STANDARDS RESEARCH

DC Microgrids in Buildings

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Executive Summary

For most of electrified history, alternating current (AC) has been the dominant form of power distribution. In all but the earliest years of the electrical industry, before a clear standard had emerged, buildings have been powered using AC power, while direct current (DC) power has been limited to a few niche applications. Recently, new technological and economic factors have made a compelling case for expanding DC power use in buildings. With the greater adoption of solid-state electronics, solar photovoltaic (PV) power sources, other renewable energy systems, and energy storage systems that supply DC power, there is increasing potential for DC-based generation, distribution, storage, and utilization equipment.

This has given rise to an interest in the concept of DC "microgrids", which are systems comprised of DC loads and distributed energy resources that can operate independently upon loss of the normal AC supply. Apart from the resiliency benefits of DC microgrids, DC power distribution can provide efficiency gains, since multiple AC/DC conversions are avoided. The benefits of DC microgrids include increased resiliency, safety, performance, efficiency, stability, as well as plug-and-play capabilities. Further, DC infrastructure can play a major part of "smart grid" power distribution, along with decentralization and digitization.

This research study reviewed current trends in DC-based distribution technology, including standards development activities, and evaluated forty-three recent DC microgrids (including commercial, institutional, industrial, and nanogrid residential projects).

An analysis of the current standards environment was conducted to determine gaps and identify the most critical steps to enable adoption of DC power systems. The highest priorities were concluded to be:

1. Establishing standard DC voltage levels and ranges;
2. Developing approval criteria for DC power metering equipment for revenue billing;
3. Establishing standard receptacle and plug configurations for DC circuits;
4. Updating product standards to enable commercialization of DC lighting, motor drives, and electric vehicle supply equipment;
5. Clarifying rules for interconnection of distributed energy resources;
6. Determining life safety installation provisions for DC microgrids; and
7. Developing product standards and installation rules for DC protective devices.

Introduction

Study Objectives

This research study seeks to assess the current state of direct current (DC) power distribution and to address the adoption of DC microgrids and DC-based distribution infrastructure within buildings. This includes items operating or intended to operate at all voltages in electrical installations for structures and premises, including factory-built relocatable and non-relocatable electrical installations structures, located indoors or outdoors.

The first stage of the research study assembled and documented global case studies for DC-powered buildings and microgrids constructed to date. Systems relevant to the research study included building projects with any DC power component, DC microgrids, and general DC power distribution systems, serving typical building loads such as lighting, mechanical systems, distribution and utilization equipment, and appliances. Wherever possible, project participants were consulted to explore their "lessons learned", and identify drivers of and barriers to the adoption of DC-based distribution systems, with respect to the relevant standards and installation provisions for the equipment. Through the case study reviews, the rationale for standardization work becomes apparent.

The second stage of the research study included a review of relevant national and international codes and standards relating to DC power. Stemming from these two efforts, the research study was able to assess industry needs in this area from a standards development perspective.

History – The War of the Currents

Today, almost every home or business is powered by alternating current (AC) power systems, transmitted from large power plants across long distances. Although we take it for granted now, this was not the case 130 years ago. Thomas Edison's design of the incandescent light bulb was a first step in moving away from gas- and oil-based lighting and making electricity a modern necessity. To connect a series of lights in an economically manageable size, Edison calculated the necessary copper wire thickness and realized that the lamp would need to run on low voltage, although incandescent lamps could be built to run on either AC or DC power.

By 1882, Edison's utility became increasingly successful at powering buildings by a 110-volt DC distribution system. Edison's system also worked well with batteries, DC motors, and generators. He even had a DC energy meter for billing purposes. However, this type of system had size limitations, because voltage drop on the wires required the generation plant to be no more than a mile from the consumer. Cost of the large copper wires that were required was also too high.

In the mid-1880's, Westinghouse engineers built the first commercial AC transformer installations, although prototypes had been developed in Europe during previous years. This was a leap forward for AC, enabling voltage to be "stepped" up or down and making high-voltage/low-current electricity transmission more efficient.

George Westinghouse had entered the AC business in 1884 and quickly became Edison's competitor. His company acquired a few of former Edison employee Nikola Tesla's AC-based patents and refined the components of the AC power systems we know today (such as three-phase power systems, transformers, induction motors, and induction disc energy meters), making AC power distribution a commercially viable alternative to DC.

Over the next few years, Edison ran a public campaign to discourage the use of AC. The campaign included lobbying state legislatures and spreading disinformation in New York's media. In his effort to show the dangers of AC, Edison even directed several technicians to publicly electrocute animals using AC power. Soon after, Edison's employees designed the first electric chair for the state of New York, using AC power to, again, publicize its risks. Around the same time, the "electric wire panic" took place in New York, when a few electrocution-related deaths spurred public debate and concerns regarding overhead distribution wires. These and other events led to the initial development of electrical safety standards and codes.

Despite the safety controversies, Westinghouse won the bid to provide power to the Chicago World's Fair in 1893. That same year, the Niagara Falls Power Company decided to award Westinghouse the contract to generate power from Niagara Falls. The project was successful and on November 16, 1896, Buffalo was lit up by AC power. This milestone marked the decline of DC for years to come.

The Return of Direct Current

Although AC power has been the dominant paradigm since the turn of the 19th century, DC power has also remained in use since that time for applications requiring battery storage or the unique characteristics of DC motors. Since power is primarily distributed as AC, though, a substantial majority of electrical products, components, codes, and standards have been designed for AC power. However, developments in recent decades have increased the practicality and benefits of DC, encouraging the reconsideration of DC systems for general power distribution.

With the invention of semiconductor electronics in the 1970s, cost-effective conversion between AC and DC became possible. DC power has since become prevalent in high voltage (HV) DC transmission lines, computing, telecommunications, light rail transit, motor drives, and in more recent years, solid-state lighting. Perhaps more importantly, modern electronics inherently operate using DC instead of AC. Examples are all around us: notebook computers, cellphones and tablets, light-emitting diode (LED) lightbulbs, flat-panel displays, and a rapidly expanding universe of smart devices comprising the "Internet of Things" (IoT). While power electronics are embedded in digital displays and control circuitry, it is also common for many appliances and heating, ventilation, and air-conditioning (HVAC) equipment to incorporate motors driven by brushless DC technology (electronic commutation) or variable frequency drives. These motor drive technologies use modulated DC power to drive AC induction motors with higher efficiency and controllability.

On the generation side, a surge of renewable energy technologies is leading the trend towards distributed energy resources (DER). Distributed generation sources such as solar photovoltaic (PV) panels inherently produce DC power onsite, while wind power uses DC power conversion to let it run asynchronously from the AC grid. Large-scale battery storage and electric vehicles (EV) are other DC power DERs that are showing rapid commercial growth.

Using such technologies with the legacy AC power from the grid requires multiple AC-DC conversions. The idea of a building run on a DC backbone is appealing because it makes use of generated DC power that is consumed by multiple DC loads. Such design promises increased efficiencies, lower operating costs, and potential independence from the grid. A DC power microgrid is also more stable, controllable and interoperable [1, 2], and potentially cheaper to install in some applications [3, 4] than its AC-equivalent.

Figures 1 and 2 show two modern buildings incorporating solar, wind and grid-tied sources, energy storage, and some typical building loads. The two distribution schemes are differentiated with red lines representing AC power and green lines representing DC power. Figure 1 reflects the typical "status quo" AC distributed building where power is converted to AC in multiple locations. Figure 2, however, depicts a DC distribution system where the only AC/DC conversion is at the grid connection. The remaining DC/DC conversions typically exhibit smaller losses.

A Word about Microgrids

Mature power grids in industrialized countries today employ primarily multi-megawatt to gigawatt-scale generation facilities and thousands of kilometres of high voltage transmission lines, along with numerous substations. In most of these countries, the primary energy source is fossil fuels, with associated emissions of greenhouse gases (GHG) such as carbon dioxide and methane. But today's grid is not a static entity – unprecedented changes are being driven by the need to reduce GHG emissions, replace aging infrastructure, and reduce electricity costs. Improving reliability and resiliency are also important: severe weather, cascading outages, and physical/cyber-attacks can compromise critical facilities such as health care and water treatment infrastructure [5].

Figure 1: *Hybrid AC/DC Microgrids – "Status Quo" (Source: EMerge Alliance)*

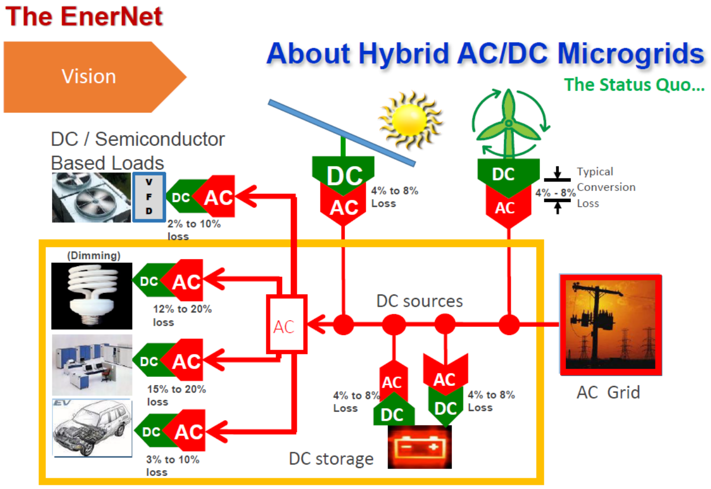
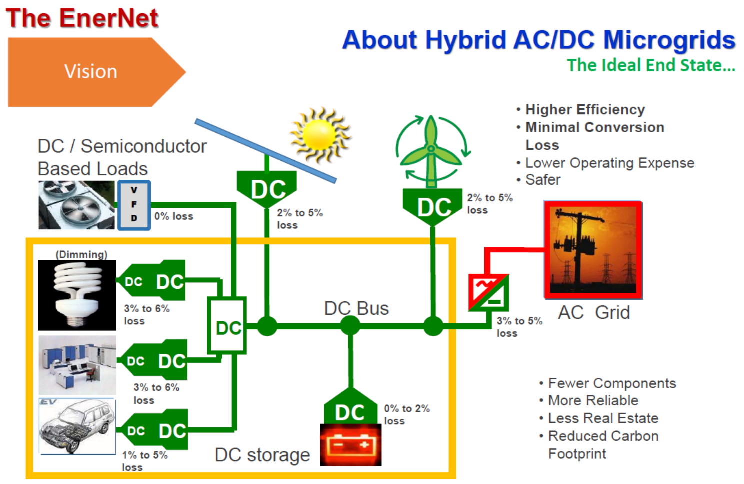


Figure 2: *HDC Microgrids - "The Ideal End State" (Source: EMerge Alliance)*



A "microgrid", as defined by the US Department of Energy (DoE), is ''a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to able it to operate in both grid-connected or island mode". Indeed, microgrids have emerged as a flexible infrastructure that, with the appropriate grid control mechanisms, answer the above challenges. Microgrids – whether a single building or a few connected entities – can enhance mature macro-grids or support rural communities with their first introduction to electricity. Brian Patterson of the EMerge Alliance has proposed the term "Enernet" as the vision of the future grid as made of layers of nano-, micro- and macro-grids interoperability.

In a way, with the advent of DC microgrids, we may finally see a migration to DC-based systems similar to Edison's vision of 121 plants distributing power to American homes at 110 V DC. As was the case in the past, and perhaps more importantly today, fire and life safety are of high priority. Hence, for this technology niche to become commercially adopted, rigorous installation and product standards are critical.

1 Background and Industry Drivers

Several global and national trends are driving the penetration of DC distribution systems in buildings. The main drivers are government green energy targets and initiatives, the growth of DER integration, the increase in DC native loads, and building automation advances.

1.1 Government Sustainability Standards and Initiatives

A 2017 Natural Resources Canada (NRCan) report stated that 17% of Canada's greenhouse gas emissions come from powering our buildings [6]. NRCan has also found that commercial and institutional energy use increased 35% between 1990 and 2015, but would have increased 58% without energy efficiency improvements [7]. In 2015, Canada joined much of the world at the Paris climate talks in pledging to reduce carbon emissions 30% below 2005 levels by 2030. Present day emphasis on clean energy presents opportunities for cost effective energy efficiency solutions and technologies such as DC power microgrids.

Build smart – Canada's building strategy is one driver for the Pan-Canadian Framework on Clean Growth and Climate Change [6]. One of its goals is for governments to develop and adopt increasingly stringent model building codes, starting in 2020, with the goal to adopt a "net-zero energy ready" model building code by 2030. As part of these efforts, since 2014, 23 residential (as well as one commercial and one institutional) net-zero energy projects were built across Canada. Canada's ENERGY STAR® for New Homes and R-2000 certification programs also help prospective home buyers choose the most efficient homes on the market. Programs like LEEP (Local Energy Efficiency Partnerships) are geared to support builder groups and manufacturers through business-to-business collaboration in achieving such projects.

Another goal of "Build smart" is a **plan** for governments **to require** labelling of building energy use by as early as 2019. Right now, buildings across Canada, representing more than one fifth of Canada's commercial floor space, are already tracking and sharing their energy performance using the "ENERGY STAR Portfolio Manager". This government tool provides a fair comparison of buildings' energy performance while also adjusting for regional differences. Similarly, the "EnerGuide" home energy rating system provides homeowners with information about the energy performance of their homes. The Canadian Home Builders' Association has also introduced its own net zero home labeling program [7]. In pairing solar PV for net zero homes with DC-based lighting and consumer electronics, full DC distribution systems could offer added value to such initiatives, which seek energy efficiency gains through reduction in conversion losses.

On a local level, responding to federal initiatives and similar global trends, cities and provinces alike have introduced their own clean energy targets. In 2017 British Columbia introduced the Energy Step Code that establishes a four-step process to transition to the construction of net-zero-energy ready buildings [8]. Ontario has committed to 20 GW of renewable power by 2020 [9], while 10 Canadian municipalities have either implemented a 100% renewable energy target or began taking steps towards such a target [10].

1.2 Growth of DER Integration

Hand-in-hand with the trend towards energy efficiency, the focus on renewable energy sources is another driver for DC power systems. Falling technology costs (particularly for solar PV and more recently for battery storage), combined with advances in technologies to manage mobile payment systems, have enabled initial DER market penetration [9]. Commercial/residential building design will usually be limited to some solar PV capacity, while industrial infrastructure can combine larger capacity wind/solar farms.

1.2.1 Solar Photovoltaics

In 2017 Canada, the capacity of the solar photovoltaic industry was 2,911 MW, wind power industry capacity was 12,239 MW, and generation of wind power was 30.5 TWh. For both industries, most capacity and generation are in Ontario [11]. Additionally, The Canadian Solar Industries Association's (CanSIA) Roadmap 2020 target is to generate 1% of electricity in Canada using PV, with 6,300 MW of installed capacity [12]. The two images in

Figure 4 show the large national growth for both industries in recent years.

Figure 3: *Canada 2005-2017 Solar PV installed capacity (Source: Natural Resources Canada)*

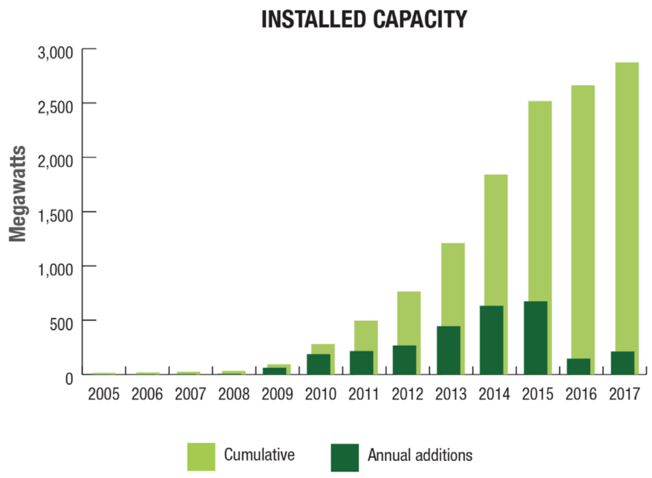
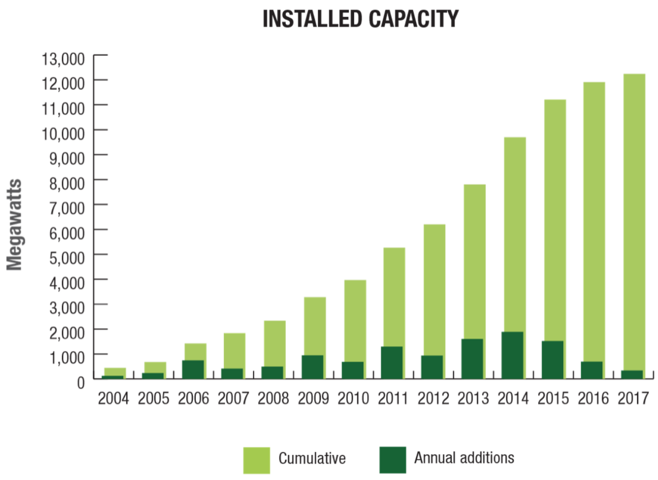


Figure 4: *Canada 2004-2017 Wind installed (Source: Natural Resources Canada)*



Further, according to Canada's Generation Energy Council 2018 report, by 2050 commercial and institutional buildings with appropriate roof size and orientation will be required to have solar installation [1].

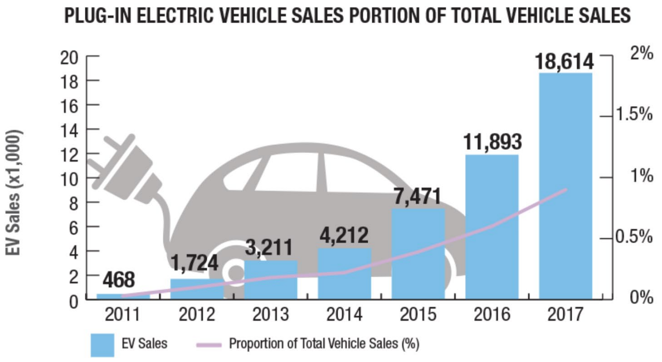
1.2.2 Battery storage

Battery storage systems for use within buildings (behind-the-meter), such as Tesla's Powerwall, have rapidly reduced in price in recent years. This is mostly due to electric vehicle (EV) market expansion and the corresponding production of larger, cheaper, more energy-dense batteries [14]. PV's drawbacks (i.e., intermittency and the daily timing imbalance between demand and production) can be overcome with battery storage, making such symbiosis more cost effective. Such a solution is especially relevant where high grid electricity prices exist with low or non-existent remuneration for solar generation. As well, since batteries inherently operate in DC, where DC microgrids are utilized, DC-generated power can be stored but also drawn directly, skipping unnecessary AC conversions that translate into power loss.

On a larger scale, electric utilities are increasingly deploying energy storage systems, and particularly batteries, to mitigate local reliability issues, shift loads, achieve greater operational flexibility, and improve their ability to handle rising shares of VRE (variable renewable energy) [9]. In Canada, BC Hydro and NRCan have both implemented battery storage projects to alleviate grid overloading and enhance customer supply reliability during sustained power outages [15, 16]. Canada also aims to become established as a global centre for energy storage technology development and deployment by 2030 [13].

As of late 2017, an estimated 400,000 public charge points were in operation worldwide representing a 100% increase from late 2015 to late 2017 [9]. In Canada, in the first quarter of 2018, electric vehicle sales made up 1.5% of total vehicle sales. Almost 19,000 vehicles were sold in 2017, up 56% from 2016. Electric vehicle sales are highest in Québec, Ontario, and British Columbia. Figure 5 represents this enormous recent national growth [17].

Figure 5: *Canada 2011-2017 EV sales growth*
(Source: Natural Resources Canada)



The strong trend in EV sales, together with growing public and private charging station infrastructure, presents another driver to DC microgrids. Synergies of EVs with the grid (as a VREs) or with buildings (as additional potential secondary power resources), are being developed through V2G (vehicle-to-grid) and V2H (vehicle-to-home) technologies to improve demand response [9, 18]. Specifically, in a building scenario, the advantage of staying in DC power for EV charging/discharging is the same as described above for battery storage.

Local initiatives include NRCan's Electric Vehicle Infrastructure Demonstrations, a $46.1M project funded by the Energy Innovation Program (EIP) with the intent to assess potential hurdles for the deployment of next-generation EV charging station infrastructure [19]. As well, Québec and British Columbia's current incentive programs offer rebates for the purchase of EVs or installation of home EV charging stations [20].

1.3 Increase in DC loads

The proliferation of DER would not on its own make a strong case for DC distribution in buildings if the end-user environment would not require DC power as well. A recent study estimated that 70% or more of residential electric load in the US is either already DC or can easily be converted to operate on DC. The remaining approximately 30% load relating to motors, can be modified to operate on DC, though it is not feasible in all cases. The study assumed a home with an EV, energy efficient appliances, and HVAC equipment using DC motors [14].

Indeed, electronics today keep rapidly growing as new wireless and mobile applications continue to evolve. Many of them, such as tablets, mobile phones, video game consoles, some desktops and computer monitors, and smaller televisions already consume DC power through external adaptors. USB-C is the latest standard used to power many smaller electronics, providing guidance for connectors, voltage, and total power draw. The development of such standards is likely to go hand in hand with the increase of products using them.

The exponential LED market growth in recent years due to declining prices, improved efficiencies, and enhanced product flexibility is another driver. As the lighting industry shifts to LEDs, DC power will gain more traction as LEDs inherently consume DC. Many manufacturers are beginning to offer LEDs with DC (instead of AC) drivers, which also open the door for Power over Ethernet (PoE) applications.

DC-ready appliances have served niche markets for decades, including telecommunications, off-grid residential, recreational vehicles (RV), marine applications, and rail transport. While these are not always easily transferable to commercial and residential buildings, recent years have seen many motor-driven devices incorporate DC motors with variable frequency drives (VFD). VFDs allow for better efficiencies as power can be reduced in times of lower load [14].

From a national context, in Canada in 2015, electricity use comprised 39.4% and 42.1% of total secondary energy use in residential and commercial sectors, correspondingly [21]. Achieving greater energy efficiency in terms of consumption is an effort on its own and is reflected in energy efficient appliance/HVAC programs such as ENENRGY STAR and corresponding long-term goals set by Canada's "Build Smart" strategy. A 2017 Berkeley report found that overall, DC products are more efficient than their AC counterparts [22]. With the additional efficiencies of having a DC distribution system, millions of dollars can be saved in electricity consumption.

1.4 Digitization of Energy and Building Automation

Another driver for DC-powered buildings relates to "intelligent" or "smart" buildings with increasing levels of automation and control, as described in the 2017 Electro Federation of Canada industry report [23]. In the residential sector, convenience and reduced energy bills are driving solutions that control lighting, security, audio, and heating systems through one centralized access point on the owner's cell phone or tablet. Similarity, in commercial buildings, more sensors and controls are introduced to provide real-time data on space utilization to control lighting and other parameters in specific areas based on changing occupancy needs. The industrial sector is ahead in this arena, as many factories already deploy numerous sensors and actuators to provide effective process controls through efficient operation of machinery. Such sensor networks, powered by low voltage DC infrastructure enable better energy efficiencies, operating flexibilities and cost-effective project budgets. As average sensor prices have continued to fall over the last 15 years, while sensor technology keeps extending to new applications, this trend is likely to continue.

Low voltage DC systems are already in the market including a suspended 24 V DC energized ceiling grid that powers lighting fixtures as well as sensors and control devices through simple plug-and-play clip-on whips. Other products feature public charging systems on touch-safe rail segments that can power up to 24 devices with sliding USB connectors. Power over Ethernet (PoE) is a low voltage DC protocol which combines power distribution with data communication and has become common nowadays. With a power-capacity of 90+ Watts in 2017, and further growth expected, the range of PoE driven applications continues to grow. Lighting over PoE is a notable trend especially with the inherent DC-based LED technology. New improvements to LED technology also allow for integration of sensors directly into fixtures [23].

Another technology that may complement DC power distribution and perhaps even revolutionize it is "Digital Electricity". Both data and power are transmitted in hundreds of high-voltage packets per second while each one is verified by the transmitter. This can be done over long distances over standard low-power cabling. The pulses are halted within 3 milliseconds if there is a short-circuit, a person touches it, or any other irregularity occurs. This highly efficient power delivery, that also promises to tackle crucial safety concerns together with the ability to digitally control a host of modern electronic devices, may form a new trend altogether. There are at least two companies that currently offer digital electricity solutions.

2 DC Microgrid Case Studies

With all the potential advantages of DC microgrids, the technology is still in its infancy. This research study documented 43 DC microgrid case studies to begin identifying any trends within this field, and, more critically, identify gaps and barriers to implementing DC power microgrids. The complete case study matrix is shown in Appendix A. This is not meant to be a comprehensive listing of all DC-powered building projects, but provides a sampling. The 43 documented projects are comprised of 18 commercial, 11 industrial, six institutional projects, with the rest being residential, research lab, medical, or a military facility. The research study focused on North American projects, while also taking account of some international work, including projects in China, Japan, Germany, Africa, and Kuwait.

The earliest projects were installed as demonstrations in 2010. These are mostly small-scale DC lighting (fluorescent or LED) projects with a DC ceiling-grid. More recent projects include a solar PV component ranging between 30 kW to 500 kW, battery storage ranging between 13 kWh to 350 kWh, some wind generation, and at times EV charging stations. Projects include PoE-powered LED lighting with most projects including a few different advanced lighting control systems that complement "smart building" designs. More advanced DC microgrid projects feature "behind the meter" peer-to-peer DC links between a group of residential houses. For all projects, typical loads were LED lighting, laptops, and computer screens, with a few DC home appliances like a coffee maker or a water cooler. About 20% of the projects featured heavier loads such as ceiling fans, air conditioners, refrigerators, or fork lift charging stations. Main DC voltages observed were consistent across North American projects at 380

> *“Proving the case for DC-powered systems is still underway. Many research institutes focus on fair comparison between AC and DC distribution design alternatives and cost/benefit analysis.”*

V for main DC distribution busses and 24 V for low voltage. These voltages vary on other continents.

Overall, communication with project participates included 23 teleconference conversations plus three email correspondences. Information was gathered from six manufacturers, five electrical designers/consultants, three research personnel, three industry experts, and four other development team members. The questionnaire sent to each interviewee in advance is shown in Appendix B.

Motivations for DC power project development as seen from this project list can be categorized as follows:

1. **Product commercialization** – Start-ups and larger corporations being able to sell manufactured products and components that the market is ready to absorb.

2. **Government renewables initiatives and a desire to be sustainable** – A few interviewees mentioned national or local green energy targets as a benchmark they hope to achieve or contribute towards. California’s 2020 Net Zero Energy home target [24] and its 2019 100% LED baseline [25] are two examples. Funding organizations and programs like the U.S.-China Clean Energy Research Center (CERC), Sustainable Development Technology Canada (SDTC), Ontario’s Smart Grid fund (SGF), and California’s Electric Program Investment Charge (EPIC), took an important role in projects’ development. China’s energy savings target also attracts manufacturers to engage in such a market. With these initiatives as a backdrop, most of the projects were of a demonstrative nature and often included monitored systems. Green tech “hubs”, such as the NextEnergy Center in Detroit and the Alliance Center in Denver, aim to foster collaborative workspaces for sustainability organizations and endeavor to create environments where businesses can build, certify, and sell DC products and respond to market demand.

3. **Research** – Proving the case for DC-powered systems is still underway and many research institutes such as Berkeley Lab, NERL, UCDavis Lighting Center and many other Universities and utilities are involved. Efforts seem to focus on demonstrating the isolated efficiencies gained from DC systems, separate, for example, from efficiencies gained by switching to LED lighting. NREL is developing an Energy Design and Scoping Tool for DC distribution Systems to accurately model AC and DC loads, provide a fair comparison between AC and DC distribution design alternatives and facilitate cost/benefit analysis [26].

3 Codes and Standards Review

To fully accommodate the safety and interoperability of product elements of DC microgrids, there are some Canadian codes and standards that will require updating, and new standards may need to be developed. The review of standards will require an in-depth look at their scope and requirements to determine the required changes. Standards will then need to be categorized in the following fashion with regards to their readiness to accommodate DC microgrids:

1. Standards requiring a high degree of change with further prioritization of High/Medium/Low;
2. Standards requiring a medium degree of change with further prioritization of High/Medium/Low;
3. Wire, cable, and bus duct standards – as wires and cables are not DC- or AC-based, specifically, small changes may be required with respect to insulation and voltage drop at the lower voltages;
4. Existing DC standards – these standards already have a DC component, therefore they will require a review and may require some adjustments for full DC microgrids;
5. Standards requiring minimal to no change – items that are generally AC/DC neutral; and
6. Medical equipment.

Within each category, standards can be broadly broken into *safety standards* that require adjustment to accommodate DC power and/or DC voltages with functional amperages, and *consumer product standards* that would require adjustment to be easily utilized in a DC grid. Medical applications are presently seen as lower priority standards, as are those in hazardous and explosive environments, because these industries are likely to be slower to adopt DC grid connections.

Additionally, Appendix C features a list of relevant international standards which can be used for reference in developing Canadian standards. The list incorporates the EMerge Alliance *Reference List for DC Codes and Standards* (as mentioned in Berkeley Lab's 2017 Report [1]). Those standards have already been updated for DC power and are from the NEC, IEC, ETSI, Europe, and China.

The Canadian work will ultimately draw upon work done in other jurisdictions, particularly the United States, since Canadian standards tend to align with U.S. standards for consumer product applications.

3.1 Standards and Canadian Electrical Code 2018 Changes

Work on updating the codes and standards has already begun. Some of the recent code changes and standards development work groups in various organizations will continue to inform the development of DC microgrids.

The latest version of CSA C22.1, *Canadian Electrical Code, Part I, Safety Standard for Electrical Installations* ("CE Code"), published in 2018, includes a new Subsection 16-300, dealing with PoE wiring, which combines DC power supply and Ethernet communications on a single set of conductors. These rule changes address issues associated with recent revisions to IEEE standards that specify higher-power PoE interfaces. In PoE systems, cables are bundled together for extended lengths and in potentially large quantities. Because of power losses in the wiring, higher power use can cause cable heating to become an issue, requiring new restrictions in installation methods. These new requirements for PoE can be found in the CE Code 2018, Rules 16-300 through 16-350 and Table 60.

Through the implementation of DC microgrids, the case studies noted that there were some codes and standards that have not yet been developed, which would assist the code authorities in accepting these installations.

3.2 Recent Code Updates – US and International

Canada is not an island unto itself; it has manufacturing and trade connections with many other countries, and specifically shares many regulations with the United States. As such, it is difficult for Canada to "go it alone" when it comes to codes and standards – Canada needs to be aware of standards in other jurisdictions in order to incorporate similar requirements allowing manufacturers to produce products effectively.

3.2.1 National Electrical Code (U.S.) 2017 Changes

In the 2017 version of the U.S. *National Electrical Code* (NEC), published by the National Fire Protection Agency (NFPA) as NFPA 70 and which governs electrical installations in the United States, several articles were added to address elements of DC microgrids. Article 691 introduced requirements for "Large-Scale Photovoltaic Electric Power Production Facilities," defined as those whose systems produce at least 5 MW power. Article 706 introduced safety labelling and shutdown requirements for energy storage systems, in conjunction with UL 9540, while stand-alone generation systems such as wind and PV (non-grid-interconnected) are covered in Article 710.

Most relevant to the microgrid discussion is the introduction of Article 712, "Direct Current Microgrids," which now governs independent energy distribution networks that include the direct coupling of power from DC sources to DC loads.

In addition to fully new articles, there were several amendments in NEC 2017, such as updates to Article 690 on solar PV systems. Of direct relevance to microgrids are the PoE updates in Article 840. Amendments for wireless power transfer, including wireless power transfer equipment for EV charging, were included in Article 625.

3.2.2 NFPA Research Foundation

This foundation held work group summits in 2017 and 2018 in attempts to clarify specific and actionable steps needed to facilitate full consideration of PoE cabling in modern infrastructure, while maintaining established levels of safety. Work groups held discussions regarding: vision statement, regulatory coordination, and research and data, as well as training, education, and awareness.

3.2.3 IEEE Standards Development

IEEE is one of the largest organizations looking after electrical installations of all types within North America. They are heavily invested in developing the requirements and maintaining standards for DC power distribution. These often guide the product manufacturing requirements and electrical codes.

The IEEE SCC21 Standards Coordination Committee on Fuel Cells, Photovoltaics, Dispersed Generation and Energy Storage has developed IEEE 2030, *IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads.* There are work groups involved in developing a *Standard for DC Microgrids for Rural and Remote Electricity Access Applications,* one specifically involved in the specification of microgrid controllers, and another developing *IEEE Standard Technical Specifications of a DC Quick Charger for Use with Electric Vehicles.* Other committees and working groups have developed:

- IEEE 1547-2018, *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*
- IEEE SA-802.3bt, *IEEE Draft Standard for Ethernet – Amendment 2: Power over Ethernet over 4 Pairs*
- IEEE SA-1627, *IEEE Draft Standard for Transient Overvoltage Protection of DC Electrification Systems by Application of DC Surge Arresters*
- IEEE SA-1653.6, *IEEE Draft Recommended Practice for Grounding of DC Equipment Enclosures in Traction Power Distribution Facilities*
- IEEE SA-946, *IEEE Draft Recommended Practice for the Design of DC Power Systems for Stationary Applications*

3.2.4 IEC Standards Development

Globally, development of DC microgrid safety and manufacturing standards has been led by the International Electrotechnical Commission (IEC). These standards have been adopted in many countries, including Canada when appropriate, or used as guidelines for developing local requirements. There are several IEC committees looking at microgrids, including:

- SyC (System Committee) LVDC – LVDC and Low Voltage Direct Current for Electricity Access
- SEG 6 (systems evaluation group) – Non-Conventional Distribution Networks/Microgrids
- SEG 9 (systems evaluation group) Smart Home/Office Building Systems

"To fully accommodate the safety and interoperability of product elements of DC microgrids, there are some Canadian codes and standards that will require updating, and new standards may need to be developed."

- IEC TS 629898-1:2017 Edition 1.0 (2017-05-18), *Microgrids – Part 1: Guidelines for microgrid projects planning and specification*
- IEC TS 62257-9-3:2016 Edition 2.0 (2016-09-27), *Recommendations for renewable energy and hybrid systems for rural electrification – Part 9-3: Integrated systems – User interface*
- IEC 62909-1:2017 Edition 1.0 (2017-05-19), *Bi-directional grid connected power converters – Part 1: General requirements*

3.2.5 "EMerge Alliance" Standards Development

With the aim to further the development of DC microgrids, the EMerge Alliance was formed in the mid 2000's. It is an open industry association that works to support the adoption of DC power distribution in commercial buildings. Because of the lack of existing standards in this field, EMerge has developed a number of its own standards (taken from 2017 Berkeley Lab report [1]), released in 2016:

- EMerge Occupied space V2.0, *DC power distribution requirements for commercial building interior*
- EMerge Residential V1.0, *DC power distribution requirements for residential buildings*
- EMerge Commercial Building V1.0, *DC power distribution requirements for commercial buildings and campuses*
- EMerge Data/Telecom V1.1, DC *power distribution requirements in data centers / telecom*

These standards can be and have been used as guides for the more recognized codes and standards associations.

3.2.6 California Building Codes

Another relevant set of installation codes are the regulations established by the California Energy Commission (CEC). The CEC regulations include part of the California Building Standards Code ("Title 24"), and are likely the most stringent energy efficiency regulations in North America, as they are designed to meet California's 2020 net-zero energy (NZE) target for residential construction. Though not addressing DC microgrids specifically, the extremely stringent efficiency mandate of the CEC is driving some DC microgrid development. The relevant codes include:

- Title 24 (Part 6) – *Building Energy Efficiency Standards for Residential and Non-residential Buildings*
- Title 20 (Division 2, Chapter 4, Article 4) – *Appliance Efficiency Regulations*

4 DC Microgrid Advantages, Challenges, and Additional Considerations

Summarizing the findings from our research study's conversations and internet research, Sections 4.1 to 4.4 outline the advantages, challenges, and specific considerations relevant to DC-powered building projects.

4.1 Advantages

The primary driver towards DC-powered buildings is the potential for energy savings, as many high-loss AC/DC conversions can be avoided. Energy savings translate into reduced GHG emissions and lower operating costs. Savings are compounded when there is DC-generated power such as solar PV or wind, battery storage, and EVs as well as DC loads and efficient DC/DC power conversion components. A 2017 Berkeley Lab report summarizes the energy savings of eight studies: a range of 2-14% was reported on four modelling projects, while 2-5.5% range was reported on four experimental studies [1].

From the standpoint of building operators, the separation between the AC grid and the building's microgrid facilitates a seamless transfer to "islanding" (stand-alone operation) without the need for expensive static transfer switches and provides resiliency during possible grid outages. While for small microgrid sizes, power regulation and management is simpler in DC because there are no issues with harmonics, power factor, and frequency regulation.

Even where DC microgrids are not seen as viable, PoE applications are seeing a surge. Specific PoE application advantages include easier integration of power, communications, controls, and monitoring in multi-sensor smart buildings using standards such as USB, PoE, Thunderbolt, and HDBaseT. The case studies in this research report and other research have found that the total labor hours necessary to install the PoE system were less than half of the time necessary for a conventional installation [3]. This coincides with similar claims by some of the bigger PoE manufacturers (e.g., Philips and Eaton) regarding significant savings in material and installation of PoE systems in comparison to conventional lighting wiring [1].

The labour savings in PoE are extensive, but other cost savings can be realized through advanced DC bus controls which provide the ability to respond to market price fluctuations by using "peak shaving" and other techniques. When retrofit applications are considered, a cost-effective value of DC microgrids operating on 380 VDC is that existing AC wiring infrastructure designed for 600/347 V in a building can be re-used to run DC power. No re-wiring is necessary for a building retrofit application, as the electric codes usually allow the re-use of wiring if the wires are labeled accordingly [28].

From a safety perspective, the dangers of electrocution of the human body by DC power is considered lower than in AC because total impedance of the human body decreases as frequency increases [27]. Further, a DC power distribution system would eliminate the need for the many conventional power supply AC-DC converters found in home electronics today, which are often "phantom power loads" that draw power even when not in use and can heat up and cause fires. Additionally, with the reduction of materials, size, and weight of electronics, consumers would need fewer power converters while manufacturers and distributors would benefit from reduced materials and shipping costs [14].

4.2 Challenges

4.2.1 Product Availability

Many interviewees mentioned the lack of DC products as a definite hurdle, in particular:

- Limited or no product selection, and ultimately a much smaller selection than the equivalent AC product selection;
- Products not available as advertised. As an example, one designer mentioned vendors advertised 20 PoE models, but only had two readily available;
- USB-C viability and finding USB-C compatible devices;
- Limited supply commercial-scale DC appliances and HVAC equipment; and
- Limited supply high-power DC/DC conversion equipment for larger power systems.

The lack of product availability translates into higher up-front costs and, as in the case of one project, equipment adding up to 40% to the project cost, which is financially unsustainable. Additionally, the small market for DC products competes against the high market demand for AC products and means that manufacturers tend to "think in AC". Consequently, in today's market, products and components are mainly developed with only AC in mind.

One researcher noted that, as with other new technologies, a chicken and egg scenario is observed: there is a lag in DC equipment and product availability and at same time procurement is costly since it currently requires custom engineering.

4.2.2 Project Development and Custom Design

One industry expert explained that one of the main development barriers is that project bidders add price for DC building work because of regulatory uncertainty due to:

- the local inspection authorities (Authority Having Jurisdiction or AHJ) and lack of product certifications;
- investor uncertainty (likelihood of developers or partners pulling out due to increased cost/complexity/delays); and
- lack of available products (less competitive prices).

In one project, funding was the main cause for the DC design to be eventually abandoned. In another, the unusual design made the electrical contractor require a different contract than originally proposed. Although the vendor stepped in at that stage, when it came to obtaining bonding insurance, uncertainty caused them to back down. One manufacturer mentioned that for the small sized start-ups that are often involved, there are warranty/service concerns from customers both on the system and component level, due to concern about longevity of the vendor itself. Design engineers and consultants also share such concerns as projects requiring guaranteed quality serviceability and maintenance of equipment in the future.

Working with new products naturally takes more time and effort. Prototype solutions can face many development problems along the way. Even when products exist such as PoE lighting, in one project, it took the designers much more time to determine which fixtures were suitable in terms of cost and function. Design time for the that project also greatly increased because of the need for additional information, as each cable rack needed a schedule and each light connection needed a PoE circuit [3].

Lastly, the lack of DC loads results at times in the need for grid tie-ins and inverters which is an obvious limitation for DC systems' efficiencies.

4.3 Design Considerations

From a design perspective, the case studies reviewed for this project noted several items that design engineers need to be aware of in developing DC microgrids. To start with, though there are no specific voltage standard within code, 380 V has become the "de-facto" voltage standard through its use in data centres, though 800 V and 1000 V DC are still used for high-power EV fast charging. If designers begin to standardize on 380 V DC distribution voltage, it will assist in reducing the proprietary voltages that manufacturers have been trying to implement. Further, like earlier adoptions of building management systems prior to BacNet protocols, DC power is currently seeing a larger variety of proprietary software for controlling their systems. Standardization will be a key.

When developing the initial grid requirements early in the design stage, calculations are key, including calculating and anticipating current inrush, DC arcing, and system energization, and calculating and mitigating arc fault and ground fault. These are large issues. The solar industry is developing requirements for arc flash, but currently there are no cost-effective products to address this. When it comes to ground fault, the definition of the ground point itself is a challenge – is it the midpoint or is it the ground fault itself? And, how does this impact the overall building grounding and bonding?

Balancing the DC voltage when utilizing a bipolar bus requires careful analysis and consideration and, when moving beyond a bipolar bus into multiple DC sources, how do designers interconnect the sources safely? It should also be noted that at the present time, most equipment that designers will specify comes from the solar market, but it often requires expensive adaptation and modifications.

Specific to PoE systems, the standards and codes for Class 2 cabling are well defined for low wattages. However, voltage drop can be an issue for longer distances, and power transmission under the standard is limited to cables #15 AWG and smaller. Thus, placement of outlets becomes a consideration. Arc suppression is also well defined under the 300 W limits. The issue becomes prominent when the end device is above 300 W.

4.4 Additional Considerations

4.4.1 Suitable Applications

In general, DC is attractive in commercial and industrial buildings possessing DC generation (PV, wind, EV vehicle-to-grid, etc.), DC energy storage with a high content of power electronics operated machinery, computer and lighting needs. On top of that, DC-DC conversions in the system need to remain efficient. Daily load scenarios make energy savings on residential projects less attractive because of the duck curve "dilemma" – the inherent timing-imbalance between peak demand (usually in evening/early morning) and solar power generation (daytime). A few interviewees noted that, overall, there seem to be more new construction applications and business cases than renovation. However, conversion of AC building to DC is possible; usually 277 VAC (RMS) will be rectified to 380 VDC (equivalent peak value). The DC voltage will come from rectified AC, but each circuit needs to be rectified separately. Hybrid buildings are possible, but economics will be compromised. Such an application is easiest in deep retrofits. Converting DC power to AC to feed back to grid has little benefit in many jurisdictions, based on grid-tie-in requirements.

With regards to low voltage systems, PoE is a suitable application in smart buildings where intelligent control of lighting, appliances, HVAC equipment, and security features are sought. As well, one interviewee suggested that energized ceiling grids would be beneficial in a dynamic lighting environment such as retail chains. When displays and lighting are frequently changed, the simple plug-and-play capabilities would be beneficial.

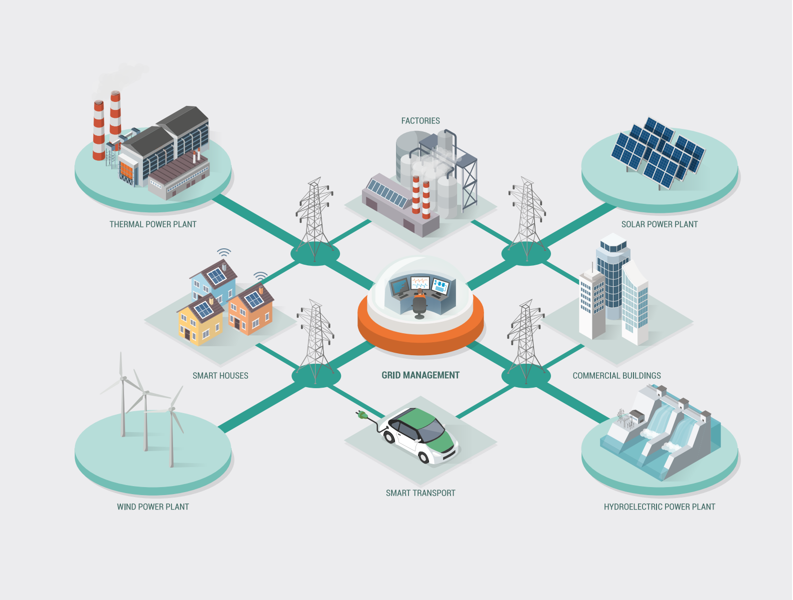
4.4.2 Products

The hunger for DC equipment was expressed often by interviewees. The need for DC compatible printers, computer screens, flat screen TVs, as well as small appliances was particularly noted. Simplifying systems to a plug-and-play scenario would also be of benefit. One researcher pointed out that, currently, many manufacturers have their own voltages and maintain proprietary software protecting third party participation, so even voltage match is not enough at times. Another complexity is the tendency of manufacturers to be protective about sharing new product information which is often considered "proprietary" in initial stages of product development. Clearly one hurdle is getting manufacturers from experimental benches to production, which means moving on a speculative base with, on the other hand, the possibility of becoming industry leaders. Organizations like CLASP support DC product development by inviting "cooperation, open dialogue, and a shared commitment among those who have a stake in generating, storing, distributing, and consuming DC power" [14].

Additional product development is also required when utilizing equipment for emergency purposes. For PoE lighting, there has been no testing completed on how long it will take for the digital switches to re-boot once the generator starts. Thus, when PoE lighting was used as emergency lighting at one of the case studies in this report, additional UPS units were added so that the emergency lighting data switches never lost power [3]. With additional product development and testing, the additional UPS may not be required.

4.4.3 Utility Interaction

The absence of utility-grade revenue metering was mentioned often by research study participants as restricting developing business models for DC distribution systems.



> *"Owners, designers, installers, and inspectors need to become educated so that more confidence can be gained in budgeting and scheduling."*

The local and national jurisdictions governing such approval differ in the US and Canada, so Measurement Canada will need to be engaged on this topic. Despite the jurisdictional differences noted above, an industry consortium including the EMerge Alliance, NSA, and Duke Energy are developing a standard for revenue grade utility metering for DC power. Another vendor-utility collaboration is working on a site-by-site certification of a DC-rated utility grade DC meter. This meter is currently UL tested though not yet certified.

4.4.4 Public Perception

As with any emerging technology, public perception can play a key role in the rate of its adoption or even its eventual rejection. One vendor mentioned that public perception can go haywire quite quickly due to some manufacturers "hyping up" their products' performance or compromising manufacturing quality. These can manifest as fiascos that reach the news fast and can have a negative impact. Some strategies to promote DC end-use devices can include creating a "DC brand" promoted through retail campaigns and utility incentive programs, developing awards and labeling programs like ENERGY STAR, and establishing financial and tax incentives [14].

4.4.5 Industry Participants' Knowledge

The need for education and commitment to training on organizational, professional, worker/contractor, and inspector levels were mentioned by a few interviewees. One realization from a PoE lighting project was that when assessing costs, the racks, data switches, and system programming need to be included. However, these components are typically part of the IT budget. Consequently, the final cost difference between installing the PoE lighting system compared to a standard AC system could not be determined in full [3]. This is but one example of possible conflicts in operational and maintenance responsibilities on DC projects compared to traditional systems. Owners, designers, installers, and inspectors need to become educated so that more confidence can be gained in budgeting and scheduling. Eventually, official training programs need to be developed. Insurance companies may need to be involved in order get to know DC systems and their safety. As confidence is gained, lowering premiums could help the trend.

Even industry participants such as the AHJ need to have enhanced training and education, because DC power microgrids are new to the industry. The training of the AHJs involved can often be the difference between a straightforward project approval and complications such as delays or design changes. Further, when the AHJs are not fully trained, multiple stakeholders and multiple inspections can be called for, which delays the final approval of the project.

5 Standards and Codes Gap Analysis

A comprehensive analysis of the relevant product standards and installation codes to enable DC power distribution in buildings is presented in the Sections 5.1 to 5.6. Although many elements require further review, it is recommended that the following items are considered the highest priorities:

- Establish standard DC voltage levels and ranges.
- Develop approval criteria for DC power metering equipment for revenue billing.
- Establish standard receptacle and plug configurations for DC circuits.
- Update product standards to enable commercialization of DC lighting equipment, motor drives, and electric vehicle supply equipment.
- Clarify rules for interconnection of DERs.
- Determine life safety installation provisions for DC microgrids (emergency power, lighting, fire alarm, and fire protection).
- Develop product standards and installation rules for DC protective devices.

5.1 Standard Voltage Levels

Standardization of DC voltage levels for building power distribution is a key early and high priority, affecting both product and installation standards. This challenge requires careful consideration, since the voltage ranges selected involve a balancing of several key factors:

1. **Safety –** Shock hazards increase with higher voltages.
2. **Cost –** Conductor size and cost decrease, while insulation requirements, maximum circuit length, and capacity increase with higher voltages.
3. **Energy efficiency –** Power losses decrease with higher voltages due to lower currents and lower voltage drop.
4. **Compatibility –** Where feasible, voltage levels should be selected based on the availability of existing components and to enable AC-to-DC system retrofit applications.
5. **Range constraints –** Allowable voltage ranges for each nominal voltage level must be narrow enough to allow load compatibility but wide enough to allow practical voltage drop and DER functionality.

Specifying the acceptable range of voltages for each standard nominal level is as important as selecting the level itself. While some products may be able to accept a wide range of voltage inputs, others may be more sensitive to voltage fluctuations. Some variation in DC voltage is also necessary to allow power flows between DERs; battery voltages drop during discharge and circuits directly-coupled to PV sources will vary based on the insolation and operating power point, while microgrid controllers can actively regulate the DC bus voltage as a control signal.

Currently, preferred AC voltage ranges are specified in CSA CAN3-C235-83 (R2010), *Preferred voltage levels for AC systems, 0 to 50 000 V.* It is recommended that either a similar standard is produced for DC, or the existing standard is adapted to include DC.

The DC voltage levels selected will affect product availability, installation requirements, retrofit potential, and the overall cost of DC installations. Collaboration with international standards organizations and manufacturers, particularly those in the U.S., is critical to ensure harmonized voltage levels. Harmonization is needed for ensuring product compatibility, reducing trade barriers, and maximizing the potential market size to encourage manufacturers to develop DC products.

Several nominal DC voltage levels have been adopted for the case studies in this report, the most common being:

- 375-380 V unipolar/750 V bipolar;
- 48 V (including PoE, with various implementations having voltage ranges of 37 V-57 V);
- 24 V; and
- 12 V.

The lower voltage levels, based on multiples of a standard 12 V nominal battery voltage, already have a wide range of products available, particularly those compatible with

PoE specifications and those from battery-based off-grid installations. Examples of such installations include RVs, boats, and critical systems with built-in battery backups such as security and telecom equipment, emergency unit lighting, and fire alarm systems. These critical systems are generally designed to use a low voltage DC battery backup with an AC power input for normal operation, which could easily be adapted for a DC input for normal operation.

The main drawback of using lower voltages are the distance and power limitations, as well as energy losses due to larger voltage drops. The corresponding increase in wire size also adds significant cost to low-voltage installations.

For these reasons, most of the pilot projects were based around a nominal 380 V DC level for general distribution and higher-wattage loads, which also aligned well with existing power conversion equipment ratings. However, there are presently few standards written to address applications at this voltage.

Another key consideration when determining appropriate voltage levels for general-use branch circuits is safety. Before finalizing installation rules for branch circuits at a level of 380 V DC or higher, the shock hazard for these circuits should be evaluated in comparison to the standard 120 V AC branch circuit level, with additional safety measures such as sensitive ground fault protection being mandated to mitigate any additional risk. This has implications for associated product standards and installation rules as well.

There also appears to be a "missing middle" between 48 V and 380 V DC, which warrants consideration. Since most North American electrical products and branch circuits have been designed around a 120 V/12 A/1440 W continuous load limit, specifying a standard voltage level in this range may permit the re-use of billions of dollars' worth of existing branch circuit wiring for DC systems, greatly increasing the retrofit potential. Lower voltages would be limited to shorter distances and lower power when used on existing wiring, therefore, requiring extensive rewiring. In some cases, where existing circuits have insulation rated for 600 V or higher, they could be re-used at 380 V DC. However, since 300 V-rated NMD ("Loomex") wiring is very common for combustible construction (i.e., in small residential and commercial buildings), a voltage level below 300 V should be evaluated.

Higher DC voltage levels should also be considered to allow larger-scale microgrids to be built, since there are practical distance limitations at lower voltage levels and PV installations up to 1500 V are becoming more common. However, since most of the initial projects have been focused on smaller installations, and power utilities will likely drive the standards development for inter-building applications, this should be considered a lower priority than the items above.

5.2 Key Product Requirements

5.2.1 Revenue metering of DC Circuits

One of the top priorities in developing a market for DC power systems is having an approved means for measuring DC power use for revenue billing. Limited means to generate revenue or recover costs from DC-coupled DERs would restrict business cases for (and investment in) these types of installations.

In Canada, electric metering for revenue billing is regulated federally by Measurement Canada and approvals are currently only available for AC metering systems. These standards will need revision to allow for DC approvals.

In the United States, local variances are more easily obtained for revenue metering approvals and several jurisdictions and utilities have been working on this, so it is recommended that their approaches be reviewed when developing the equivalent Canadian regulations.

While many aspects of DC metering can conform to the existing AC requirements, there is a fundamental difference between the two: DC metering uses shunts to measure current (i.e., fixed low resistance elements that produce a voltage drop proportional to the current), because the current and voltage transformers (CTs and VTs) used for AC metering rely on magnetic induction, which is only possible with varying (typically sinusoidal) waveforms.

5.2.2 Standard Receptacle/Plug Configurations

Many of the interviewees mentioned the lack of standardized receptacle and plug configurations for DC as a key barrier. Until such connectors are available, every portable DC device would require attachment of a proprietary plug type matching the proprietary receptacle configuration available. This literal lack of "plug-and-play" functionality presents a barrier to mass-market adoption, and fewer manufacturers of consumer electric appliances would make DC versions of their equipment as a result.

For lower-power devices, interface standards such as USB-A and USB-C are relatively widespread as low-voltage DC power outlets in the 5 V to 20 V range, as well as RJ45 PoE ports in the 37 V to 57 V range. However, the power limits of these interfaces are below 100 W, which is too low for many residential- or commercial-grade products that are in use every day such as microwaves, toasters, refrigerators, projectors, portable heaters, power tools, etc. Another point to be considered is that USB and PoE interfaces use integrated electronic controls to negotiate the power transfer. This can be desirable for small "smart" devices, but for many applications, a simple power coupling interface would be sufficient, as well as less expensive, more reliable, and less likely to become obsolete as new power transfer standards are developed.

Designing DC outlets that operate at higher current levels is also more challenging than for their AC counterparts. This is primarily due to the difficulty in extinguishing arcs when a plug is removed while DC current is flowing; AC current has 120 zero-current crossings per second, and arcs can be extinguished more easily at these points. Product standards for DC outlets will have to take this effect into account.

5.2.3 DC Protective Devices

For fire and life safety reasons, DC circuits need protective measures similar to those for AC circuits. The protective measures for AC circuits primarily include:

1. Overload (protection from overheating due to high load currents);
2. Overcurrent (protection from arcing and heating due to high-level short circuit currents);
3. Ground fault (early detection of short circuits involving earth-connected components); and
4. Arc fault (early detection of high-impedance or intermittent short-circuits, and protection from fires due to series arcing).

These protective measures are typically provided by circuit breakers or fuses, with specialized ground fault circuit interrupter (GFCI) breakers and receptacles, as well as arc fault circuit interrupter (AFCI) breakers used as required by installation codes. Alternate ground fault protection schemes are also available, though typically reserved for larger installations due to their technical complexity.

While circuit breakers and fuses rated for general DC application are currently available, many of these devices are only suitable for lower voltages or are only approved for use with PV systems, so procuring the appropriate protective devices for a DC system may be difficult or costly.

Current wiring rules (CE Code, Section 26) require arc fault and ground fault circuit interrupters on specific circuits (AFCIs on residential branch circuits, GFCIs near sinks and showers, outdoors, etc.), and these types of protective devices are currently not available for DC circuits. Consequently, either equivalent rules for protection of DC circuits in these areas will need to be developed, or these products and associated standards will need to be developed.

5.2.4 DC Power Conversion Devices

A key component of DC power systems is the power conversion devices, which step DC voltages up or down like AC transformers and regulate the voltage/current levels needed for battery charging, PV power output optimization, and microgrid control. Rectifiers and inverters, which convert between AC and DC, are critical for AC-coupled sources and loads as well. All of these products are generally electronically-controlled solid state devices.

"Because of their function as key links in a DC power distribution system, certification and standardization of power conversion equipment is critical to enabling these systems to be more widespread and reliable."

Because of their function as key links in a DC power distribution system, certification and standardization of this equipment is critical to enabling these systems to be more widespread and reliable. While protective measures for transformers are clearly incorporated into the installation rules and product requirements, there may be gaps in the equivalent requirements for solid-state power conversion devices, since their use in supplying building wiring has been limited so far and latent reliability, compatibility, or safety issues can take a long time to manifest when they have only been applied in a limited range of real-world conditions. One only needs to look at the rapid evolution of PV installation rules in the CE Code and NEC for a clear example of this. These power conversion devices will also require harmonization with standardized voltage ranges for the reasons noted in the sections above.

Since none of the case study interviewees for this report specifically mentioned this as a barrier for their pilot projects, it appears that the current product standards (such as CSA C22.2 No. 107.1-16, Power conversion equipment) likely have enough provisions for the basic implementation of these systems. However, a thorough review of these standards is recommended to confirm suitability for widespread DC microgrid applications.

5.2.5 Lighting

Though most new lighting installed today utilizes LED technology, which inherently operates on low-voltage DC, most luminaires have been designed and certified for AC power input in the 120 V-347 V range, since these are the voltages in use in most building power distribution systems.

In residential applications, most fixtures are designed around 120 V bulbs with E26 "Edison" screw bases (as well as smaller E17 and E12 screw bases), and most residential-grade LED bulbs are built with these connector types and bulb-integrated drivers adapted to this voltage. For future residential applications, a DC equivalent of these screw bases would need to be developed if easily replaceable lamps are needed; alternately, residential DC lighting installations would use the hard-wired lamps, drivers, and range of connectors common to larger buildings.

For applications in larger commercial and institutional buildings where screw bases are less common, the requirements are somewhat different because drivers are integrated into the luminaires and certified as an assembly. Although swapping an AC-input driver for a DC-input driver is a relatively trivial measure, it is hard to implement in practice because of the limited market for DC luminaires and challenges in recertifying fixtures. As a result, there are few DC fixtures on the market and implementing a typical building project with a wide range of luminaire types requires extensive product recertification or field approvals.

A simplified process for recertifying AC fixtures for DC input (e.g., with a simple driver swap) would make the transition to DC easier during the initial period before a large market exists to encourage luminaire manufacturers to offer DC options. Ideally, luminaires should be able to be dual-certified for either AC or DC input, eliminating requirements for re-certification and re-testing.

5.2.6 Mechanical Equipment

The AC induction motor is often referred to as the workhorse of industry, due to its simplicity, versatility, and very widespread use. Most mechanical equipment for building applications that uses electric motors, including fans, pumps, compressors, and elevators, uses AC induction motors. This appears unlikely to change even where DC power systems are adopted.

The main reason for this is that the control methods of AC induction motors have changed drastically in the past few decades, making them more suitable for DC applications. Traditional motor control systems for large buildings usually involved motor control centres (MCCs), which were a practical way to centralize power distribution and control wiring, starters, and protective devices for motors. Motor starters were used to change motor speed and direction and manage inrush currents using a range of techniques, from simple on-off contactors to changing the voltage by reconnecting motor windings. However, these methods only provide coarse speed control, and do not fully eliminate inrush currents. A key consequence of this is reduced energy efficiency, as motors can rarely be run at their optimal speed under varying system conditions.

With the advent of affordable power electronics, it has become economical to use variable frequency drives (VFDs) for control of all but the smallest induction motors. These drives allow smooth (zero-inrush) starting and fine-grained, dynamic speed control, resulting in large energy savings that quickly pay for the cost of the drive. As a result, most motors above 5 HP are now controlled by individual VFDs. VFDs control motor speed by rectifying 60 Hz AC power to DC, then modulating the DC power to a variable voltage, variable frequency AC waveform that is highly controllable. Since VFDs inherently include DC power, they can easily be adapted for DC input, which would also improve their overall efficiency because of the elimination of the input rectifier.

In recent years, there has been a more modest trend towards electronic control of smaller, single-phase motors, for similar reasons. However, instead of AC induction motors with VFDs, these smaller motors are “brushless DC” types, also known as “electronically-commutated motors” (ECMs). In most cases, these motors are built as permanent magnet synchronous AC motors, but are powered by modulated AC waveforms sourced from a DC power bus with the drive electronics built into the motor itself. Despite the “DC” moniker, they are typically built for 120 V AC input because of its widespread availability. However, like VFDs, they can easily be modified for DC input, with corresponding efficiency gains.

There are few manufacturers currently involved in developing DC-input VFDs and ECMs for mechanical equipment used in buildings. Having product standards available for certifying equipment with DC input would enable a large class of building loads (e.g., heating, ventilation and air conditioning systems, pumps, refrigeration equipment, and elevators) to be powered by DC. Without DC-powered mechanical systems available, most buildings would still be dependent on hybrid AC-DC systems, reducing the overall system efficiency and restricting full DC microgrid implementation.

One other aspect of electronic motor drives, which fits well into the DC microgrid paradigm, is that they can be used for regenerative braking, returning power to the grid. This is already a common feature of elevator drives, although the implications of loads occasionally acting as power sources are not clearly accounted for in current installation codes. Developing clear installation requirements for regenerative drives is, therefore, also recommended for both AC and DC systems.

5.2.7 Electric Vehicle Supply Equipment

Electric vehicle supply equipment (EVSE), or EV chargers, is currently designed for AC input only. However, similar to LEDs, electric vehicles are inherently DC devices and, similar to VFDs, DC EVSE can easily be adapted to AC systems just by removing the rectification component.

Since the use of electric vehicles is rapidly expanding, it is recommended that the product standards for EVSE are reviewed to allow installation of DC-input chargers. Automotive manufacturers should be included in this process, as lower-power Level 2 charging (7 kW and below) is typically done with AC EVSE and vehicle-integrated rectifiers/charge controllers, while DC charging is typically 15 kW and above, with external rectifiers and charge controllers. Level 2 DC charging at 7 kW and below would likely be the most prevalent type in DC buildings due to infrastructure/cost constraints, so existing DC EVSE and vehicle interface standards need to be reviewed to confirm compatibility.

5.2.8 Storage

Electrical energy storage systems are becoming more prevalent in all types of buildings. Though typically connected to AC distribution systems, the most common building-integrated types such as enclosed batteries (lithium ion, lead acid, etc.), flow batteries (vanadium, molten salt, etc.), and fuel cells are DC devices.

Regardless of whether they are connected to an AC or DC distribution system, rules around combustibility and ventilation need updating with respect to the ventilation and air quality. Different battery types have different requirements, and there is a concern with fires for batteries that have not been properly tested and certified for DC distribution applications. The product and installation standards for energy storage should be thoroughly reviewed, including the relevant sections of building and fire codes.

5.2.9 Wiring

Wiring is relatively platform-agnostic when it comes to being applied in AC or DC power distribution systems. The voltage rating for each type of wiring corresponds to both nominal root-mean-squared (RMS) AC voltage and nominal DC voltage. However, there are still some challenges within wiring when it comes to certification and codes.

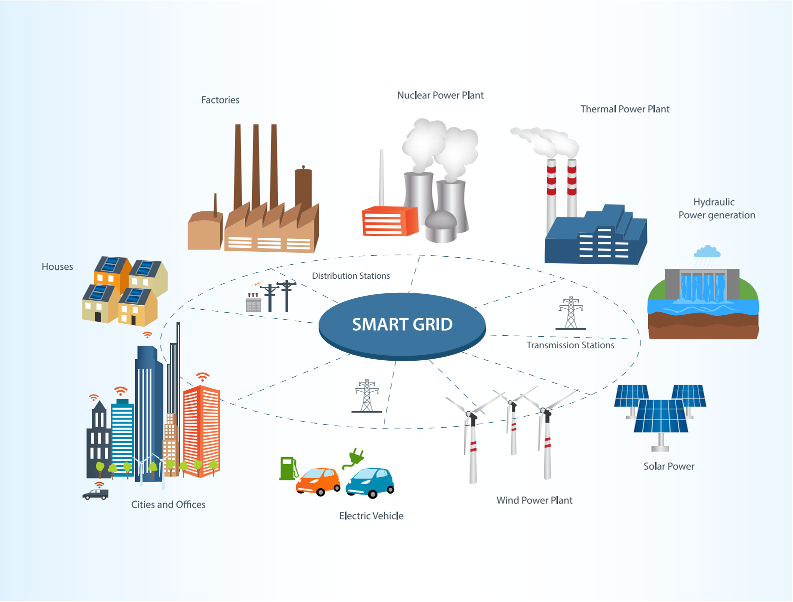
As standard DC voltage ranges are being determined, it should be confirmed that certified wiring is available for the proposed applications, and that the tests and voltage ranges specified are adequate. For application of Class 2 DC circuits, the wire size limitations in the product standards are an issue in some installations. For higher wattage DC systems (above 300 W) insulation questions need to be addressed, along with the testing requirements.

Currently, for the cabling certified for PoE, sustained loading has caused some overheating of cabling and connectors, and CE Code installation requirements have recently been updated in response. Further CE Code changes and improved insulation standards may be required as higher-power PoE options become available.

5.2.10 Other Products

Ultimately, to have a fully DC-compatible electrical safety system, all electrical equipment categories will need to be assessed for suitability with DC circuits. This includes standards for consumer products, HVAC equipment, kitchen equipment, medical equipment, and industrial equipment. However, as these are less likely to be implemented in the early stages of DC adoption (unless specifically mentioned above), these should not be considered an early priority.

A reasonable approach to allow widespread DC adoption without having to review every single product standard, is to provide a generic DC certification standard with criteria applicable to all product categories. Most product certification standards currently have minimal DC requirements, resulting in expensive field testing and evaluations required for recertification. Even when approval is achieved by field evaluation, the requirements of CSA SPE-1000, Model code for the field evaluation of electrical equipment are not clear and specific for DC products. CSA C22.2 No. 60950-1, Information Technology Equipment - Safety - Part 1: General Requirements is another standard that could be used for evaluation, but it is tailored to information technology equipment and not overly specific with respect to general DC equipment requirements.



> *“Current installation standards also present a barrier, and updates are needed along with specific training for electricians and AHJs on the DC-specific requirements.”*

5.3 Key Installation Requirements

The required product standards updates are significantly limiting the wider adoption of DC microgrids. However, current installation standards also present a barrier, and updates are needed along with specific training for electricians and AHJs on the DC-specific requirements. Adoption or revision of the relevant installation requirements will allow safer installations with fewer uncertainties related to inspection delays and costs.

As electrical, building, and fire codes are large documents that are highly technical, a comprehensive review was not possible within the scope of this report. This section is limited to summarizing different types of installation issues or barriers related to DC power distribution systems, which may not be addressed by the current codes. It is recommended that a comprehensive review of each relevant code section is undertaken with these issues in mind to ensure DC system compatibility and safety.

5.3.1 Interconnection of DER

CE Code, Sections 64 and 84 currently include extensive rules for interconnecting DERs (power production sources and energy storage) in buildings. These rules have been significantly updated in the last few editions of the CE Code Part I. Traditionally, building systems have been powered by a single AC utility source, with backup power supplied by local sources, such as diesel generators or battery-based uninterruptible power supplies (UPS), which are typically switched so that only a single source is connected at a time. In larger facilities, generators and UPS systems are often paralleled for redundancy, but even in these cases, the sources are at the “top” of the system and most components can be safely isolated with a single switch.

DERs have complicated this situation. With local PV systems, batteries, regenerative elevator braking, vehicle-to-grid connections, closed-transition transfer switches, and other distributed power sources, power flows are more complex and isolating components becomes more challenging. Being able to safely de-energize parts of the system for maintenance is critical. Other system requirements such as ampacity and interrupting current ratings are also more difficult to determine when there are distributed sources, and the emerging application of active demand management is another key concern.

With these points in mind, there should be a comprehensive review of the interconnection rules to address the following issues:

1. **Islanding –** When a system involves a DC microgrid, the most common type of grid interconnection, anti-islanding, may not be suitable, since the ability for the DC grid to keep running during utility outages is a major reliability advantage. Developing clear requirements for islanding DC microgrids will reduce the costs, delays, and restrictions associated with complex utility and AHJ approvals.

2. **Conductor sizing –** Where multiple sources are connected to a conductor, the total current in that conductor may exceed the sum of the source breaker ratings. Conductor sizing rules and required locations of protective devices where multiple sources are tied together should be clarified for all DER connection scenarios.

3. **Interrupting current –** with multiple sources at different locations in a system, calculations of worst-case fault current become complex. The requirements for adequately rating protective devices should be clarified. For example, should a breaker with sources on both sides be rated for the worst-case simultaneous fault current from either line side or load side, or should it be rated for the sum of all fault currents from both sides?

4. **Interconnection locations –** Distributed energy resources are, by definition, distributed. Their connection locations should therefore be restricted as little as practicable. This is most important in large buildings with microgrids, where one resource (e.g., solar panels) may be a large distance away from another (e.g., a vehicle-to-grid connection), and directly wiring them together may be cost-prohibitive. Requiring DERs to be connected at a limited number of system hubs (such as the service entrance or designated consolidation points) would minimize the associated issues with ampacity, interrupting current, and isolating means. These requirements could be reconciled by a flexible approach which defines different classes of equipment and circuits with different sets of requirements, based on whether they are "radial" (i.e., loads only, with isolation from a single switch) versus "network" types (i.e., multiple sources). Each class of circuit could have specific identification requirements such as colour coding on "network" breakers and wires to reduce the potential for identification errors. Ultimately, the choice will be a trade-off between enhanced safety and improved costs/convenience; restricting DER connections to a single point in a building is incompatible with their distributed nature.

5. **Isolating means –** Clear rules for types and locations of isolating means for circuits with multiple power sources are critical to standardizing microgrid designs. There is some ambiguity and inconsistency in where isolating means are required in relation to power sources. It should be specified whether isolating means must be installed at points where voltage is stepped up or down, where conversion between AC and DC occurs, and which types of power sources are included/excluded from consideration (e.g., When are capacitors considered energy storage devices? Should PV inverters be treated differently from battery system inverters?). It should also be clearly specified where visible means of confirming disconnection are required and what types of systems require them.

   In one example from the case studies, the AHJ required an emergency power off (EPO) system with dedicated shutoffs to trip loads, the photovoltaics and batteries in three separate locations. The lack of defined standards for emergency power safety can thus add prohibitive costs and uncertainty in permitting.

6. **Microgrid control and demand management –** A certain level of controllability is needed to make a microgrid function properly. Whether this is accomplished by voltage level controls or digital communications, the permitted methods should be clearly specified to ensure component compatibility and allow black start capability. Of importance is demand management rules for circuits where multiple loads are connected that exceed the circuit ampacity, but which are actively managed to prevent circuit overload. This is currently permitted by CE Code Rule 8-106 for EVs, but the expansion of this rule for general application should be considered.

5.3.2 Electrically Connected Life Safety Systems

Due to its critical nature in building design, the emergency power rules in CE Code Sections 32 and 46, associated building code rules, and product standards should be evaluated to ensure that they are compatible with DC building distribution. This includes:

1. Emergency lighting requirements;
2. Emergency unit lighting;
3. Automatic transfer switches;
4. Fire pumps; and
5. Fire alarm systems.

The emergency power rules should clearly specify the requirements for DC system redundancy and under what conditions distributed energy resources in a microgrid configuration would be considered sufficient emergency backup power sources.

5.3.3 Class 2 Circuits

Class 2 circuit rules are presently set out in CE Code Section 16, with possible adjustments required for insulation and connectors.

5.3.4 Grounding Requirements

CE Code Section 10 will need careful review with respect to DC-specific grounding issues. Grounding conductor sizing, unipolar versus bipolar system ground requirements, the potential for corrosion due to galvanic DC currents, bonding conductor sizing, and resistance grounding methods should all be reviewed with respect to safety, cost, and reliability concerns.

For higher voltage DC systems, the step-and-touch voltage requirements of CE Code Section 36 should be adapted for DC shock hazards to ensure personnel safety.

5.3.5 Circuit Protection Requirements

For AC transformers, circuit protection requirements are clearly specified in CE Code Section 26. However, equivalent requirements should be prescribed for devices that step DC voltages up or down, or convert between AC and DC. Requiring breakers or fuses on each side of these devices may be unnecessary with proper thermal protection and wire sizing, or it may be necessary for safety. Further investigation is required.

Similarly, requirements for ground fault protection and arc fault protection of DC circuits should be evaluated to ensure an equivalent level of safety as their AC counterparts.

This evaluation may also be a good opportunity to explore alternate means of circuit protection, like that employed in the “digital electricity” pulsed power concept, which checks the circuit for faults multiple times per second and provides near-instantaneous isolation if needed, limiting the total fault energy in circuits above Class 2 voltage and power limits.

5.4 Retrofit Applications

One area not specifically addressed in the applicable codes is how to certify AC-to-DC retrofit applications. Can clear rules be provided for safely and effectively converting existing AC infrastructure to a DC microgrid when product availability begins to warrant this type of upgrade?

5.5 Utility and Non-Utility Services

Generally, the above requirements deal with systems within a single building or property, as utilities are exempt from the CE Code, Parts I and II. If the power utility chooses to offer DC power services in the future, service requirements analogous to the AC service requirements in CE Code Section 6 must be created along with requirements for utilization of electrical equipment that is designed, constructed, tested, and certified in accordance with Canadian Standards Association (“CSA”) safety standards for electrical products.

An alternate type of service should also be considered to allow non-utility DC links between properties for bidirectional power transfer. This would enable larger microgrids or multi-level microgrids to be constructed.

5.6 Code Development Methodology

The overall quantity of codes, and their applicability to and suitability for DC distribution, can cause confusion in the early adaptation stages. One of the lessons learned from the case studies is to approach code development through the codification of industry “best practice” rather than trying to incorporate all “technical debt” (old standards), as many of the old AC standards simply do not apply to the DC microgrid paradigm.

"DC-powered systems promise a few advantages over AC, but in its current state, the technology is still in its infancy. "

Conclusion

Modern electricity systems have spawned exponentially in the last 130 years and are today almost exclusively reliant on AC power at the distribution level. However, the advent of modern solid-state electronics and the proliferation of PV and wind, together with energy storage systems and EVs, are giving rise to a different paradigm: building-level microgrids where DC power is generated, distributed, stored, and consumed. DC-powered systems promise a few advantages over AC, but in its current state, the technology is still in its infancy. This report's industry survey found that the growing numbers of DC microgrid projects are still of a demonstrative nature and many are driven by developers with a strong desire to be sustainable backed by government energy efficiency initiatives and funding. Simultaneously, many research efforts were undertaken by various research facilities and universities in collaboration with innovative utilities and manufacturers. Some market readiness was also observed, as some small and large-scale manufacturers experience growing success with their product commercialization.

The status quo is well entrenched: most current design methods, industry practices, manufacturing, and safety standards are geared towards AC. As a response to the need for change, this research study analyzed the current standards environment to determine gaps and identify the most critical steps to enable adoption of DC power systems. The following are the seven highest priority items that were identified:

1. Establish standard DC voltage levels and ranges. In determining these, key factors that need to be balanced are: safety, cost, energy efficiency, compatibility, and range constraints.
2. Develop approval criteria for DC power metering equipment for revenue billing. This is a crucial cornerstone for this technology to become commercially competitive.
3. Establish standard receptacle and plug configurations for DC circuits in order to enable plug-and-play functionality which would be crucial for mass-market adoption. The widely used USB and PoE interfaces only address lower-power devices.
4. Update product standards to enable commercialization of DC utilization equipment, with lighting equipment, motor drives, and electric vehicle supply equipment being the most immediately relevant.
5. Clarify the rules for interconnection of DERs. As distribution systems with DERs become more complex, updated rules are needed to accommodate these dynamic environments. The main issues to be considered are: islanding, isolating means, interconnection locations, microgrid control and demand management, conductor sizing, and interrupting current.

6. Determine life safety installation provisions for DC microgrids, namely, emergency power, lighting, fire alarm, and fire protection.
7. Develop product standards and installation rules for DC protective devices.

While an immense amount of detailed technical work will be needed to address these topics, the bigger picture of today's shifting smart-grid should be held in sight, as more changes are sure to come.

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Appendix A

CASE STUDY MATRIX

SCOPE	SPECIFICATIONS	SOURCE	MAIN BARRIERS
▪ DC power distribution ▪ LED lighting ▪ Inverters for AC power outlets ▪ Mechanical systems (elevator)	▪ Type: Institutional ▪ DC voltage: 380, 24 ▪ Project area (m^2): 10,000 ▪ Designed: 2012 ▪ Operational since: 2015 (DC power component not implemented)	Teleconference with manufacturer August 20, 2018	▪ Funding – DC upfront costs are high in current market demand ▪ DC arc and ground faults need to be addressed
▪ PV, battery, DC power distribution ▪ DC LED lighting ▪ DC laptop computers, monitors, telephone, task lights ▪ Pump motors, fans	▪ Type: Institutional ▪ DC voltage: 380, 24 ▪ Project area (m^2): 37,000 ▪ Designed: 2015 ▪ Operational since: 2016	Teleconference with designer, September 18, 2018	▪ Not able to get boded for insurance ▪ Purchasing issue with signed contracts ▪ Too far into design phase when DC concept was brought up
▪ 1800 PoE VAVs ▪ CAT6 patch cables providing a maximum of 25.5 W at 36 VDC using the PoE+ protocol	▪ Type: Commercial ▪ DC voltage: 36 ▪ Project area (m^2): 1,000,000 ▪ Operational since: 2014	https://gblogs.cisco.com/ca/2015 /12/03/building-the-most-innovative-workspace-in-Canada/ Accessed August 10, 2018	
▪ Development of a full 380 V DC microgrid distribution network ▪ Two separate PV solar arrays (50 kW) + 380 V DC Rectifier ▪ 13.2 kWh battery ▪ Distribution of 24v DC Class 2 power for office and high bay lighting ▪ DC computing centre ▪ Full integrated automatic lighting controls system ▪ Multiple electric vehicle (EV) charging stations @100kW (400kW planned)	▪ Type: Commercial ▪ DC voltage: 380, 38 data servers, 24 lighting ▪ Project area (m^2): 70,000 ▪ Designed: 2002 ▪ Operational since: 2005 (DC microgrid commissioned in 2015)	Teleconference with developer, August 29, 2018	▪ Receptacle standardization ▪ Creating environment where businesses can build/certify/sell standard DC systems and products and build/respond to market demand ▪ Certification issues were avoided by being permitted to operate as a lab
▪ 3.1 kW PV solar ▪ 13.1 kWh battery ▪ DC floor heating ▪ DC ceiling fans ▪ DC appliances ▪ EV charging ▪ Floor heating ▪ DC Appliances	▪ Type: Residential ▪ DC voltage: 380, 24 ▪ Project area (m^2): 400 ▪ Designed: 2013 ▪ Operational since: 2016	Teleconference with developer, August 29, 2018	

SCOPE	SPECIFICATIONS	SOURCE	MAIN BARRIERS
▪ Second most diverse DC microgrid in the US ▪ Currently, one of the most finely metered and monitored systems ▪ Purpose-built with a DC backbone as the base bid	▪ Type: Institutional ▪ DC voltage: 380, 24 ▪ Project area (m²): 62,000 ▪ Designed: 2016 ▪ Operational since: In construction	Teleconference with: ▪ Manufacturer, August 7, 2018 ▪ Research consultants: August 20, 2018 and August 17, 2018	▪ No power transmission is permitted on gauges 15 or larger for Class 2 DC wiring – CSA 22.2 No. 244. ▪ Multiple DC sources – how do we interconnect safely? ▪ DC metering ▪ Challenge to list/approve DC products – IEC 60950 is the closest standard but somewhat generic ▪ What are the installation rules applicable to 380V DC sources? ▪ Energy storage rules need update to address combustibility and ventilation concerns ▪ Chicken and egg scenario – lag of DC equipment and product availability, but at same time it is not easy to go out and procure as currently it require custom engineering ▪ Standards that need development – voltages and connectors, communication for 380 V/48 V.
▪ Roof-mounted 150 kW PV solar arrays ▪ 380 V distribution ▪ Series of 380 V to 24 V DC to DC Power Server Modules (PSM units) ▪ 24 V, 20 kW DC LED lighting ▪ 40 kW EV charging station ▪ 30kW air conditioning system	▪ Type: Institutional ▪ DC voltage: 380, 24 ▪ Project area (m²): 5,000 ▪ Designed: 2012 ▪ Operational since: 2015	Teleconference with manufacturer on August 7, 2018	
▪ Direct coupled® DC power from either PV solar or AC power sources ▪ DC LED lighting	▪ Type: Commercial ▪ DC voltage: 24 ▪ Project area (m²): 1,000 ▪ Designed: 2014 ▪ Operational since: 2015		
▪ 380 V DC power distribution ▪ Array of 380 V to 24 V DC PSM units ▪ Class 2 power to LED high bay lighting fixtures ▪ BacNET network – automated control of power and fixtures	▪ Type: Industrial ▪ DC voltage: 380, 24 ▪ Project area (m²): 200,000		
Study that compared DC-powered LED lighting solutions with automated wireless controls against traditional T8 32 fluorescent technology	▪ Type: Commercial ▪ DC voltage: 380, 24 ▪ Project area (m²): 10,000		
▪ Fully independent functional DC microgrid system ▪ PV solar arrays and battery based energy storage ▪ PSM-based DC distribution and control system	▪ Type: Military facility ▪ DC voltage: 380, 24 ▪ Operational since: 2011		
One of a dozen of lighting and controls projects	▪ Type: Medical		

SCOPE	SPECIFICATIONS	SOURCE	MAIN BARRIERS
▪ 10 kW natural gas generator ▪ 16 kW solar PV ▪ 100 kWh battery ▪ DC LED bay lighting ▪ 12 kW AC rectifier ▪ 30 kW bi-directional converter ▪ DC air conditioner ▪ DC refrigerator	▪ Type: Industrial ▪ DC voltage: 380 high bay LED loads, 750 DC bus, 375 line to neutral ▪ Project area (m^2): 46,000 ▪ Designed: 2016 ▪ Operational since: 2017	Teleconference with manufacturer, August 24, 2018	▪ No protective devices for the application of DC in distribution systems. Most equipment comes from the solar market but frequently requires adaptation or modification. As a result, cost is increased highly. ▪ Breakers are available but not certified for North America, additional testing was required. Due to the lack of components, developer was forced to manufacture in house most of the power conversion parts. ▪ There were no standards for equipment or installations for DC systems – the CE has to be interpreted to take in account the differences between classic AC system and DC systems. ▪ Obtaining construction permits was difficult because of the lack of understanding and experience by the organizations providing the permits. ▪ Special consideration when addressing current inrush, DC arcing, system energization and DC voltage balancing when using a bipolar bus. ▪ Small size of the organizations involved cause warranty/service concerns from customers both on the system and component level.
▪ 44 DC lighting fixtures ▪ 150 kW of solar arrays ▪ 100 kWh of energy storage ▪ 4 DC ceiling fans	▪ Type: Military facility ▪ DC voltage: 380 ▪ Service size (Amperage): 50 ▪ Designed: 2014 ▪ Operational since: 2015	Teleconference with: ▪ Designer, August 7, 2018 ▪ Research consultant, August 20, 2018	▪ Vendors – products not available as advertised ▪ Price and serviceability of custom made/prototype components ▪ Emergency lighting a challenge with inspectors (for PoE system) ▪ Mechanical equipment – universal voltage levels that don't match
▪ 625 DC LED lighting fixtures ▪ 12 DC ceiling fans ▪ 12 DC electric forklift chargers ▪ 286 kW of solar arrays ▪ 180 kW/540 kWh of energy storage	▪ Type: Industrial ▪ DC voltage: 380, 24 ▪ Project area (m^2): 10,00 ▪ Service size (Amperage): ▪ Designed: 2015 ▪ Operational since: 2018	http://boschbgt.com/ Accessed August 10, 2018	
▪ 30 kW of solar PV ▪ 40 DC LED lighting fixtures ▪ 2 DC ceiling fans ▪ Forklift chargers ▪ Flow battery & battery chargers ▪ UPS ▪ DC winch ▪ DC power strips for various DC loads	▪ Type: Industrial ▪ DC voltage: 380, 24 ▪ Project area (m^2): 15,000 ▪ Service size (Amperage): 1000 ▪ Designed: 2015 ▪ Operational since: 2017	Teleconference with designer, August 7, 2019	▪ Vendors - products not available as advertised ▪ Price and serviceability of custom made/prototype components ▪ Emergency lighting a challenge with inspectors (for PoE system) ▪ Mechanical equipment – universal voltage levels that don't match
▪ 139 DC LED lighting fixtures ▪ 4 DC Ceiling Fans ▪ 74 kW of solar arrays ▪ 30 kWh of lead acid battery	▪ Type: Industrial	http://boschbgt.com/ Accessed August 10, 2018	

SCOPE	SPECIFICATIONS	SOURCE	MAIN BARRIERS
▪ 1442 LED light fixtures ▪ 1914 PoE connections ▪ 54 Cisco racks	▪ Type: Commercial ▪ DC voltage: 380, 24 ▪ Project area (m²): 150,000 ▪ Designed: 2016 ▪ Operational since: 2017	Teleconference with designer, August 7, 2018	▪ Vendors – products not available as advertised ▪ Price and serviceability of custom made/prototype components ▪ Emergency lighting a challenge with inspectors (for PoE system) ▪ Mechanical equipment – universal voltage levels that don't match
▪ Solar PV - 25.4 kW ▪ Battery storage - 83 kWh ▪ 24 retrofitted laptops/screens + LED lighting in a single suite ▪ Future considerations: battery backup for elevator, emergency lighting, replacing VAV boxes	▪ Type: Commercial ▪ DC voltage: 780 (PV), 380, 48, 24, 12, 5 ▪ Project area (m²): 40,000 ▪ Service size (Amperage): 400 ▪ Designed: 2017 ▪ Operational since: In construction	Teleconferences with: ▪ Building Ops manager, August 17, 2018 ▪ Contractor, August 14, 2018 ▪ Research consultants, August 20, 2018 and August 17, 2018	▪ Use of proprietary DC PSM results in only 95 W reaching desktop devices ▪ No considerable commercial DC appliances ▪ Residential DC appliances exist but are typically not US domestic ▪ Plug load voltage levels need standardization
▪ 50 kW solar PV ▪ 10 KW Wind power ▪ 70 kWh storage battery ▪ EV chargers for forklifts ▪ 150 LED Lighting, computers	▪ Type: Industrial ▪ DC voltage: 380 ▪ Project area (m²): 55,000 ▪ Operational since: 2016	Teleconference with industry expert, August 29, 2018	▪ Public utility approval (unique to the US) – wires owners are not allowed to own generation after deregulation ▪ 380 V is the "sweet spot" for voltage in buildings, but what are the appropriate voltage levels for larger facilities/areas/utility distribution, etc. - 750V? 1500V?
▪ 30 kW Solar PV ▪ 50 kWh Battery storage ▪ Removing old wiring ▪Dash EV connection	▪ Type: Commercial ▪ DC voltage: 380 ▪ Project area (m²): 20,000 ▪ Operational since: 2018		
▪ 5 MW 15 kV AC input, distribution sub within building ▪ 4160, 480, 120/220 AC within building ▪ DC microgrid up to 1 MW ▪ 500 kW solar PV ▪ Vertical axis wind turbines ▪ Dash EV ▪ Natural gas generation onsite (existing) ▪ Dedicated feed from utility substation (Duquesne Light Co.)	▪ Type: Lab Demo ▪ DC voltage: 380, 24 ▪ Designed: 2015 ▪ Operational since: 2016		
▪ 3 MW load ▪ 200 kW solar PV ▪ Wind generation ▪ 3 large scale battery storage ▪ Existing diesel-fueled generators	▪ Type: Industrial ▪ DC voltage: 380, 24 ▪ Operational since: 2018		
▪ Solar PV ▪ 20 LED lighting ▪ Notebook computers, monitors and water cooler for 10 offices	▪ Type: Commercial ▪ DC voltage: 380 (nominal), 200 ▪ Project area (m²): 1,100 ▪ Designed: 2018 ▪ Operational since: 2018	Teleconference with research consultant, August 20, 2018	▪ Chicken and egg scenario – lag of DC equipment and product availability, but at same time it is not easy to go out and procure as currently it require custom engineering ▪ Standards that need development – voltages and connectors, communication for 380 V/48 V

SCOPE	SPECIFICATIONS	SOURCE	MAIN BARRIERS
▪ 19 buildings behind-the-meter interconnection ▪ 2.8-4.2 kW PV per house ▪ 4.8 kWh Battery storage per house ▪ DC air conditioner, DC IH oven, DC coffee-maker, DC takoyaki cooker ▪ Bidirectional dc-dc converter	▪ Type: Residential ▪ DC voltage: 380, 100 ▪ Service size (Amperage): 7 (DC microgrid), 15 (DC appliances) ▪ Operational since: 2014	Email Correspondence with designer, September 7, 2018	▪ Prevention of arc-spark on the DC outlet – needed to custom-design an arc-free module ▪ Difficult to find DC appliances for cooking – needed to modify existing AC appliance for DC use
▪ 400 kW of solar ▪ SuperModule™ containerized energy storage •Office space and operations centre loads	▪ Type: Commercial ▪ Operational since: 2016	Teleconference with manufacturer, September 14, 2018	▪ Canada/US have lots of hydro, coal, etc. for generation – weak business case for PV ▪ Not everybody sees value of resiliency ▪ Difficulties getting receptacles approved
180 kW PV system 112 kWh energy storage	▪ Type: Industrial ▪ Operational since: 2017		
▪ 400 kW of solar PV onsite ▪ 2 EnSync Energy SuperModule™ systems in 20-ft containers which house: 850 kWh of hybrid energy storage	▪ Type: Industrial ▪ Operational since: 2017		
▪ 750 kW photovoltaic panel-covered canopy ▪ 500 kWh energy storage system ▪ Individual modules interconnected by the proprietary True Peer-to-Peer DC-Link behind each unit's utility meter	▪ Type: Residential ▪ Operational since: in construction		
EMerge standardized plug and play fluorescent DC lighting	▪ Type: Commercial ▪ DC voltage: 24 ▪ Project area (m2): 10,000 ▪ Designed: 2010 ▪ Operational since: 2010	Teleconference with designer, September 18, 2018	▪ No options for lighting fixtures: manufacturer didn't have UL certification for bulb with Nextek driver which required recertification, delayed manufacturing and project line as well as added costs and time •2 bulb fluorescent lighting with DC driver – circuit power consumed quite quickly ▪ Some corridor and emergency lighting – could not find cost-effective DC lighting fixtures at all ▪ Not many people think in DC so design takes more time and effort
DC ceiling grid	▪ Type: Commercial ▪ DC voltage: 24 ▪ Project area (m^2): 1,000 ▪ Operational since: 20112	Teleconference with designer, August 9, 2018	▪ Not much equipment available for DC (such as computers) ▪ Low voltage system requires various AC to DC converters
Classroom installation and lab testing of various DC fluorescent lighting	▪ Type: Commercial ▪ Operational since: 2010	Teleconference with researcher, August 22, 2018	
DC ceiling grid, 100' track heads	▪ Type: Commercial ▪ Project area (m^2): 1,000 ▪ Service size (Amperage): 20 ▪ Designed: 2011 ▪ Operational since: not built	Teleconference with designer, August 16, 2018	▪ No selection of DC fixtures at the time

SCOPE	SPECIFICATIONS	SOURCE	MAIN BARRIERS
Solar-powered DC ceiling grid, 1000W, 6 LED fixtures	▪ Type: Commercial ▪ DC voltage: 90 ▪ Project area (m²): 200 ▪ Service size (Amperage): 20 ▪ Designed: 2010 ▪ Operational since: 2010	Teleconference with designer, August 7, 2018	▪ Vendors – products not available as advertised ▪ Price and serviceability of custom made/prototype components ▪ Emergency lighting a challenge with inspectors (for PoE system) ▪ Mechanical equipment – universal voltage levels that don't match
▪ 70 kW of PV solar energy ▪ Nextek PSM units distribute class 2 power to all LED general lighting	▪ Type: Commercial ▪ Project area (m²): 5,000 ▪ Operational since: 2010	Teleconference with manufacturer, August 7, 2018	▪ No power transmission is permitted on gauges 15 or larger for Class 2 DC wiring – CSA 22.2 No. 244 ▪ Multiple DC sources – how do we interconnect safely? ▪ DC metering ▪ Challenge to list/approve DC products – IEC 60950 is the closest standard but somewhat generic ▪ What are the installation rules applicable to 380V DC sources? ▪ Energy storage rules need update to address combustibility and ventilation concerns
Armstrong DC Flexzone energized ceiling grid	▪ Type: Commercial ▪ DC voltage: 24 ▪ Operational since: 2016		
Eight full floors of LED luminaires and IPV6-based controls	▪ Type: Institutional ▪ DC voltage: 380, 24 ▪ Project area (m²): 110,000 ▪ Designed: 2016 ▪ Operational since: 2017		
Evaluation of DC lighting systems: R&D, evaluation of cost, efficiency, and technical issues	▪ Type: Lab demo ▪ DC voltage: 24 ▪ Operational since: 2018	Teleconference with researcher, August 22, 2018	▪ PoE is fine for low voltage, but voltage drops also affect lighting efficacy which needs to be included when calculating efficiencies
▪ 32 kW PV array ▪ 350 kWh battery storage ▪ 30 kW multi-port converter ▪ No DC loads	▪ Type: Industrial ▪ Operational since: 2016	https://content.equisolve.net/idealpower/news/2016-04-26_Aquion_Energy_s_AHI_Batteri es_and_Ideal_Power_s_568.pdf Accessed August 23, 2018	
▪ Luminaire-integrated controls ▪ 45,000 PoE based LED lighting points	▪ Type: Institutional ▪ DC voltage: 380, 24 ▪ Project area (m²): 70,000 ▪ Operational since: 2016	https://escholarship.org/uc/item/ 2dd536p1 Accessed August 23, 2018	
▪ DC lighting system ▪ 24 V DC nanogrid for electronic loads ▪ DC EV charger ▪ DC µCHP unit ▪ DC PV MPPT units ▪ Central rectifier and grid controller unit ▪ Mixed AC/DC power monitoring unit	▪ Type: Industrial ▪ DC voltage: 380, 24 ▪ Operational since: 2016	https://www.researchgate.net/publication/308277390_Energy_effici ent_low-voltage_DC-grids_for_commercial_buildings Accessed August 23, 2018	
▪ PV array ▪ Li-ion battery storage ▪ LED lighting ▪ A refrigerator ▪ Electronics ▪ EV charging	▪ Type: Commercial ▪ DC voltage: 380, 24 ▪ Operational since: 2018	https://escholarship.org/uc/item/ 2dd536p1 Accessed August 23, 2018	

Appendix B

CASE STUDY INTERVIEW QUESTIONAIRE

DC Buildings Case Study Questionnaire

The intent of this questionnaire is to gather information for a CSA research study on DC (direct current) powered buildings. The research study aims to assemble global case studies for DC buildings or portions of buildings constructed to date, including relevant information such as voltage, service size, building area, and the extent of the DC systems.

Systems relevant to the research study may include DC data centres, DC microgrids, and general DC power distribution systems serving typical building loads such as lighting, mechanical systems, occupant equipment and appliances.

Another part of the same research study will examine the drivers and barriers to adoption of DC power systems, including a review of the relevant codes and standards. Responses to this questionnaire will be invaluable in identifying this information and helping to assess industry needs in this area from a standards development perspective.

1. Please provide a brief summary of the DC power building project(s) that you were involved in:

a. What were the main project objectives and drivers?

b. Why was a DC power system chosen?

c. Who were the developers and design team? Were there any research / funding partners involved?

d. Are there any contacts within the design or development team that you would recommend for further information on the project?

e. Provide a basic outline of the project scope and approach: Type of facility and building occupancy, building area, construction cost, voltage levels used, power service size, heating/cooling system design, products/components used, extent of DC power systems, unusual DC power applications (e.g. elevators, industrial equipment), etc.

2. What challenges and barriers were encountered that could prevent further adoption of DC power within buildings?

a. What elements were missing that made DC power designs hard to implement – in terms of technology, economic reasons, and codes? How were the gaps addressed?

b. What challenges were encountered in sourcing components (e.g. wiring types, breakers, power conversion equipment, connectors, end-use appliances, etc.)?

c. How were the designs and installations approved by the electrical inspector/AHJ? e.g. does the electrical code (CE Code /NEC) cover all of the installation requirements? Were variances/special permission required? For which aspects?

3. Summarize the key lessons learned from the project:

a. Advantages and ideal applications of DC power systems

b. Drawbacks and less-suitable applications for DC power systems

c. Unique considerations for DC buildings

d. Key areas for future research, product development and standards development

Appendix C

INTERNATIONAL STANDARDS

STANDARDS ORGANIZATION	STANDARD NUMBER	TITLE CATEGORY
NFPA (National Fire Protection Association)	70-2017	National Electrical Code
	Article 408	Switchboards, switchgear and panel boards
	Article 480	Storage batteries
	Article 690	PV systems over 600 Volts
NFPA (National Fire Protection Association)	70B-2016	Recommended Practice for Electrical Equipment Maintenance
NFPA (National Fire Protection Association)	77-2014	Recommended Practice on Static Electricity
NFPA (National Fire Protection Association)	Article 250 Section VIII	Grounding & Bonding – Direct Current Systems – Articles 250.160-250.169
NFPA (National Fire Protection Association)	Article 393	Low-voltage suspended ceiling power distribution systems
DIN (German Institute for Standardization)	VDE 0100-100	Low-voltage electrical installations – Part 1: Fundamental principles, assessments of general characteristics, definitions
DIN (German Institute for Standardization)	VDE 0100-410	Low-voltage electrical installations – Part 4-41: Protection for safety – Protection against electric shock
DIN (German Institute for Standardization)	VDE 0100-530	Low-voltage electrical installations – Part 530: Selection and erection of electrical equipment – Switchgear and controlgear
DIN (German Institute for Standardization)	VDE 0100-540	Low-voltage electrical installations – Part 5-54: Selection and erection of electrical equipment – Earthing arrangements and protective conductors
DIN (German Institute for Standardization)	EN 61557-2	Electrical safety in low-voltage distribution systems up to 1000 V a.c. and 1500V d.c. – Equipment for testing, measuring or monitoring of protective measures – Part 2: Insulation resistance
DIN (German Institute for Standardization)	EN 61557-8	Electrical safety in low-voltage distribution systems up to 1000 V a.c. and 1500V d.c. – Equipment for testing, measuring or monitoring of protective measures – Part 8: Insulation monitoring devices for IT systems
DIN (German Institute for Standardization)	EN 61557-9	Electrical safety in low-voltage distribution systems up to 1000 V a.c. and 1500V d.c. – Equipment for testing, measuring or monitoring of protective measures – Part 9: Equipment for insulation fault location in IT systems
IEC (International Electrotechnical Commission)	60050-614	International electrotechnical vocabulary – Part 614: Generation, transmission and distribution of electricity Operation
IEC (International Electrotechnical Commission)	60034-1	Rotating electrical machines – Part 1: Rating and performance
IEC (International Electrotechnical Commission)	61362	Guide to specification of hydraulic turbine governing systems
IEC (International Electrotechnical Commission)	60308	Hydraulic turbines – Testing of control systems
IEC (International Electrotechnical Commission)	61992	DC switchgear
IEC (International Electrotechnical Commission)	60038	Standard voltages
IEC (International Electrotechnical Commission)	62848-1	DC surge arresters
IEC (International Electrotechnical Commission)	62924	Stationary energy storage system for DC traction systems

STANDARDS ORGANIZATION	STANDARD NUMBER	TITLE CATEGORY
IEC (International Electrotechnical Commission)	62053-41	Electricity metering equipment (DC) – Particular requirements
IEC (International Electrotechnical Commission)	61378-3	Converter transformers
IEC (International Electrotechnical Commission)	62620	Performance of lithium ion batteries for industrial apparatus (unit battery/ battery pack)
IEC (International Electrotechnical Commission)/TS	62735-2	DC plugs and socket-outlets to be used in indoor access controlled areas – Part 2: Plug and socket-outlet system for 5,2 kW
IEC (International Electrotechnical Commission)	61869-14	Specific Requirements for DC current transformers (CDV)
IEC (International Electrotechnical Commission)	61869-15	Specific requirements for DC voltage transformers (CDV)
IEC (International Electrotechnical Commission)	61180	High-voltage test techniques for low-voltage equipment: Definitions, test and procedure requirements, test equipment
IEC (International Electrotechnical Commission)	60947-2	Low-voltage switchgear and controlgear – Part 2: Circuit breakers
IEC (International Electrotechnical Commission)	60947-3	Low-voltage switchgear and controlgear – Part 3: Switches, disconnectors, switch disconnectors and fuse combination unites
IEC (International Electrotechnical Commission)	61439-8	Low-voltage switchgear and controlgear assemblies – Part 8: Assemblies for photovoltaic installations
IEC (International Electrotechnical Commission)	60079-14	Explosive atmospheres – Part 14: Electrical installations design, selection and erection
IEC (International Electrotechnical Commission)	60079-17	Explosive atmospheres – Part 17: Electrical installations inspection and maintenance
IEC (International Electrotechnical Commission)	60300 Series	Dependability management
IEC (International Electrotechnical Commission)	60364-1	Low-voltage electrical installations – Part 1: Fundamental principles, assessment of general characteristics, definitions
IEC (International Electrotechnical Commission)	61010-1	Safety requirements for electrical equipment for measurement, control, and laboratory use – Part 1: General requirements
IEC/IEEE (International Electrotechnical Commission/Institute of Electrical and Electronics Engineers)	60079-30-1	Explosive atmospheres – Part 30 1: Electrical resistance trace heating — General and testing requirements
IEC/IEEE (International Electrotechnical Commission/Institute of Electrical and Electronics Engineers)	60079-30-2	Explosive atmospheres – Part 30 2: Electrical resistance trace heating — Application guide for design, installation and maintenance
ANSI (American National Standards Institute)	B77.1	Passenger Ropeways — Aerial Tramways, Aerial Lifts, Surface Lifts, Tows and Conveyors — Safety Standard
ANSI (American National Standards Institute)	C84.1	American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz)
ANSI/IEEE (American National Standards Institute/ Institute of Electrical and Electronics Engineers)	487	IEEE Standard for the Electrical Protection of Communications Facilities Serving Electric Supply Locations — General Considerations
ANSI/ISA (American National Standards Institute/ International Society of Automation)	12.27.01	Requirements for Process Sealing Between Electrical Systems and Flammable or Combustible Process Fluids
ANSI/ISA (American National Standards Institute/ International Society of Automation)	RP 12.06.01	Recommended Practice for Wiring Methods for Hazardous (Classified) Locations — Instrumentation — Part 1: Intrinsic Safety
ANSI/NEMA (American National Standards Institute/ National Electrical Manufacturers Association)	WD 6	Wiring Devices — Dimensional Specifications

STANDARDS ORGANIZATION	STANDARD NUMBER	TITLE CATEGORY
ASTM International	E11	Standard Specification for Woven Wire Test Sieve Cloth and Test Sieves
IEEE (Institute of Electrical and Electronics Engineers)	484	IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications
IEEE (Institute of Electrical and Electronics Engineers)	802.3	IEEE Standard for Ethernet
IEEE (Institute of Electrical and Electronics Engineers)	835	IEEE Standard Power Cable Ampacity Tables
IEEE (Institute of Electrical and Electronics Engineers)	837	IEEE Standard for Qualifying Permanent Connections Used in Substation Grounding
IEEE (Institute of Electrical and Electronics Engineers)	844	Recommended Practice for Electrical Impedance, Induction, and Skin Effect Heating of Pipelines and Vessels
IEEE (Institute of Electrical and Electronics Engineers)	835	IEEE Standard Power Cable Ampacity Tables
IEEE (Institute of Electrical and Electronics Engineers)	484	IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications
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IEEE (Institute of Electrical and Electronics Engineers)	837	IEEE Standard for Qualifying Permanent Connections Used in Substation Grounding
IEEE (Institute of Electrical and Electronics Engineers)	844	Recommended Practice for Electrical Impedance, Induction, and Skin Effect Heating of Pipelines and Vessels
IEEE (Institute of Electrical and Electronics Engineers)	902	IEEE Guide for Maintenance, Operation, and Safety of Industrial and Commercial Power Systems (Yellow Book)
IEEE (Institute of Electrical and Electronics Engineers)	1202	IEEE Standard for Flame-Propagation Testing of Wire and Cable
IEEE (Institute of Electrical and Electronics Engineers)	1584	IEEE Guide for Performing Arc Flash Hazard Calculations
IEEE (Institute of Electrical and Electronics Engineers)	1673	IEEE Standard for Requirements for Conduit and Cable Seals for Field Connected Wiring to Equipment in Petroleum and Chemical Industry Exposed to Pressures above Atmospheric (1.5 kPa, 0.22 psi)
ANSI/NEMA (American National Standards Institute/ National Electrical Manufacturers Association)	Z535.4	Product Safety Signs and Labels
*CEA Standards are available through CEATI International (Centre for Energy Advancement through Technological Innovation).	266 D 991	Clearance Distances Between Swimming Pools and Underground Electrical Cables
IEEE (Institute of Electrical and Electronics Engineers)	C62.41.1	IEEE Guide on the Surge Environment in Low-Voltage (1000 V and less) AC Power Circuits
IEEE (Institute of Electrical and Electronics Engineers)	C62.41.2	IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and less) ACPower Circuits
IEEE (Institute of Electrical and Electronics Engineers)	P1020/D12	IEEE Draft Guide for Control of Small (100 kVA to 5 MVA) Hydroelectric Power Plants
ISA (International Society of Automation)	12.01.01	Definitions and Information Pertaining to Electrical Equipment in Hazardous (Classified) Locations
ISA (International Society of Automation)	12.12.03-2011	Standard for Portable Electronic Products Suitable for Use in Class I and II, Division 2, Class I Zone 2 and Class III, Division 1 and 2 Hazardous (Classified) Locations

STANDARDS ORGANIZATION	STANDARD NUMBER	TITLE CATEGORY
ISA (International Society of Automation)	12.20.01-2009 (R2014)	General Requirements for Electrical Ignition Systems for Internal Combustion Engines in Class I, Division 2 or Zone 2, Hazardous (Classified) Locations
ISA (International Society of Automation)	(non-numbered publication)	Magison, Ernest. Electrical Instruments in Hazardous Locations, 4th edition, 2007
ISA (International Society of Automation)	TR12.12.04:2011	Electrical Equipment in a Class 1, Division 2 / Zone 2 Hazardous Location
NFPA (National Fire Protection Association)	91	Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Non-combustible Particulate Solids
NFPA (National Fire Protection Association)	96	Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations
NFPA (National Fire Protection Association)	505	Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operation
TELECOM AND DATA CENTER		
ETSI (European Telecommunications Standards Institute)	EN 300132-3-0	Power supply Interface and input to telecommunications and datacom (ICT) equipment
ETSI (European Telecommunications Standards Institute)	EN 3061605	Earthing and bonding for 400VDC systems
ITU (International Telecommunication Union)	T L.1200	Specification of DC power feeding interface
YD/T (China)	2378	240VDC 336V direct current power supply systems
ATIS (Alliance for Telecommunications Industry Solutions)	0600315	Voltage levels for 400VDC systems
IEC (International Electrotechnical Commission)	62040-5-3	DC UPS test and performance standard
IEC (International Electrotechnical Commission)	62040-5-1	Safety for DC UPS
IEC (International Electrotechnical Commission)	TS62735-1	400VDC plug & socket outlet
YD/T (China)	2524-2015	336V HF switch mode rectifier for telecommunications
ELECTRICAL VEHICLE CHARGING		
CHAdeMO		DC fast-charging
SAE/CCS		DC charging

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

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