in use by 2035, all of them based on direct current (DC) power, the major question that needs to be answered is: What is the future prospect of DC microgrids in terms of its economic and technological feasibility?

The European Technology and Innovation Platform (ETIP), in a Strategic Research Agenda [21], has already considered this challenge and suggested that research has to be focused on low voltage direct current (LVDC) networks with PV and micro-generation achieving an increase in market share by 2035 [22]. Moreover, the U.S. Department of Energy under the project "Direct-DC Power Systems for Energy Efficiency and Renewable Energy Integration with a Residential and Small Commercial Focus" is investigating the energy-savings potential, benefits, and barriers of using DC generated by on-site renewable energy systems directly in its DC form, rather than converting it first to alternating current (AC) for distribution [23]. Several authors [19,24–29] have stated that LVDC microgrids could be one of the most cost effective solutions to this policy objective. Microgrids (MG) emerge as the perfect complement to DERs on the way to increase the efficiency of the energy system [7,8,30–32]. A MG is defined as a group of interconnected loads and DER (within clearly defined electrical boundaries) that acts as a single controllable entity without a utility grid. MGs offer several advantages and benefits such as an increased reliability, an improved energy efficiency, a higher resiliency, a reduced cost, lower transmission losses, $CO_2$ emission reduction, and other environmental benefits [33].

This paper aims to develop a comprehensive review of the advantages and disadvantages of LVDC-MGs to help planners decide what sort of MG is the most suitable for their applications. The main contribution is to present a holistic analysis of three technical aspects: the interaction with the utility grid, the schemes for distribution and the interconnection of DREs with loads, and finally the consensus of DC voltage standards. Furthermore, the existing link between LVDC-MGs and social development and welfare will be assessed. Probably, the primary strength of this paper is its extensive analysis of all the problems that LVDC-MGs will tackle after a massive deployment.

The rest of the paper is structure as follow. Section 2 provides an introductory analysis about LVDC-MGs. Section 3 explains the methodology used and Section 4 details the different grid connections. Then, Section 5 analyzes distribution topologies and Section 6 assesses the efforts on voltage standardization efforts. Last but not least, Section 7 explains the social impacts and gathers some thoughts about the future evolution of LVDC-MGs. Finally, Section 8 draws out the main conclusions and some recommendations for future studies.

## 2. LVDC microgrids and distribution advantages

Traditional networks are usually composed of generation units, consumption units, and energy storage systems. Nevertheless, four new agents are present in MGs:

1. **Coupling point or point of common coupling**: this is where the generated power is distributed to the end-user. An interconnection between the MG and utility grid becomes the distribution junction [34,35].
2. **Prosumers**: these agents self-consume and sell electricity surpluses. Prosumers can be active market participants by controlling their real-time energy consumption and producing devices [36,37]. Prosuming offers consumers and vehicle owners the potential to re-evaluate their energy practices to recover their capital investments. Some researchers have achieved up to 20% savings when solar PV is distributed to homes [38], making prosuming essential in guaranteeing the system's proper operation feasibility.
3. **Energy Storage systems**: these elements play a crucial role in distributed generation. They add flexibility, increase the quality of the energy at the facility, and raise MG efficiency [39]. Remarkably, electric vehicle (EV) technologies in many cities use mobile chargeable batteries that help correct the distortions produced in the grid by high energy demands. EV is a reliable ancillary system that can help reduce the initial MG investment and help to smooth peak consumption [40,41]. The electrification of the transportation sector is a critical and popular strategy to achieve SDGs. In this sense, EV could be considered a battery that can store energy (to smooth the spike in generation or consumption [42]) and shift load from peak periods or share energy between different MGs. DC fast charger is one of the most promising systems for trading energy by using DC buses [38,43,44].
4. **Energy control units**: MGs usually lack a central control unit. Therefore, the energy control units are distributed through the MG (usually attached to the energy storage system) and maintain the power quality.

A graphical representation of microgrids is represented in Fig. 1. Moreover, the main parameters that characterize microgrids are:

- **Current flows:** MGs can be categorized into three major groups regarding the form in which electric power is delivered to businesses and residences: AC, DC, or AC–DC (hybrid). These have

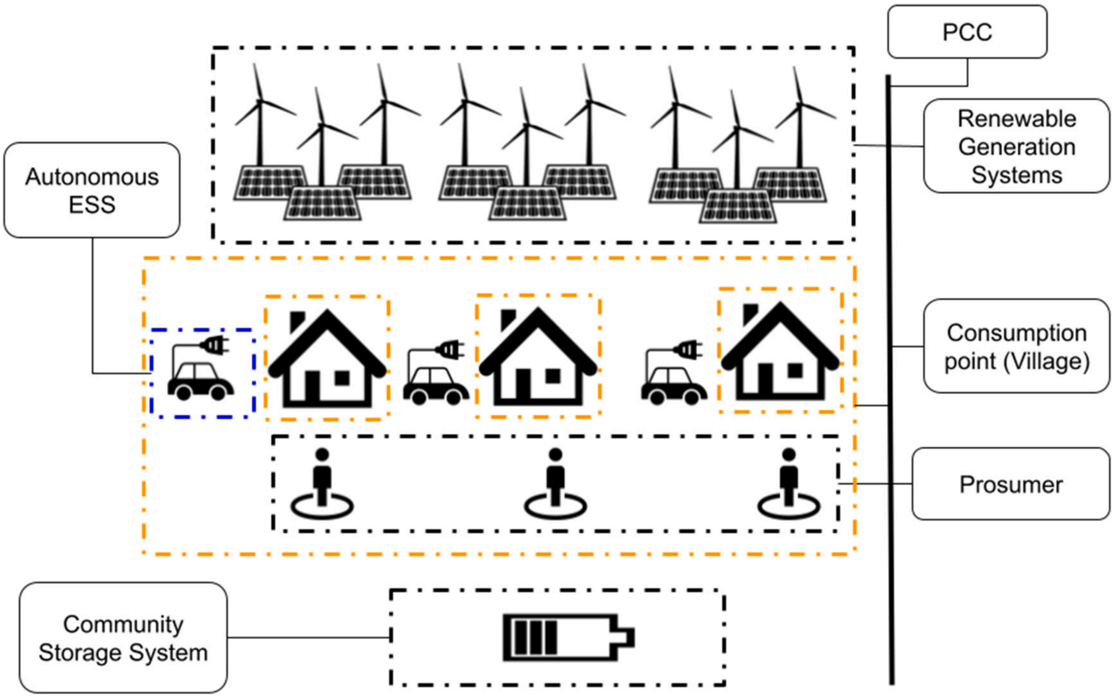

**Fig. 1.** Low voltage DC microgrid self-sustained.

different pros and cons, and the selection of each type depends on the end-user requirements. AC MGs are the best option if one is prioritizing the integration with existing AC networks [24,45]. However, DC-MGs are said to be the most efficient [24,46]. Thus, hybrid designs are the best option when migrating from existing AC to DC networks, as it concentrates the benefits of both [45,47–49]. Technology-wise, AC networks are considered matured to DC networks (currently a research area).

- **External interconnections:** DC-MGs can be grid-connected, partially connected, or off-grid. Grid-connected networks can connect to an external network (AC or DC) [50], reducing the size and the cost of the storage system [51] or even avoiding its usage [32]. Alternatively, off-grid MGs rely on well-sized storage systems [52,53] in order to guarantee the energy supply [25,52–54] to isolated consumption points [55–58]. Partially connected DC-MGs can operate both as grid-connected or off-grid depending on the time of the day and its energy needs.
- **Internal interconnections:** : LVDC-MGs can be configured implementing a bus, ring, or radial interconnections between its components. The interconnection mechanism is heavily dependent on practical experience, as each configuration may have its shortfalls [59]. Nevertheless, bus interconnections appear to be the most used.
- **Voltage:** DC-MGs are also classified according to their voltage. High voltage (HV) MGs are well known for their use in power transmission [60]. So far, there are two standards from Siemens and ABB [44] for the interconnection of cities and generation centres. Conversely, medium voltage (MV) MGs are less defined backbones intended to integrate renewable sources, ESSs, and high loads [61]. There are no technical guidelines or experiences of public MVDC-MGs that lead to their deployment [62]. According to standard IEC 61643–331, low voltage systems operate at around 1000 $V_{AC}$ or 1500 $V_{DC}$. Moreover, MGs are even more suitable to generate and distribute renewable energy [63] and can perfectly integrate storage systems such as batteries, fuel cells, super-capacitors, or electric vehicles [15,64–66]. Therefore, LVDC-MGs is an appropriate technology which can be used in zero emission zones (ZEZ), zero energy buildings (ZEB), zero carbon buildings (ZCB), etc. [28,59,60,63,67]. For the former reasons. Integrating DRERs could create positive energy buildings that could power other energy zones when required. A LVDC distribution system could help develop this ZEZ and ease the ESS integration [68] since most DRERs are based on DC [69].

Most renewable systems produce DC power. Moreover, most of the residential loads internally consume DC power and require rectification to operate. Therefore, LVDC systems are called to be the cornerstone of the energy transition model based on DRERs [23]. In fact, 33% of residential electricity could be saved by converting all AC-appliances to high-efficiency DC-appliances [23]. DC power systems can offer additional savings by eliminating the AC to DC conversions which produces on average 14% losses. This makes DC a more efficient solution to deliver power to households in peripheral areas where the utility grid is out of reach [70] and in urban areas where it is perfectly feasible [71].

A key benefit of LVDC-MGs is the possibility to connect and disconnect it from the grid, enabling its operation in both grid-connected and off-grid modes [33,72], getting the best advantages from both. Moreover, DC distribution grids can be immune to ground faults by proper grounding [73], their wiring is simpler for power distribution [73] and they allow 2.2 to 3.9 times more power transmission than AC depending on the configuration of the conductors or the DC distribution system [74]. Particularly, in a three-wire DC configuration (+pole, 0, -pole), voltages above 400 V have a significant increase in power transmission capacity (about 30%) over the equivalent configuration in AC [75]. Definitely, DC distribution systems have a better power quality [76], especially when DER or ESS are used [26]. Indeed, in LVDC-MGs there is no reactive power, synchronization problems, conversion losses, or harmonic currents [45]. They require fewer conversion stages [68,77,78], ergo, they are more efficient. Wiring remodelling and even wall modification can be avoided to replace old wiring in installations intended for AC to DC operation [27,60]. Last but not least, they have a similar return over investment (ROI) to AC systems [31,38,55,79]. Specifically, [80] obtained a 7-year ROI for a commercial building, [63] obtained a levelized cost of electricity (LCOE) of 0.35$/kWh, and [81] reduced the LCOE between 14% and 24% using an on-site storage system.

**Table 1**
Some interesting cases of use of LVDC microgrids worldwide.

| Country | Name | Type | Size | Power | External | Voltage (V) | Generation | ESS | Capacity (kW) |
|---|---|---|---|---|---|---|---|---|---|
| California | University of California | prototyped | house | DC | Grid-tied | 48, 380 | PV | Batteries | 0.4 |
| Eindhoven | High Tech Campus | real | building lighting | hybrid | Grid-tied | 380 | PV | N.A. | 2 |
| Pakistan | Laboratory | prototyped | small village | DC | Off-grid | 120, 240, 320, 400 | PV | N.A. | 1.6 |
| Mexico | N.A. | prototyped | house | DC | Off-grid | 100, 140 | PV | Batteries | 1.3 |
| Tunisia | N.A. | prototyped | house | DC | Off-grid | 48 | PV, WIND | Batteries | 1.1 |
| Xiamen | School of Energy | real | building | DC | Off-grid | 380 | PV | Batteries | 150 |
| Germany | Fraunhofer IISB | real | two buildings | Hybrid | Grid-tied | 380 | PV, OTHERS | Batteries, Fuel Cells, Electric Vehicles | 9 |
| Japan | NTT group | real | building | DC | Grid-tied | 380 | | Batteries | 500 |
| USA | Illinois Institute of Technology | real | building | DC | Grid-tied | 1000 | PV, WIND, OTHERS | Batteries | 308 |
| USA | University of Wisconsin | real | house building | DC | Partially | 326 | PV | Batteries | 102 |
| USA | North of Caroline | real | building | DC | Grid-tied | 277 | PV | N.A. | 41 |
| China | Shenzhen | real | N.A. | DC | Grid-tied | 380 | PV, WIND | N.A. | 10 |
| Nepal | Ruksibhanjyang village | real | village | DC | Off-grid | 408 | PV, WIND | Batteries | 40 |
| Swiss | NEST | prototyped | building | Hybrid | Grid-tied | 24 | PV | Batteries | 10 |
| Australia | Flinders Island | real | island | Hybrid | Off-grid | N.A. | PV, WIND, OTHERS | Batteries | 1.9 |
| Tunisia | Laboratory | prototyped | laboratory | DC | Off-grid | 48 | PV, WIND | Batteries, Super Capacitors | 1.1 |
| Finland | Oy | pilot | village | DC | Grid-tied | 900 | | N.A. | 100 |
| USA | Missouri S&T | prototyped | 4 houses | DC | Grid-tied | 120 | PV | Batteries, Fuel cell | 57.4 |
| India | Tamil Nadu | prototyped | laboratory | DC | Off-grid | 24 | PV | Batteries | 0.1 |
| Japan | Okinawa | prototyped | 3 houses | DC | Off-grid | 380 | PV | Batteries | 10 |
| China | Laboratory | prototyped | laboratory | DC | Off-grid | 12, 24, 48, 380 | | Batteries, Super-capacitor | 70 |
| India | C-DAC Thiruvananthapuram | real | small village | Hybrid | Partially | 48 | PV | Batteries | 1.3 |
| USA | North of Caroline | prototyped | laboratory | DC | Grid-tied | 380 | PV | Flow battery | 10 |
| New Zealand | Ports of Auckland | real | laboratory | DC | Off-grid | 220 | PV, OTHERS | Batteries | 0 |
| Sweden | UPN AB IBM | real | data centre | DC | Grid-tied | 24, 350 | PV | Batteries | 5 000 |
| UK | CREST | real | N.A. | Hybrid | Grid-tied | 380 | PV, OTHERS | Batteries | 310 |

Many LVDC-MGs exist as a result of several public and private initiatives [82]. Table 1 shows a list of LVDC-MGs already installed around the world. MGs are more appealing for consuming energy on-site [53] and therefore they can reach places where the traditional networks may not without having to invest in additional generation and transmission lines [24,64]. They are normally designed to meet the requirements of local areas [5,8,9,19,83–86] or they are configured according to user needs [26,31,87]. Moreover, MGs are even more suitable to generate and distribute renewable energy [63] and can perfectly integrate storage systems such as batteries, fuel cells, super-capacitors, or electric vehicles [15,64–66]. For these reasons, MGs are the best solutions to achieve zero-emission zones, in particular, ZEB [28]. Integrating DRERs could create positive energy buildings that could power other energy zones when required. A LVDC distribution system could help develop this ZEZ and ease the ESS integration [68] since most DRERs are based on DC [69].

## 3. Survey methodology

The survey is based on a specific query (Table 2) over the two major scientific databases, SCOPUS and Web of Science (WOS), to get a systematic state-of-the-art of LVCD-MGs. The results from both databases are combined to remove duplicates and outputs that are out of scope, e.g. contributions that focus on control and that do not fully describe the MG setup. Finally, the list is completed with some of our own set of articles that addressed the subject. As a result, 198 papers were assessed. Each author reviews each article and completes a template with each paper's most relevant contributions on the eleven aspects (paying special attention to the topics discussed in this survey which are four: *grid connections, distribution topologies, voltage standardization, and the link between this grids and the welfare*):

- **Objective:** The main objective of the article.
- **Conclusions:** The main conclusions in relation to these aspects (if any): the type of energy exchange method used, energy management (based on tariff, renewable availability, etc.) methodology, tasks performed, the cost-savings achieved, the energy storage systems used, and the proposed MG sizing methodology.
- **Circuit:** The figure used to represent the MG.
- **Dimension:** The size of the MG.
- **Connection:** Type of interconnection with the utility grid (connected, off-grid or partially connected).
- **Topology:** Type of interconnections with the elements of the MG (bus, radial, star, mesh or combinations of them).
- **Voltage:** The voltage level(s) used in the MG. Only DC voltage levels up to 1500 V are considered.
- **Renewable Sources:** Renewable generation sources used.
- **Batteries:** Amount and type of storage included in the MG.
- **Simulation Tools:** Simulation software used to carry out MG design or evaluation.
- **Comments:** Any other comment of interest from the author.

**Table 2**
Queries performed on SCOPUS and WOS databases.

| Database | Query | Results |
|---|---|---|
| SCOPUS | `( TITLE-ABS-KEY ( ‘‘low-voltage’’ ) AND TITLE-ABS-KEY ( ‘‘DC’’ ) AND TITLE-ABS-KEY ( ‘‘microgrid’’ ) ) AND (PUBYEAR AFT 2013) AND ( LIMIT-TO ( SUBJAREA , ‘‘ENGI’’ ) OR LIMIT-TO ( SUBJAREA , ‘‘ENER’’ ) )` | 392 |
| WOS | `TI = ( ‘‘low voltage’’ AND ‘‘DC’’ AND ‘‘microgrid’’ )` | 50 |

The following sections analyse the outcomes from the state of the art regarding the grid connection, the topology of DC distribution, the DC voltage standardization, and their impact on social impact indicators of MGs. Fig. 2 illustrates how these parts are related. Please note that several of the concept introduced in Fig. 2 are not considered in this survey (like protection schemes, interlinked converters and control strategies) as they will be tackled in a future document. Finally, the file with the raw information compiled by the authors can be found in [88].

## 4. Grid connections

This section details the main strategies found in the literature about MGs' external connections. As stated before, there are three prime means to connect a MG with the main grid: grid-connected, partially connected, and off-grid. Whereas the first two types are interconnected with the utility grid, the last is not. A graphical representation of these

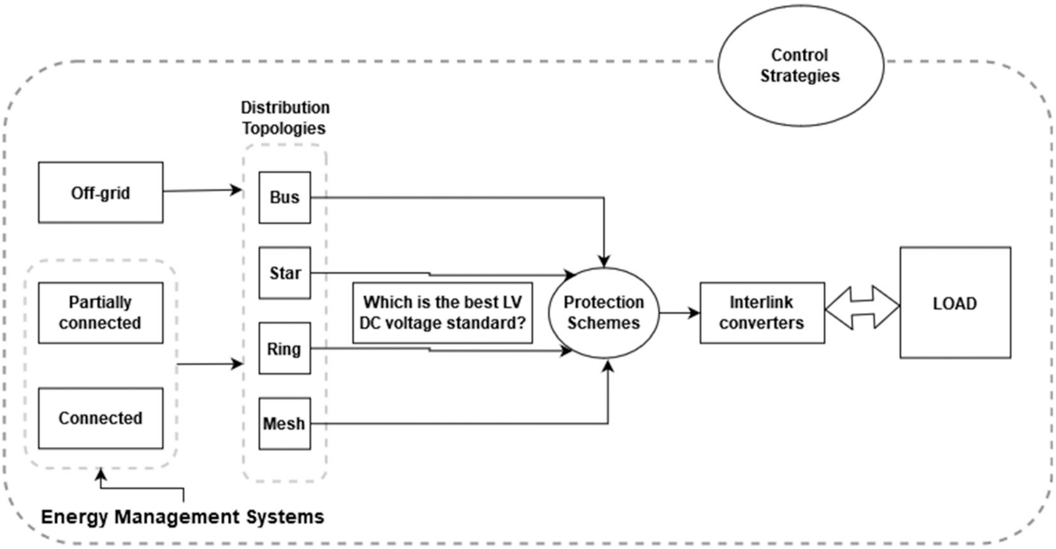

**Fig. 2.** Microgrid features that need to be assessed before implementation.

three types is shown in Fig. 3. Grid-connected and partially connected systems, both linked to urban centres, are considered in 63% of the articles surveyed, while off-grid systems, which are commonly used for isolated areas, are used in 27% of the articles. In the next subsections, aspects of LVDC-MGs for all types of connections are summarized, like the energy storage used, the efficiency achieved, cost-savings, and energy management performed.

### *4.1. Grid-connected system*

This MG is always connected to the utility grid to support temporary gaps in DRERs generation [89]. Fig. 3 (left) shows the schema of this type of connection. A grid-connected LVDC-MG is usually sized to provide electricity to municipalities, villages, or groups of dwellings. Grid-connected systems can import or export energy through bi-directional AC–DC converters, reducing the cost of electricity [90,91]. The main benefits of grid-connected LVDC-MGs are a larger power transfer capacity, improved reliability, better voltage quality, and improved cost-effectiveness. The power transfer capacity calculations indicate that it is possible to replace medium voltage AC branch lines up to 8 km long with LVDC distribution [92]. Moreover, some evidence points to the fact that LVDC systems could supply high-quality power to loads [93]. Grid-connected systems can transfer the DRERs generation surpluses to the utility grid [17,94], improving efficiency, and economic returns. More features, according to their interaction with the utility grid, are shown in Table 3 including LVDC-MGs advantages and drawbacks.

Grid connections have demonstrated grid parity. For example, authors [95] present a LVDC-MG powered by a PV system that achieves grid parity[1] in residential and industrial applications. They also demonstrated that using solar tracking systems is by far the most promising technology. In 20 years, the facility's net present value (NPV) was about 3500 kWp. This system had a payback period of between 5.5 to 6.5 years, including the Italian tax deduction of 50% for residential systems. Since there is no tax deduction for industrial systems, longer payback is expected. LVDC systems are reliable and improve smart-grid functionalities (such as large power transfer capacity with low voltage and improvements to reliability, voltage quality, and cost-effectiveness) [92]. Furthermore, its technical suitability has been proven as part of the distribution network. Finally, grid-connected LVDC distribution has good utilization potential based on the electrotechnical and customer outage costs analysis.

### *4.2. Off-grid system*

The electrification of rural areas requires substantial investment in infrastructure that can only be recovered over long amortization periods. It is in such instances that off-grid solutions are crucial. Electricity transmission is one of the most significant places of loss in an electrical system [97]. The World Bank [98] estimates that about 9% of losses worldwide are due to transmission. Indeed, several studies reveal that savings ranging from 15% to 30% can be achieved by avoiding transmission [63,66,85,97,99]. Additionally, energy-efficient home appliances can contribute about 50% cost reduction in the electrification process without inducing any significant economic burden since it is relatively easier to convert AC appliances to DC [100,101].

Fig. 3 (right) represents off-grid systems. These MGs often consist of one or more DRERs (PV [54], wind [102], and hydroelectric power [103,104]), ESS (batteries [102,105], fuel-cell [105,106], supercapacitors [107], EV [108]) to overcome the inherent intermittency of energy harvest and demand curves. Thus, energy is produced and consumed in situ with no connection to the utility grid. These MGs can need up to 18% less primary energy compared to other systems [77,109,110]. Modularity is their basic characteristic [111].

As the system expands, large numbers of DRERs can be integrated into the LVDC-MG without communication burdens. [112] demonstrated how to include additional generation and storage elements utilizing a distributed control system.

In off-grid systems, using ESS is a hard requirement as DRERs may not guarantee the power supply every time [113]. ESS can be centralized or decentralized [5,104,105,114] depending on load size, deployment cost, and the reliability of the entire installation [80,114]. The centralized option is less costly and less reliable due to its dependence on a single supply point [19]. On the contrary, the decentralized system is more efficient as it can manage the variation in consumption and resource sharing optimally [85,115] and can reduce voltage drops and currents between MG zones as it feeds the loads with closer DRER [116]. Nevertheless, as this technique increases the control complexity [105,117,118] it also enhances the systems reliability because of the multiple supply points. ESS systems also have the advantage of providing reliability and flexibility to MGs at a very low environmental cost [105].

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[1] This occurs when the cost of the electricity generate achieve the same cost or lower than the electricity generated by the utility grid. For example, PV electricity production at a cost less than or equal to the average price of grid electricity [96]

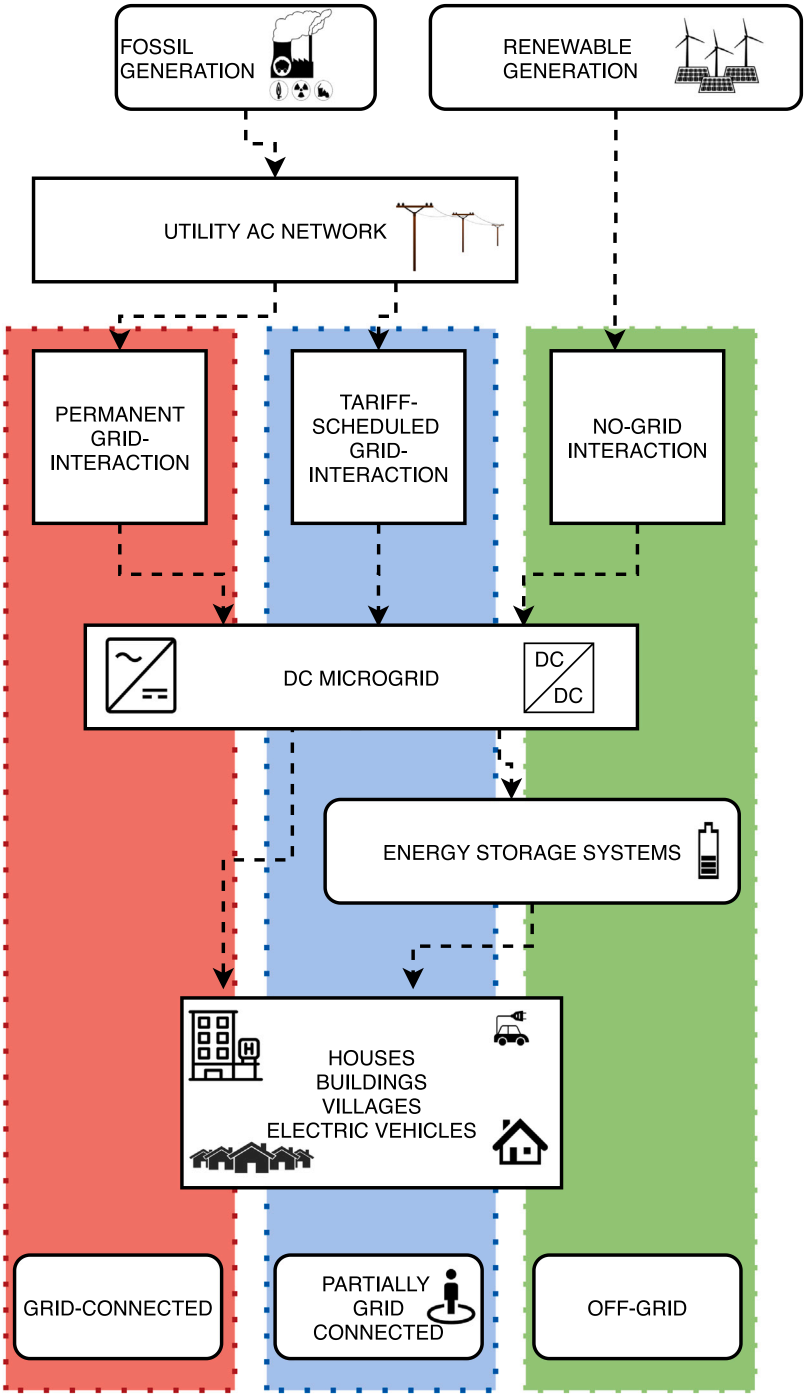

**Fig. 3.** The different kinds of grid interaction with the utility grid.

Nevertheless, the need to have this large ESS means that these systems face high initial investment costs. To maintain the system's financial viability at an acceptable rate, sizing methodologies become vital. 15%–50% reductions in the amount of generation and capacity compared with recommendations [31,54] that do not compromise availability have been proposed by different authors. [112] recommended to adequately size the generation to ensure the daily demand. [119] showed a technique for preventing the total shortage in the system employing the priority load without affecting the storage backup time at night hours. [81] used a fuzzy expert system based on a meta-heuristic method for battery sizing and energy management. [[120] designed a sizing methodology that takes into account the ageing of the battery. [121] developed a process based on an alteration of rural consumers' consumption time without compromising the demand. Finally, [52] uses extreme weather values to size the different components.

### 4.3. Partially connected system

Partially connected MGs are a mix of grid-connected and off-grid configurations, combining the strengths of both configurations. Even as there is a connection between the partially connected MG and the main grid, partially connected MGs could operate in island mode for long periods as off-grids do. This opens up an opportunity to institute

**Table 3**
Advantages and drawbacks according to its interaction with the utility grid.

| Grid Interaction | Advantages | Drawbacks |
|---|---|---|
| Connected | Grid-supported | Fossil energy consumption |
| | Less initial investment | Electrified areas are required |
| | Easy payback scheme | |
| | High maturity | Medium management complexity |
| Off-grid | Autonomous | High dependence on the meteorological conditions |
| | High efficiency | |
| | Empower people | |
| | Brings welfare to poor communities | |
| | No transmission losses | |
| | Decentralized either or centralized power-sharing mode | |
| | Cleaner energy | Higher initial investment cost |
| | Energy storage supported | |
| | High modularity | |
| | Scalability feature | |
| | Money saving in long term | |
| | It can reach anywhere on the planet | Non-grid supported |
| Partially | Less polluting than grid-connected but larger than off-grid | Electrified areas are required |
| | More economical investment than off-grid models but larger than grid-connected | An initial investment cost must be assumed |
| | Promotes small and medium size enterprises based on energy trading | |

different business models and services to the utility grid. For instance, partially connected MGs can adjust the tariff bands to reduce ROI on buying and selling electricity [29,80] or they could provide different flexible services [122]. Fig. 3 (middle) illustrates the major differences between partially connected grids and the other two configurations.

Ships are the perfect example of partially connected MGs [123]. They have long periods of off-grid operation (where the system must continue meeting the energy using their ESS and fossil generator system) and reconnect to the utility grid at the ports. [124] analysed the efficiency of shipboard power systems and their relation to fuel saving. The results indicated that shipboard DC systems with energy storage could provide fuel savings of around 7% compared to DC systems without energy storage.

Partially connected MGs systems maintain the flexibility and modularity of off-grid systems while also keeping the reliability of grid-connected systems [109,125]. However, these systems can shorten the ROI by selling electricity to the utility grid through a community link [80] and they have to install redundant equipment (like CHP [17]) or oversized ESS [60] to keep working on off-grid mode [126,127]. Payback periods ranging between 5 and 20 years are expected depending on the ESS capacity and the time the system could work connected to the main grid [80].

### 4.4. Main conclusion

Table 3 summarizes the most important differences among the grid connections discussed in this section. When a utility grid is not accessible, the only possible alternative is the off-grid system. That is the only configuration to supply energy to remote/isolated areas (small towns, villages, farms, etc.). On the other hand, when the utility grid is accessible, a grid-connected configuration becomes the most suitable and economically sound alternative. Hence, this is the most dominant LVDC system setup according to literature, accounting for 53% of the total available LVDC-MG. Nonetheless, partially connected grids can accommodate new services (peer to peer (P2P) markets, flexibility providers, etc.), supplying its customers and the utility, creating new revenue streams that could tip the contribution balance of both configurations shortly.

## 5. Distribution topologies

Recently, several standard DC distribution protocols have been updated allowing to integrate even more loads into a DC-MG. For example, power over ethernet (PoE) has updated its standard (IEEE 802.3bt) allowing loads of 80 W over a regular ethernet cable [128]. Moreover, universal serial bus (USB) power delivery revision 3.1 has recently updated its specification allowing it to plug in appliances up to 240 W over a USB-C cable [129]. Finally, there are different standards defined to recharge electric vehicles [12]]. This brings into discussion both the internal topology of LVDC-MG [130] and standardization issues, which will be discussed in Section 6. While we devoted the last section to how MGs configure its external connections, this section is used to describe how the different internal components and loads are connected. The main topologies found in the literature are bus, radial, ring, and mesh. Bus was found to be the most used topology accounting for 72%. Fig. 4 shows a connection diagram of each topology. This section compares and contrasts the different topologies based on their reliability, stability, and efficiency.

### 5.1. Bus distribution

As illustrated in Fig. 4*(a)*, this distribution topology is similar to an electrified common bar where each generator, consumer, and ESS is connected to the same shared electrified-bar, supplied by a point of common coupling feeder. Thus, a bus effectively integrates various sources, energy storage units, and loads at a common side [131].

Buses are classified as single bus [59], multi-bus [132] or reconfigurable [125]. Generally, the single-bus configuration is what the LVDC-MG adopts. [67] made a three-wire distribution (positive, neutral, negative pole) bipolar configuration, which brings significant advantages for LVDC distribution in building/residential applications. This topology allows a reduction in the distribution voltage with respect to the ground, which offers three different voltage levels and improves safety ($+V_{DC}$, $-V_{DC}$, and neutral) since the voltage is divided in half making it less hazardous. Moreover, loads with varying power ratings can be connected to the voltage that better suits them.

The end-use loads are all electrically connected in parallel, as shown in Fig. 4 *(a-bus)*. This feature improves the system's reliability and protects the rest of the systems from sudden failure. According to [75], networks using this topology usually have equilibrium values ranging from 68% to 100%, and stability values from 77% to 100%[2].

One of the main difficulties associated with the bus topology is the drop in voltage due to the long distances of the cables employed to interconnect generation points with consumption points. [133] demonstrated that battery charge controllers solve bus fluctuations.

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[2] The equilibrium in a network is reached when the different lines are balanced in terms of loads. On the other hand, a system is stable if the voltage and currents are within the defined power rating band-gap

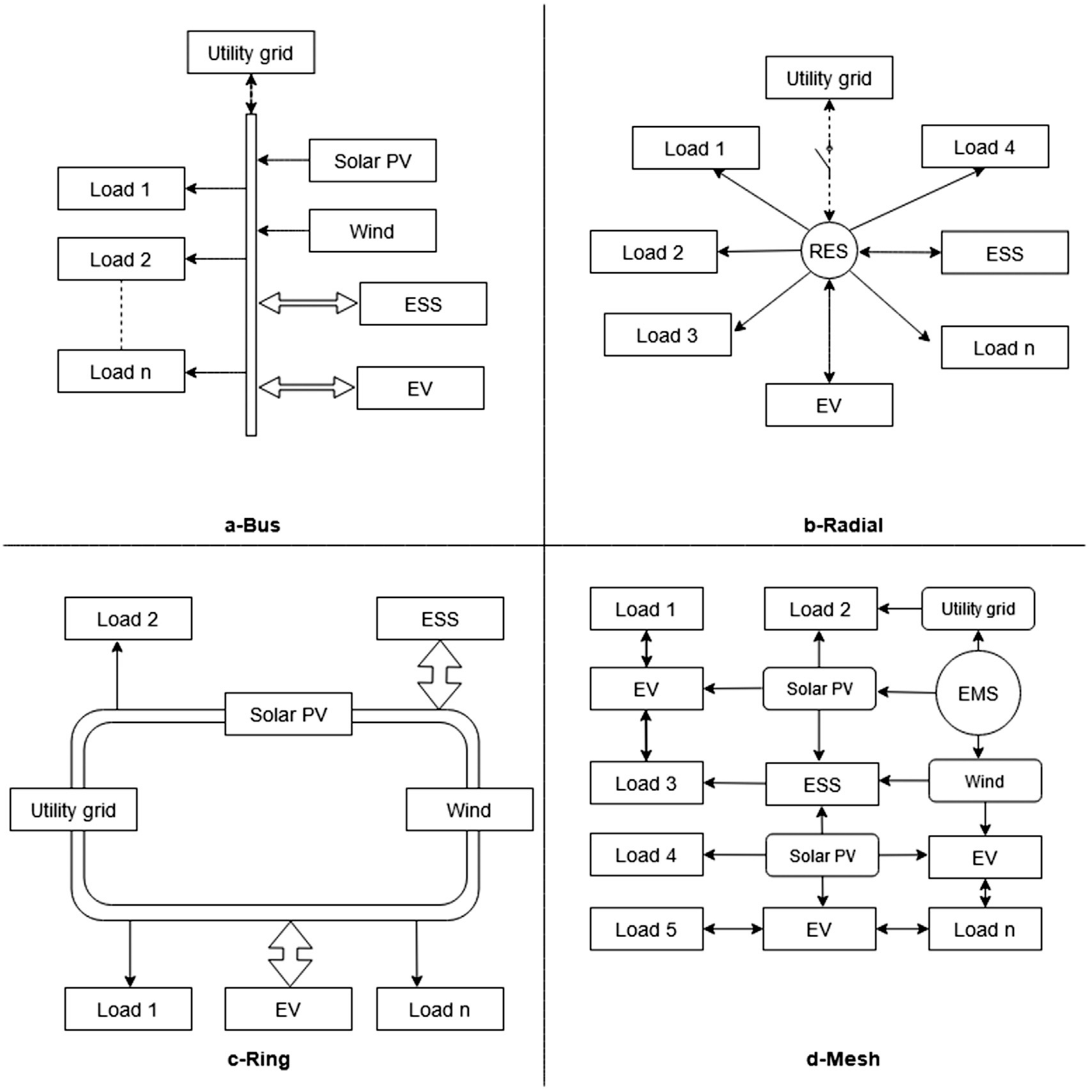

**Fig. 4.** Diagrams of the different distribution topologies schemes found in the literature.

Again, [134] stated that the power conversion efficiency of a DC bus topology could be increased by about 8% compared to AC-bus. [135] highlighted that connecting batteries to DC buses can cause fluctuations in the bus voltage and inrush current, therefore shortening the battery's lifetime. Hence, DC–DC converters are typically recommended for interfacing battery systems to the DC bus.

In the end, the DC bus is preferred to match many appliances' voltage levels and avoid extra DC–DC conversion stages. Even in variable loads setups (DC and AC), buses can easily operate aided by a DC–DC or an AC–DC converter. This distribution is very appealing with LVDC-MGs like residential buildings, and where renewable energy is the primary power source [28].

### *5.2. Radial distribution*

The radial structure follows a point-to-point connection among power sources and sinks. Therefore, every load requires a dedicated cable line to interconnect with a source [136]. Fig. 4-(*b*) graphically demonstrates this topology. The *parallel radial* architecture increases system reliability by disconnecting sections that contain faulty branches (buses), thus allowing a smooth operation of the properly functioning buses. Notwithstanding, this system is known to have different interconnections to MGs, thus increasing reliability and distribution costs [60].

The *series radial* architecture may have stability issues during off-grid mode citeKumar2017, like a total blackout if the main generator fails. According to [75], this system usually presents equilibrium and stability values between 24% to 35% and stability values of 81% to 100%. Thus, a radial distribution is probably immune to a wide range of faulty modes in a LVDC system. [137] proposed a series voltage regulation which suppresses voltage fluctuations. This strategy, addressing radial DC distribution systems issues, maintains the rated voltage within 2.7% of deviation.

A radial MG can provide high power quality through the inverter (DC–DC or AC–DC) rather than a transformer [136]. [60] stated that this type of distribution network is only possible for DC systems. It is the topology used by DC standards like the one introduced above. Nonetheless, [138,139] stated that this type of distribution has been widely used in AC systems and can be used in LVDC systems to avoid significant system transformation.

Radial systems are used to electrify villages [140]. According to [25], a radial-based configuration consisting of a distributed generation and storage architecture in a rural setting can increase its efficiency by approximately 5% more than other topology. The study found that distribution at 120 V was generally less efficient compared to 400 V. Meanwhile, [28] concluded that the radial DC-MG configurations could offer several advantages such as simplicity, multi-voltage level (bipolar), and the ability to share power from neighbouring buses (in multi-bus architecture). It must still be noted that the series radial architecture is fault intolerant. For example, a single fault can affect all customers connected to a single bus system. [141] stated that a radial grid has lower availability but is less vulnerable to faults, unlike a meshed grid with higher availability but also more vulnerable to faults. Furthermore, it is harder to control the power flow in a meshed system than a radial distribution. Some studies advise that the old radial structure will work if AC systems are converted into DC distribution systems [141], reducing the retrofitting cost.

### 5.3. Ring distribution

Ring distribution is a serial distribution Fig. 4-c. The main advantage of this system is its reliability over the radial. If any part fails, the entire power system gets interrupted. [142] introduced a way to manage failures to reduce the likelihood of total blackout for the rest of the system, dividing ring distribution into segments between the nodes. [143] designed a sort of bus-ring to increase the reliability of this distribution topology. They concluded that the proposed scheme is a highly effective approach for protecting a DC-MG without de-energizing, which is also easily implemented in other configurations. [28] concluded that the ring type distribution system has considerable reliability compared to radial systems, but these MGs systems depend on the AC grid supply. If any fault occurs in the AC feeder, the DC-MG system gets no supply from the AC grid. [25] conducted a test with 40 households using a typical cable with a cross-section of 2.5 $mm^2$. The configuration was ring-based. The results were a distribution efficiency of up to 96% at a rated voltage of 120 V, portraying a peak load sharing capability. According to [75], this system usually presents equilibrium values between 39% and 43%, with a 81% to 100% stability.

### 5.4. Mesh distribution

This topology is widely implemented in massive MG systems such as MV and HVDC power transmission (shown in Fig. 4-*d*) [62,144]. However, the mesh is more suited in cities and interconnections with AC systems, and it is not recommended to be implemented on renewable energy based systems since the intermittent of these sources of energy, such as PV and wind, increase the complexity for controlling the network [145]. The limited research on this distribution system prevents an in-depth analysis of its operation within a LVDC environment.

### 5.5. Main conclusion

While mesh is the most common AC distribution topology used, it is least suitable at the LVDC distribution level [86,145]. The bus distribution topology is the most extensive LVDC distribution system worldwide as it is the most common at house distribution. However, radials or schemes that combine bus-ring, bus-radial, and ring-radial are more suitable for connecting towns. This way, it is possible to overcome some bus, radial, or ring distribution deficiencies by strengthening its immunity to failures. Finally, it is possible to use the current AC distribution infrastructure for the new DC distribution in the long run. In this regard, [74] stated that great part of the distribution systems at the present AC systems will still be compatible with LVDC to reduce investment costs. Table 4 summarizes the main conclusions of this section.

## 6. Voltage standardization

This section aims at analysing the standardization efforts around LVDC networks. Section 5 presents different standardization initiatives. Well-known organizations have already started to work in this area. Table 5 outlines a list of the current efforts found in the literature. This section will present the different levels of voltage found during the review, safety considerations, the wire features that each standard should fulfil, and the corresponding LVDC loads found.

Standardization is surely the major slackening factor in LVDC-MG proliferation. The creation of an international standard is the gateway to better, safer, and cost-effective systems. Plenty of research supports this claim [8,28,59,91,134,146]. Lacking this standard also hinders other relevant aspects from fostering the creation of LVDC-MGs, e.g., creating scale economies for devices, components, cables, and forming the workforce that design, install and operate such networks [38] (see Table 6).

### 6.1. Most prevalent values for LVDC and supporters

Fig. 5 shows a bar chart of the most used voltages on LVDC-MGs. A bimodal distribution can be an observer with 48 V and 380 V as the most used values. [158] claimed that 48 V distribution systems for residential areas near the DC power resources could be a more economical system. Opposing the previous statement, the use of 380 V may not be suitable in a low power consumption home. However, according to [158], several organizations approved the 380 V for power distribution. Hence, 380 V was suggested for power distribution in the United States data centres [179]. [179] also stressed that the data centre market is beginning to standardize systems around two voltages, 380 V and 400 V. Extensive studies conducted by Lawrence Berkeley National Laboratory with Intel Corporation confirm that 380 V has already started to gain traction [179].

Unfortunately, there is no consensus on the appropriate standard for residential LVDC. Key stakeholders such as the IEEE, EA, IEC, ETSI, ITU-T, EPRI, or society of automotive engineers (SAE) have provided their vision (see Table 5). Still, there is no clear pattern in practice. It is interesting to follow the discussion carried out in the automotive sector as there is some parallelism in the building sector. While there seems to be consensus on 12 V or 24 V being good choices for low power applications [155], there is no clear agreement on the standard for the power train or storage. As a guideline, the European Commission set a few criteria for battery-powered vehicles, including the power-train *IEC TS 62840-1:2016* and energy storage systems as well *ISO 6469-1:2009* to rule on this matter [197]. 24 V seems to be gaining some traction in residential sectors throughout the occupied spaces standard, but [155] claims that higher voltages are more suitable. Compared to the 48 V, [198] pointed out some advantages of using 380 V, such as a 15% less up-front capital cost, a 33% less floor space, 36% lower lifetime cost, and 20 to 100 times less copper for converters.

### 6.2. Safety considerations

Guaranteeing safety in LVDC networks is fundamental when deciding the standard since these systems will be used for all inhabitants. [161] conclude that the use of 48 V ensures an outstanding safety level. [59] stated that voltages lower than 15 V are user safe, whatever the application's power is, and from 15 V to 100 V, provided the current is less than 1000 W. Under these hypotheses, both authors claim that protection should not be mandatory. On the other hand, for voltage higher than 100 V or currents higher than 40 mA, [59,155] suggest that protections should be compulsory.

### 6.3. Wiring features for implementing a LVDC system

Several authors propose to modify the MVAC grid with a LVDC grid. Besides, same cables used for AC systems can be efficiently utilized for the new DC distribution in the long run. The recycling or re-use of the wires and other materials used at the present AC systems is still be compatible with LVDC, and hence it reduces investment costs [74].

[67] proposed a bipolar (+375 V, −375 V) where the power exchanges between the different systems can be controlled using local voltage set points. Since DC increases the power transfer capacity of

**Table 4**
Advantages and drawbacks according to the internal topology.

| Topology | Advantages | Drawbacks | Type | Usages |
|---|---|---|---|---|
| Bus | Easy implementation and operation<br>High flexibility<br>Low cost | Highly vulnerable to connection failures<br>Affected by voltage regulation | AC/DC | Isolated villas and systems |
| Radial | Very simple in its installation and electrical protections<br>Relatively straightforward<br>Useful when the generating is at low voltage | Highly vulnerable to feeder failure<br>Fairly expensive<br>When load on the distributor changes, the consumers at the distant end of the distributor face serious voltage fluctuations | AC/DC | Small towns and isolated systems |
| Ring | Security and reliability | Average control complexity | AC/DC | Small towns and villages |
| Mesh | Large-scale networking | High control complexity | Mainly AC | Huge cities |

**Table 5**
Useful standards for LVDC systems.

| Standard | Supported | Aimed to | Year |
|---|---|---|---|
| 946 | IEEE | provides guidance in selecting the quantity and types of equipment, the equipment ratings, interconnections, instrumentation and protection. | 2020 |
| 1547 | IEEE | provides a set of technical specifications for, and testing of, the DG interconnection to utility Electric Power Systems. | 2018 |
| NFPA70 | NEC | contains articles that regulate the utilization and installation of DC technologies. | Not Provided |
| Occupied Space | Emerge Alliance | defines low voltage DC power distribution system requirements for use in commercial building interiors. | Not Provided |
| Data/Telecom Center | Emerge Alliance | it is aimed to facilitate the hybrid use of AC and DC power within data centers and telecom central offices. | Not Provided |
| C37.14-2015 | IEEE | it deals with service conditions, ratings, functional components, temperature limitations and classification of insulating materials, dielectric withstand voltage requirements, test procedures, and application enclose low-voltage DC power circuit breakers. | 2015 |
| C 15-100 | NF | requires that the voltage drop between the origin of the low voltage installation and any point of use does not exceed 3% for lighting and 5% for other applications. | Not Provided |
| GS OEU 006 | ESTI | define sustainable levels of ICT sites including operator sites, operator data centres and corporate data centres as defined in European Commission. | 2015 |
| 60479-1 | IEC | provides basic guidance on the effects of shock current on human beings and livestock. | 2018 |
| EN 301 605 | ETSI | this document applies to earthing and bonding of ICT equipment installed in data and telecom centres within voltage range up to 400 VDC | 2013 |
| 7671 | BS | requires wiring systems within buildings to be adequately supported against their premature collapse in the event of a fire. | 2018 |
| 62040-5-3 | IEC | establishes the performance and test requirements applied to movable, stationary and fixed electronic DC UPS | 2016 |
| 61643-331 | IEC | it is a test specification for metal oxide varistors (MOV), which are used for applications up to 1 000 VAC or 1 500 VDC in power line, or telecommunication, or signalling circuits. | 2017 |
| 61643-311 | IEC | it is applicable to gas discharge tubes used for overvoltage protection in telecommunications, signalling and low-voltage power distribution networks with nominal system voltages up to 1 000 V (r.m.s.) AC and 1 500 VDC. | 2013 |
| T L.1201 | ITU | this Recommendation aims at providing an architecture reference for an up to 400 VDC power feeding system with high reliability, safety and manageability. | 2014 |
| T L.1202 | ITU | provides a comparative performance assessment of the up to 400 VDC power feeding system using the interface described in [ITU-T L.1200] and installed in telecommunications centres, data centres and customer premises. | 2015 |
| YD/T 2378 | CCSA | describes the technical requirements, test methods, inspection rules and marking methods for 240 VDC power distribution system in telecom centers. | 2011 |
| YD/T 3091 | CCSA | describes the terminology definitions, evaluation requirements and methods for post-operational evaluation of 240 V/336 VDC power distribution systems in telecom centers. | 2016 |

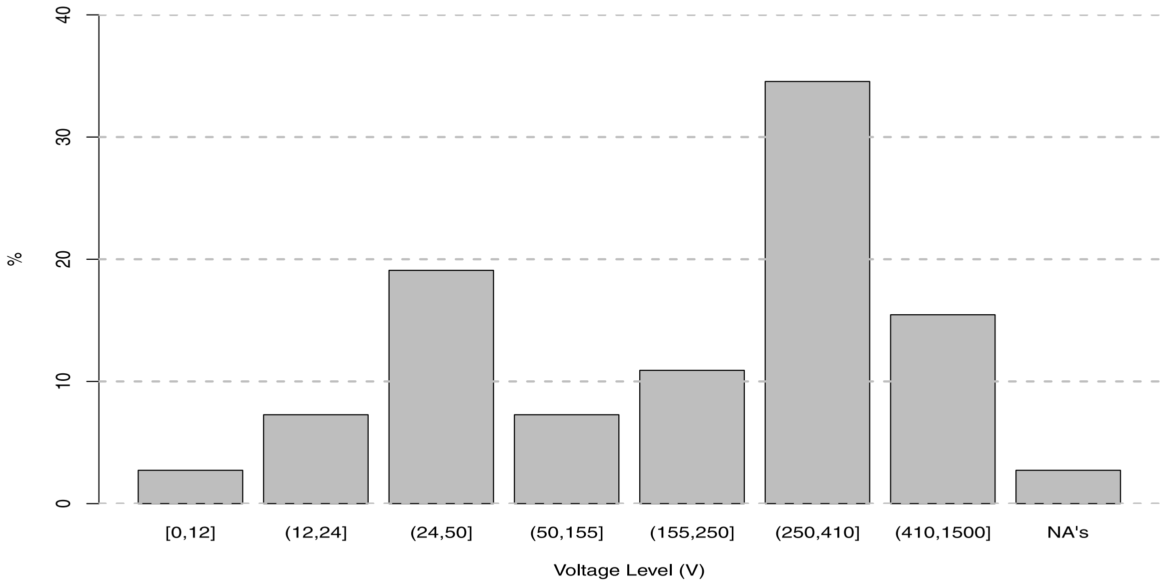

**Fig. 5.** Some of the most used LVDC voltages.

the LV, the low-power branches of the distribution network can be replaced by LVDC distribution [199]. [92] suggested modifying the MVAC distribution grid of Elenia Oy, Finland, with LVDC buses. Thus, only a secondary transformer is needed to be replaced by a centralized inverter, and the LV distribution network can be kept unchanged. The main drawback is the absence of a cable designed explicitly for a LVDC power of 1500 $V_{DC}$.

[161] carried out a comparative study of wiring performance using 12 V, 24 V, 48 V, and 110 V to power a building interior and concluded that the losses for 12 V and 24 V were too high. Yet, 110 V outperforms

**Table 6**
Voltage levels presented in the literature analysed.

| Voltage (V) | Application | Standard | Reference |
|---|---|---|---|
| 12 | Home, Automobile, Very low power home appliances | Standard in automotive industry | [67,147–149]. |
| 24 | Only designed for appliances with low-power requirements, Home, Building, Laboratories, Small Cities, Nano-grid | A standard promoted by Emerge Alliance | [17,66,80,121,140,150,151]. |
| 48 | Home, Building, Laboratories, Data Centres, Telecomunication Systems, Multilevel Inverter, Nanogri,d Microgrid | A standard already in the telecommunication market | [60,63,77,109,115,140,152–162]. |
| 100 | Home, Nanogrid | No | [163–165]. |
| 120 | Nanogrid, Limit for extra-LV definition, No need for protection system against indirect contacts | No | [25,85,166,167]. |
| 200 | Buildings, Microgrid | No | [154,168–170]. |
| 230 | Nanogrid, Protection, Compatibility with pure resistive loads | No | [67,85,142,149,171]. |
| 240 | Microgrid | CCSA | [166,172,173]. |
| 360 | Microgrid | No | [89,174]. |
| 380 | Home, Office, Building, Laboratories, Data Centres, Telecomunication Systems | Voltage standard developed by EPRI and Lawrence Berkley National Laboratory for data centres and also by Emerge Alliance. It usually appears divided in 190 V and neutral line | [17,46,60,67,115,135,156,175–181]. |
| 400 | Data Centres, Telecomunications systems | Supported by ETSI ITU | [67,85,108,170,182–188]. |
| 700 | Microgrid, Protection Systems | No | [143,189,190]. |
| 750 | General-purpose, high-speed, semi-high-speed, rectifier circuit breakers, protection systems | Supported by IEEE | [154,191]. |
| 800 | Villages, Protection systems | Supported by IEEE | [185,192,193]. |
| 1000 | Transmission, protection, security systems | Supported by IEEE IEC | [53,192,194,195]. |
| 1500 | Transmission, protection, security systems | Supported by IEEE IEC | [191,196]. |

48 V when long distances are involved but given the distances considered, the difference between these was in the 3%–4% range. [200] compared LV distribution systems with two voltage levels, i.e., 24 V and 48 V, against a 230 VAC distribution system. They found that the 48 V systems with cables using a large cross-section had the lowest power losses. Additionally, [201] conducted a simulation feasibility study with four different DC voltage levels, i.e., 48 V, 120 V, 230 V, and 326 V. The voltage drops and power losses were estimated and compared from an economic viewpoint. The results indicated that 326 V is the most suitable because it is readily applicable to the current setup infrastructure.

### 6.4. LVDC loads

Several home appliances operate at either 12 V or 24 V [23,59]. 12 V is very prevalent today due to its popularity in the automobile industry, low-power uninterrupted power system (UPS) systems, and off-grid PV solar solutions. 24 V is also used in truck batteries and UPS systems. Then, 48 V is used in telecommunication and UPS systems. Some loads operating on 48 V also exist on the market, but they are not yet as common. Finally, high voltage-rated DC loads are seldom found in commercialized forms and quantities [161]. Recent development in LVDC systems has attracted a wide number of applications, many of which use the DC grid to improve load performance. This is evident in the telecommunication sector, where the 48 V system has been used for many years [28]. Since DC distribution systems have been widely implemented in the telecommunication industry, the voltage levels used for residential applications seem to converge to the standards used in data centres (380–400 V) [91].

### 6.5. Main conclusion

Table 7 presents the main findings of the section. According to state-of-the-art, DC voltage must not be over 100 V for safety reasons. However, for residential appliances, two voltage levels come across as the most appealing for researchers: 48 V and 380 V. It is thought that the former is suitable for everything except for high power loads (white appliances), whereas the 380 V is a reasonable threshold. It is essential to point out that most home appliances run internally on DC, with voltages around 12 V and 24 V. Finally, the fragmentation in the current state-of-the-art is apparent. The lack of a clear standard hinders the possibility of benefiting from economies of scale, thus delaying the transition to LVDC.

## 7. A comprehensive view of LVDC microgrids impact on society and future implementation feasibility

### 7.1. LVDC microgrids social linkage with welfare

This section will critically assess the advantages and burdens that a massive deployment of LVDC-MGs could have on society. First, details from several articles propose different indicators to assess the social impact of micro and mini-grids. Moreover, the literature around the definition of key performance indicators (KPI) in a wide and exhaustive review is gathered in Table 9 which summarizes the main conclusions. The four main articles considered are [208–211]. Table 8 presents the different indicators proposed in each article.

From a social perspective, about 1.2 billion people worldwide do not have electricity [205]. An off-grid system would thus be the best solution to power these isolated towns or villages and eliminate energy poverty. Indeed, the inhabitants of remote places can improve their social welfare by implementing LVMGs [212]. The main problem to overcome is the initial investment required to set up the facility. Nevertheless, [5] suggests that the social costs of inaction would be greater as these areas continue to be in a situation dominated by energy poverty [54,213]. The authors of [214] analysed the trade-off for MGs in isolated communities and concluded that any MG is either one of two combinations: expensive/high quality versus cheap/low quality. So, if MG designers do not seek to cut back on the social aspects resulting

**Table 7**
Advantages and drawbacks according to voltage level.

| Voltage (V) | Use | Features |
|---|---|---|
| $V \leq 48$ | Automobile, USB, lighting, single room, small house, fans, entertainment electronics, direct battery connection and standalone facilities | Highly safe but with important losses. No need for security measures. [12,138,158,202–205] |
| $48 < V \leq 100$ | For low-power appliances, lighting, residential, telecommunication industry, and standalone facilities | Still safe but with important losses. No need for extra security measures for loads of few kW. Can reuse actual wiring. [138,202,204] |
| $100 < V \leq 400$ | Residential, major appliances, data centres and industry | Few losses, security measure must be installed since from 120 V DC becomes lethal. This is suitable for power up to 500 kW. This can be unipolar but it is more often bipolar [198,202,205–207] |
| $400 < V \leq 1500$ | Shipboard, aircraft, last-mile power distribution, power train, transportation (especially traction) | Almost nonexistent losses. Compulsory security measure has to be installed. This is appealing for medium to large loads. Power range up to 1 MW for systems below of 1000 V and up to 10 MW for systems over 1000 V. Bipolar system. [123,205] |

**Table 8**
Social impacts found by the different authors.

| Indicator | [208] | [209] | [210] | [211] |
|---|---|---|---|---|
| Health and environment | X | X | X | X |
| Improved community facilities (schools, hospitals, street lighting) due to electricity supply | X | X | | |
| Gender equality | | X | X | |
| Quality of life | | X | | |
| Improvement in productivity and time savings (e.g. collecting water or firewood) | | X | | X |
| Access to electricity services for all households that want it | X | X | | |
| Poverty reduction and wider social development | | X | | |
| Energy Poverty reduction | | | | X |
| Affordability of electricity rates | X | | X | X |
| Community participation | | | | X |
| Education and literacy | | X | | X |
| Social acceptance | | | X | |
| Urban exodus | | | X | |
| Job creation | X | | X | |

**Table 9**
How some MGs impact on communities.

| Indicator | Off-grid | Bus or ring | DC |
|---|---|---|---|
| Community participation | Positive | | |
| Energy poverty reduction | Positive | | |
| Poverty reduction | Positive | | |
| Social acceptance | | Positive | |
| Affordability of electricity rates | Negative | | Negative |
| Health and environment | | | Positive |
| Job creation | Positive | | |

from lack of electrical supply, they must do so in terms of electricity rates.

Additionally, setting up off-grid and partially connected systems may lead to a local energy market where the neighbours trade their surpluses. This can produce a significant step forward to bridge the gap between developed and undeveloped nations. These may be beneficial to local stakeholders, it will shorten the time to payback for the facility, and might promote community storage [99,215]. [216] presents an example where some local entrepreneurs started a small firm to ease loans to install non-farming MG facilities. [213] is another example where communities are empowered by the creation of social-energy enterprises that preserve their local traditions.

Concerning other KPIs, it is worth noting that partially connected and off-grid contribute to gross development product (GDP). In particular, they boost the construction sector, generate local jobs, and diminish energy poverty [2,217]. The EU predicts that by 2030, between a million and a half new jobs based on renewable energy systems will be created [218].

According to some authors [219,220], there is a higher likelihood that individuals will adopt new technologies when the usefulness and ease of use are apparent. Therefore, we can state that selecting a bus or ring topology for LVDC-MGs could have a positive impact as they are easier to implement in rural areas.

Finally, as seen in Section 4.2, the voltage standard is directly linked with safety. This is critical in off-grid systems since the population is not used to dealing with electrical systems. Moreover, the lack of technical support will push locals to solve these problems when they arise. Furthermore, DC home appliances are more expensive than AC ones, maybe because the market for these products is limited to off-grid systems, marine, industrial, and vehicles [139]. Nonetheless, *minor modifications are required to make them DC-ready [71]*. Taking this into consideration, a value up to 100 V seems to be the most suitable for residential cases.

### *7.2. The potential future of the LVDC microgrids*

This section of the paper gathers a reflexive analysis about how authors figure the near future of the LVDC systems out and the role they could play to achieve the targets for global emissions established by the UN Framework Convention on Climate Change and ratified in the 2021 United Nations Climate Change Conference (COP 26) [221]. Any transformation will have to overcome many barriers. The migration towards more DC networks will not be exempt from these barriers. In particular, the main obstacle is the amount of amortized infrastructure already deployed. Even as DC networks are more efficient, reliable, eco-friendly and empowering, it cannot compete with 140 years of installed AC systems. However, a different situation is presented where there is any “amortized infrastructure” or where systems could be easily adapted.

We strongly believe that DRES based on renewable energy and LVDC is the cornerstone to achieve the 7th SDG. Off-grid is the only configuration that could definitely provide energy to the remote/isolated areas at both low cost and low impact on the environment. Moreover, the selection of an off-grid LVDC connection could have a positive impact on the community participation and energy and general poverty reduction. DRERs facilities can easily handle towns’ or small villages’ needs, reducing the losses by long distance transmissions and due to the use of AC rectifiers in home appliances. We are sure this configuration is the most suitable for developing countries where the whole geography is not interconnected.

However, LVDC networks has a few disadvantages. In particular, the deployment of LVDC networks continue to be a capital intensive investment with a large amount of uncertainties that keep investors out of it. Moreover, there continue to be problems with the diversity of the safety and protection equipment which make some experts to question if LVDC networks are as secure as their equivalent LVAC networks, and this low of availability in these gears also increase the cost of them. And, the lack of standards impact negatively on the deployment and development of these grids. Last but not least, current workforce is not properly instructed in design, deploy and maintain LVDC systems [64,91,222,223]. These are probably biggest bottlenecks that LVDC networks will phase in the coming years.

This might be a very interesting opportunity to deploy innovative business models. Even as the initial investment required is grand for local communities, they can be taken on (if compared to the deployment of a full-scale grid) by any small enterprise from a developed country. This opens a new market to bring innovative electricity to these communities [31,213,216]. Moreover, DC house's tenants are favoured by the benefits of DC networks, despite the high initial investment of DC systems [224]. These are more efficient, and they drop in prices after the initial investment is paid. This business model is more appealing for well aware families committed with climate change issues [225]. In case the members of the community could not afford to pay for energy (since they remain below the poverty line), there are lessons learned in India where some are subsidized by the government which guarantees access to electricity [226].

As a consequence, based on the very seldom evidence found, we believe that bus and ring are the configurations most suited to be deployed given the easy implementation by locals and its lower complexity compared to mesh schemes.

On the other hand, when a utility grid is geographical accessible (as it happens in most developed countries), there is also a reason to deploy LVDC networks. For example, one of the main objectives of the "Clean Energy for All" policy package [227] is to foster citizen participation in the energy system. The main objective is to foster the amount of prosumers in the system (i.e., end users that produce and consume their own energy). Nevertheless, the second revision of the Renewable Energy Directive (REDII) [228] introduces the energy community concept. Energy communities are entities that will produce, consume, store, and sell renewable energy and will also help advance energy efficiency in households, support the use of renewable energy and at the same time contribute to fighting poverty through reduced energy consumption and lower supply tariffs. The use of LVDC networks on energy communities could bring a lot of benefits like the ones described in this article (reduction of losses, improvements on reliability, etc.). In those cases, the clever decision is the integration through a grid-connected scheme, as well as dramatically reducing the initial investment and shortening the ROI. This scheme brings plenty of technical advantages for the users such as about 15% lower capital costs, potential increases in reliability, a smaller carbon footprint, simpler design, flexibility, new business models, it is easily controllable, it has large power transfer capacity with low voltage, voltage quality and cost-effectiveness. Furthermore, not only is there a reduction of up to 30% in energy consumption in data centres, but household energy consumption is also lowered [12,92,130,138,229].

Finally, we used to believe that the main challenge which was delaying the massive deployment of LVDC systems was the cost of the technology involved, but now these technologies have been experiencing a drop in prices. Even though ESS technologies still remain expensive, and as stated on a webinar organized by the European Commission where different experts on the field discussed the topic, the lack of training regarding new engineering practices is the key barrier for this transformation to take place [230].

The lack of a consolidated voltage standard is becoming a burden to LVDC systems, and this could be one reason why engineers do not make their new projects suitable for LVDC. This could also explain the lack of protection gear available which is a hard requirement to foster its adoption in regular households. In any case, the authors think that the definition of a standard would immediately solve these problems as both industry and academic institutions will adopt it to definitively move towards a new DC home appliances market. It seems we are getting closer to reach a consensus for a standard voltage for LVDC. Namely, 48 V seems like the most used voltage in the residential sector for brown appliances and 380 V for white appliances (including heat, ventilation, and cooling systems [17,60]). This consensus seems a good compromise between safety and the reuse of infrastructure and appliances already installed.

In this wide literature review results clearly highlight DC's benefits. LVDC systems are the future, and they seem to be gaining AC spaces gradually. Yet to come massive LVDC distribution systems adoption have arisen the development and proposals of standards and specifications which are essential to pave the way to later commercialize DC ready products, promising a bright future for LVDC [231]. Another feature to consider is the significant benefits that ESS brings to DC systems though it adds more complexity in facility management [162]. The massive use of electric transport will pave the way to further develop LVDC based systems.

It is remarked that the LVDC microgrid is an energy efficient architecture that can transform the existing AC system to DC home systems [162]. The increased use of DC in home appliances brings forward the idea of connecting DC sources and loads in a DC MG [138]. Despite LVDC benefits, we must recognize the challenges of leaving behind a mature and worldwide AC system. Nonetheless, a wise approach might be implemented in early-stage buildings like LED lighting combined with USB Power Delivery and PV interconnected on DC, which can be an early business case for office buildings [229].

## 8. Conclusions

This final section closes on the research question, *Is it feasible a massive deployment of LVDC microgrids renewable-based?*. A conclusion for every feature assessed through the entire survey will be provided.

The most remarkable conclusions have been achieved after analysing the most novel and updated investigations. For starters, prosumers are playing a pivotal role in LVDC systems since they can achieve meaningful savings. Nonetheless, a massive increase in prosumers would challenge integrating the surpluses into the utility grid. In some countries, this is solved by introducing a Sun tax that hinders surplus generation. Yet, using a partially connected MG and new business models that could be implemented bring forth different solutions.

A second conclusion, using bus distribution makes easier the integration among the systems with renewables and its property of fault isolation makes it a more appealing approach to networks. On the other hand, it is definitely the lack of standardization and regulation (voltage selection) that is still the foundational challenge this technology needs to overcome before massive adoption is possible. It appears all efforts are narrowing down to two standards: 48 V and 380 V. The former is more suitable for low power residential use, whereas the latter is for commercial loads and high-power unit home appliances.

Last but not least, it is unquestionable that MG systems will bring tremendous impact to *social welfare*. Off-grid systems could be the only opportunity to increase quality of life in isolated towns and villages. The remaining solutions then are safer, more efficient, and easily integrated with renewable energy sources. Thus, they will empower citizens, and create more local jobs.

## Declaration of competing interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rser.2022.112198. and https://doi.org/10.5281/zenodo.5914926.

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