Expert assessments on the future of direct current in buildings

Brock Glasgo1,3, Inês Lima Azevedo1,3 and Chris Hendrickson2

1 Engineering and Public Policy, Carnegie Mellon University, 129 Baker Hall, 5000 Forbes Ave., Pittsburgh, PA 15213, United States of America
2 Civil and Environmental Engineering, Carnegie Mellon University, 119 Porter Hall, 5000 Forbes Ave., Pittsburgh, PA 15213, United States of America
3 Author to whom any correspondence should be addressed.

E-mail: bglasgo@andrew.cmu.edu

Keywords: direct current, expert elicitation, non-technical barriers, microgrid, codes, standards

Supplementary material for this article is available online

Abstract

Increasing adoption of distributed generation, improving power electronics, and growing electronic loads in buildings have led researchers to propose increased use of direct current (DC) power distribution systems in buildings. As these systems have proven safe and reliable in other applications, they are now being considered for more widespread use in commercial and residential buildings. But nontechnical obstacles remain that have not been addressed in the technical engineering and economic analyses conducted thus far. In this paper, we report on an expert elicitation of 17 experts from industry, research organizations, and the implementation or operation of DC systems to better understand the biggest nontechnical challenges to deploying these systems more broadly. Because these challenges vary based on location, the focus of this study is on the United States of America.

Results show that the two biggest barriers are industry professionals unfamiliar with DC and small markets for DC devices and components. To address these, experts proposed developing training programs for engineers and electricians, and developing pilot projects to prove the benefits of DC in niche applications where DC power distribution holds a clear advantage over AC. Experts also identified lasting and inherent benefits of DC that make these systems better suited to serve future building loads. These include their ability to interface with distributed generation and onsite DC generation sources such as solar photovoltaics, as well as their ability to communicate and supply power over a single distribution line. Finally, experts identified research priorities to make a better case for what appears to be a promising technological solution to safely and reliably powering future buildings.

1. Introduction

Recent research on direct current circuits and devices has largely concluded that these systems have the potential to generate modest energy and cost savings in residential and commercial buildings by centralizing and reducing the number of power converters serving building loads and implementing efficient DC internal end uses [1–3]. Supported by these findings, researchers, manufacturers, and industry groups are now turning their attention to demonstration projects and the development of products and standards to capitalize on what is seen as a new market for energy-efficient devices and services [4–7]. But investment in DC technologies may be premature. Widespread adoption of DC microgrids will depend on a number of factors, only a fraction of which have been captured by the engineering and economic analyses conducted thus far.

In this paper, we explore the nontechnical barriers to more widespread adoption of DC circuits and devices in residential and commercial buildings. Many such barriers have been identified in previous studies, but not analyzed in detail. These include a lack of standards, small markets for DC devices and components, uncertain utility interaction, and public perceptions...
that DC is dangerous or foreign, among others [1, 3, 8, 9]. Developing a better understanding of these barriers can serve to inform and direct future research and development activity to minimize or eliminate their impact on the deployment of DC.

Current research and development efforts in DC power systems for buildings are international [8, 10–15]. In Japan and South Korea, partnerships between government, academic, and industrial groups have made these two nations leaders in the technological development of DC-powered buildings and microgrids [8]. Together with these countries, the US-based EMerge Alliance is leading the development of standards to simplify and accelerate adoption of DC power systems in buildings. As these standards gain traction, attention is now turning to additional challenges to the adoption of DC buildings. Many of these are related to various standards, codes, and other regulations that are largely defined and adopted at a national level, making many of these challenges country-specific. Thus, while the future of DC buildings will be determined by international research and development efforts, the focus of this paper is on the United States where these nontechnical challenges are relatively well-understood and efforts are underway to overcome them.

Expert elicitation is a tool intended for instances where analytical methods are unable to handle some factors relevant to the research questions at hand. This makes the method well-suited to analyzing the trajectories of developing technologies where ongoing research and development efforts, policy interventions, public perceptions, and other non-technological factors are critical to future deployment. Expert elicitation is also useful in identifying and better understanding key parameters that will determine the fate of emerging technologies, and identifying critical research and development efforts needed to move those technologies forward.

These elicitions often aim to define subjective probability distributions of key uncertain parameters, often related to system costs, which can be used to compare a given technology to alternatives. For example, [16] used expert elicitation to assess future module costs of several solar photovoltaic (PV) technologies under varying policy scenarios. This allowed for conclusions to be reached not only about the future cost-competitiveness of solar PV, but also about the effects of different policy interventions.

Such methods are not restricted to defining distributions for uncertain parameters. Rao et al. used expert elicitation to assess possible improvements in key parameters which determine the performance and cost-effectiveness of existing CO₂ capture technologies, thus allowing a comparison to more novel and unproven systems [17]. In addition to estimating 4 key defining parameters of these systems, the study also asked participants to classify 19 research objectives as high-, medium-, or low priority in minimizing the overall cost of CO₂ avoidance. The resulting rankings allow the most pressing research needs to be identified and compared to the focus of recent research in the field.

A more comprehensive expert elicitation was conducted jointly by CMU’s Center for Climate and Energy Decision Making, the International Risk Governance Council, and the Paul Scherrer Institute to assess the feasibility of deploying small modular nuclear reactors (SMRs). At a two-day workshop attended by an international assembly of nuclear experts, a workbook format was used to elicit judgments on a wide range of topics [18, 19]. This format included traditional methods of determining subjective probability distributions of important parameters, but also asked more open-ended questions and included a variety of exercises that help identify and address potential risks and non-technological barriers that would need to be overcome for SMRs to be adopted.

We adopt this format and apply it to better understanding the challenges and uncertainties facing increased adoption of DC circuits in residential and commercial buildings. In section 2, we discuss these challenges as they have been identified in the existing literature. Section three discusses the experts and elicitation methods used. Section four presents the results of the elicitation and section five provides a discussion of these results and conclusions reached.

2. Literature

The existing literature on DC power systems in buildings and microgrids identifies a number of barriers to more widespread adoption of this technology. In this section, these barriers are described and summarized before experts identify which are most pressing.

2.1. Shock and electrocution risk

There is presently no scientific consensus as to whether alternating current (AC) or DC power is more harmful physiologically if contacted. Some argue that DC poses more risk, as a direct current shock could cause muscles in the forearms and hands to clench and lock the victim to the exposed conductor. Dalziel and Massoglia conducted a study in the 1940s and 1950s to test this by measuring the ‘let-go’ currents and voltages of AC and DC power [20]. While the paper is still widely cited, the study design and testing method of simply administering electric shocks until study participants could no longer release an electrode prevent any reliable conclusions from being drawn.

The National Fire Protection Association’s (NFPA) National Electrical Code (NEC) and Standard for Electrical Safety in the Workplace provide further evidence of the uncertainty surrounding the relative safety of AC and DC power systems. The NEC does not currently distinguish between AC and DC for
circuits carrying less than 600 volts, meaning that both types of circuits face the same functional safety requirements regardless of current form [21]. The Standard for Electrical Safety in the Workplace does provide separate guidelines for workers approaching exposed AC and DC conductors. However, at the distribution voltages present in buildings, the recommended precautions are nearly identical [22].

Much of the preliminary work on developing standards for future DC systems has sought to minimize potential hazards of DC systems and ensure future electrical code compliance. The Emerge Alliance Occupied Space Standard was developed with this in mind, resulting in a 24VDC standard which falls into the NFPA’s Class 2 circuit designation [9]. Class 2 circuits are considered intrinsically safe, providing ‘acceptable protection from electrical shock’ [23]. Higher voltage circuits will not fall under this classification, and will need to be designed, installed, and inspected to ensure they pose no greater shock and electrocution risk than equivalent, existing AC circuits.

2.2. Fire risk
DC circuits are prone to arcing during switching or circuit breaking, as there is no natural passage through zero current to quench arcs as occurs in AC circuits [24]. Without appropriate arc quenching capabilities, DC circuits may therefore pose increased fire hazard over comparable AC circuits. Direct current circuit breakers are commercially available that provide one line of defense against potentially dangerous arc faults [24]. In AC circuits, Ground Fault Circuit Interrupters (GFCIs) provide a second level of defense. The intended purpose of these devices is to prevent electrical shocks to people during ground faults at much lower currents and powers than would be required to trip a circuit breaker [25]. The same functionality means that these devices simultaneously reduce fire risks caused by small arc faults. Unfortunately, GFCIs are only available to protect AC circuits. While technological solutions exist to provide similar protection in DC circuits, these devices are not yet commercially available. This lack of DC GFCIs could be seen as incrementally increasing the risk of DC circuits in buildings.

2.3. Public perceptions of DC
While it is unclear whether AC or DC circuits are more dangerous in the event of an electric shock and the fire hazard of DC circuits is likely only incrementally higher than in AC circuits, public perceptions of these risks will play a role in determining their adoption. Additionally, consumers’ fundamental lack of familiarity with DC power systems may cause concern among the public about the safety, reliability, and costs of DC circuits and devices.

Similar concerns arose around the deployment of smart meters. Raimi and Carrico explored perceptions of smart grid technologies in response to a small but vocal minority view that smart meters posed health, privacy, and cost risks [26]. In that case, consumers ultimately have little control over widespread adoption of smart meters. But adoption of DC circuits will be voluntary, so public perceptions of these systems could affect their deployment.

2.4. Reduced reliability
Proponents of DC distribution systems argue that the reduction in power electronics required to serve DC native loads will actually make these devices more reliable as their power supplies are simplified [10]. However, the power electronics and end-use appliance technologies proposed as replacements for our current AC devices are not currently manufactured at large scale. At the scale needed for widespread deployment, these would essentially be new products for many manufacturers and could potentially suffer the same reliability issues as new devices.

2.5. Engineers, electricians, inspectors, regulators, and others unfamiliar with DC
DC distribution systems in buildings are still uncommon, so very few professionals have experience with these systems. Simply overcoming this lack of information and experience to design, build, certify, and regulate these circuits will pose a challenge. Until these professions develop experience with DC, this lack of familiarity could magnify concerns surrounding the safety, reliability, and cost of their implementation and operation of these systems.

A lack of trained electricians was identified as a challenge to DC distribution systems and servers in data centers by Ton et al [27]. The authors of that report called for the development of training programs for both work safety and recommissioning of these systems.

2.6. Uncertain utility interaction
There is no clear model for how a utility interacts with a DC building or microgrid. Technical analyses of these systems typically assume that a customer-owned rectifier or bidirectional inverter will be installed downstream of the utility meter, and therefore should not pose any challenges to the existing utility-customer interface. However, potential nontechnical barriers have been identified and discussed by Savage et al [9]. These include uncertainties surrounding net metering, utility ownership, and renewable electricity standards. Additional issues with existing utility agreements were identified in [3]. These issues were related to the wording of these agreements referring only to traditional AC systems, which would need to be modified if DC systems are more widely adopted.

One concern that utilities may have with widespread use of these systems relates to the power factors seen at building-level rectifiers or bidirectional inverters. At a smaller scale, power factor requirements are now included in ENERGYSTAR requirements for some electronic devices [28]. Similar requirements
would be needed for the large rectifiers and bidirectional inverters converting grid AC power to DC at the building level. Absent these requirements, power factor penalties might one day be needed at the residential level similar to their application to utilities’ industrial customers.

2.7. Power quality concerns
Several papers cite improvements in power quality as a potential benefit of DC power systems [1, 29]. However, there is some disagreement as to whether this would actually be the case. Whaite et al reviewed examples of applications of DC architectures and found that power quality concerns in datacenters, homes, telecommunications systems, and renewable collector systems need to be better understood to properly design future DC systems [30].

2.8. Regulatory uncertainty
The National Fire Protection Association’s National Electric Code is the standard by which nearly every state and municipality in the US ensures safe electrical practices are followed [31]. The NEC does not currently distinguish between AC and DC for circuits carrying less than 600 volts [9]. While this means DC systems technically fall under the existing code, the lack of distinction and specific reference to DC could be cause for concern. Savage et al argue that DC systems should be better specified in this code to avoid this concern.

2.9. Lack of standards
In addition to the NEC ensuring safe electrical practices, there are a number of other relevant standards that address other aspects of building electrical systems. Organizations such as the National Institute of Science and Technology (NIST), the American National Standards Institute (ANSI), the National Electrical Manufacturers Association (NEMA), and the Institute of Electrical and Electronics Engineers (IEEE) all maintain standards that govern aspects such as line voltages and tolerances, metering accuracy, and device safety. While many of these organizations have standards that apply to DC power systems in niche roles, most of these were never intended for widespread public adoption of DC circuits and devices.

The 24 VDC standard being promoted by the Emerge Alliance is the most advanced effort to establish a voltage standard for DC circuits in buildings [6]. However, this has not yet been formally adopted by government or other bodies [2]. Before DC power systems can be widely deployed, applicable standards will need to be developed and accepted to ensure the safe, reliable, and efficient operation of these systems.

2.10. Diversification of buildings and appliances
Adoption of DC circuits in buildings will mean devices and services cannot be universally exchanged between buildings without specifying the circuit type. This increases uncertainty and complicates equipment purchasing decision-making and prospects for reselling of equipment at a later date. A similar issue was identified in [27] that called for additional labeling to clarify whether a system is AC or DC for personnel working on and interacting with the system.

A counterargument is that universal adoption of DC would improve interoperability between countries and continents as specifying the line frequency would no longer be an issue.

2.11. Small markets for DC devices and components
While nearly all devices and components can be made to operate on DC, manufacturers will see a risk in serving what will initially be a small market of early adopters. As a result of this lack of economies of scale, prices for these components and devices are currently much higher than for equivalent AC devices [3]. Consumers might also see uncertainty in purchasing DC devices and components from companies that might abandon their DC product lines, or that might not exist if DC does not flourish in the near future. This creates a disincentive where, without outside intervention, both manufacturers and consumers will be skeptical of this new market and progress and adoption will be slow.

3. Methods

3.1. Identifying the experts
Experts in this study were all based in the United States and came from a variety of backgrounds. The majority came from research institutions such as universities, national labs, and industry research institutes. These participants were identified based on their recent publications on topics either directly or indirectly related to the deployment of DC circuits and devices in homes and commercial buildings. Industry experts came from companies that either currently manufacture devices or components for DC circuits, have expressed interest in this new market, or oversee and implement standards that regulate the safety and reliability of DC devices and components. Many of these industry experts were identified through their participation in an industry group called the Emerge Alliance. This is an open industry association dedicated to developing standards for the adoption of DC circuits in commercial and telecommunications applications [6]. Finally, practitioners such as electrical engineers, contractors, and project managers with experience in DC systems provided their hands-on expertise in dealing with these systems. These individuals were identified based on their experience in the design, construction, and operation of a DC microgrid located in Pittsburgh, PA [4]. The final set of experts included 17 individuals from industry (6), research organizations (6), and the implementation or operation of DC systems (5).
A total of 32 experts were recruited to participate in this study. This number was reached following an extended review of individuals’ backgrounds and experience. In identifying experts, our first priority was finding individuals with the necessary knowledge to support informed decision making regarding the future of DC power systems in buildings. Our second priority was ensuring that these individuals’ professional experiences were diverse enough to present a broad view of the challenges and opportunities associated with this technology. The final sample of experts strikes a fair balance between these two competing priorities.

3.2. Elicitation protocol
Following previous protocols [18, 32], an online survey was designed to gather and record responses from the experts. Individuals were initially contacted by email, and the elicitation took place over the phone while the experts completed the online survey on their own computers. Responses were either entered into the online survey form or discussed over the phone and transcribed. A copy of the material and questions included in the online survey can be found in the supporting information available at stacks.iop.org/ERL/13/074004/mmedia.

The survey began with a brief introduction to the subject matter, format, and goals of our study. To familiarize the participants with the confidence intervals they would be providing in response to the elicitation exercises, three calibration questions were administered. The answers to these questions were then provided to the experts and they were given feedback to inform them of possible overconfidence in their responses. Experts were then asked to rank the applications most likely to adopt DC power systems in the near future. This was followed by two similar exercises which asked the experts to rank the positive characteristics that make the strongest case for more widespread use of DC, and the negative characteristics that pose the greatest challenge to that adoption.

Next, a hypothetical commercial office building was described to frame the next few questions. Experts were asked to estimate the costs of implementing DC and hybrid AC/DC circuits in this building now and in the future. Then voltage standards were elicited, with experts describing the most likely voltages and system architecture for the building. Finally, a series of open-ended questions were posed about long-term trends and their effects on adoption, potentially disruptive technologies, and research priorities to address in moving forward.

Experts’ responses were recorded by the online survey tool, and audio recordings of the interviews were transcribed to record responses to open-ended discussion questions. All responses were sent to the experts to review both their short-form question responses and their transcribed discussions.

4. Results

4.1. Applications for DC
Experts were asked to rank the three applications which they thought are most likely to adopt DC power distribution in the future. Figure 1 shows these results. The four highest ranked applications were datacenters, developing world microgrids, commercial buildings with both AC and DC circuits, and electric vehicle charging stations.

To see how these results vary by experts’ backgrounds, figure 1 and all subsequent figures are reproduced in appendix B with experts from industry, research, and operation of DC systems shown separately.

4.2. Key characteristics of DC
Figure 2 shows experts’ rankings of the positive characteristics of DC circuits that make the strongest case
for more widespread use of DC in commercial and residential buildings.

Energy savings from reduced power conversions was the most highly cited positive characteristic of DC systems. Many experts highlighted the fact that this was the biggest selling point being used in efforts to drive adoption of DC as the reason for their ranking. Others said that while energy savings make for a convenient talking point, they would not be enough to drive adoption on a large scale.

Nearly as commonly cited were the potential reliability improvements offered by DC distribution systems and end uses. The reasons offered for this were largely twofold. First, the reduction in power conversion steps required to serve DC-internal end uses simplifies the failure-prone power supplies to these devices. Secondly, many experts mentioned the ease of integrating storage in DC systems and raised the potential for creating building-level microgrids to deal with grid outages. This was closely related to the next most commonly cited benefit that DC systems enable efficient energy storage. Discussion of these responses often described a future where on-site renewables, battery storage, and DC end uses were connected by a common DC bus. DC was seen as a solution to simplifying and reducing the costs of such systems. Similar discussions were provided as reasons for the next two most commonly cited benefits: solar PV and overall system capital cost savings.

Next, experts were shown the list of 11 negative characteristics ascribed to DC circuits from section 2 and were asked to identify the three that pose the greatest challenge to more widespread use of these systems. While more than the top three such barriers will need to be addressed for DC to be adopted on a large scale, experts’ responses to this exercise provide a measure of the relative priority of these barriers as they are currently understood. Figure 3 shows experts’ rankings.

Small markets for DC devices and components was the most highly cited negative characteristic of DC systems. Many experts described this as a chicken-and-egg problem where manufacturers are hesitant to build devices and components for a small and uncertain market and consumers are therefore faced with high prices for the few devices that are available.
Similarly ranked was the characteristic that engineers, electricians, building inspectors, regulators, and other industry professionals are unfamiliar with DC power systems. This prevents DC systems from being deployed as there are simply not many professionals familiar enough to recommend them at the early stages of a project. As a secondary effect, engineers and electricians will initially charge more to design and install these systems. These professions prefer to follow proven, standard designs and heuristics. Departing from those standard practices requires extra time to ensure the systems are safe and reliable.

Finally, a lack of universally accepted standards was in over half of the experts’ top three negative characteristics. Standards were seen foremost as a means of providing manufacturers with technical guidelines from which they can design and build devices. But standards also were mentioned as providing both consumers and manufacturers a measure of confidence that DC systems in buildings are a vetted and viable technology alternative.

4.3. DC distribution system costs
Experts were asked to estimate the overnight capital cost to outfit a standard commercial office building with DC circuits. To reduce variance in the responses experts were told to consider only the distribution system itself. The additional costs of building-level power electronics, appliances, and controls are not included here. These components would add a large capital cost that was intentionally excluded from this exercise. To serve as a reference point, experts were told that the cost for an equivalent AC system—providing 1000-amp service with panel boards and feeder lines—was $3.66 per square foot of floor area [33]. There is undoubtedly uncertainty around this value that is not presented. For the purpose of this exercise we provide only the point value estimate as given in RSMeans, an industry standard construction cost estimation database. Figure 4 shows experts’ estimated 95% confidence interval and best estimate costs for (a) an all DC building under current market conditions, (b) a hybrid system serving only lighting and computer workstations under current market conditions, and (c) an all DC building to be constructed 10 years in the future.

Based on a lack of confidence in their own abilities to estimate DC system costs now or in the future, five of the 17 experts did not provide responses to any of the three questions in this exercise. Of the 12 remaining experts, only nine elected to estimate current system costs for an all DC system. The remaining three did not think an all DC system was feasible at this time. Results show that most respondents believe that all-DC systems would be—to varying degrees—more expensive than equivalent AC circuits. In explanations of their responses, experts frequently mentioned higher equipment costs for DC systems due to their relative scarcity, but lower labor costs as a result of low voltages which allow for less qualified workers.

All 12 responding experts thought a hybrid AC/DC building was now feasible, and were willing to provide cost estimates. Responses show that nine experts believe such a system could reduce capital costs compared to the traditional AC system, while two others believe that the same system could be over twice the baseline AC cost.

Finally, experts were asked to estimate costs for the all-DC system 10 years into the future assuming there is no major outside intervention to prevent or impede the adoption of DC power systems. Of the 12 responding experts, 1 did not believe an all DC system would be feasible even after 10 years of development. Most estimates show future all-DC system cost ranges that either include or are slightly below the current AC system cost. Two responses, from experts E and L, indicate that prices for these systems will increase slightly over the next 10 years. This goes against typical trends with new technologies that learning curves and economies of scale drive costs down over time. While these responses were not explicitly discussed, these results likely indicate changing technologies and increasing power electronics costs in the DC distribution circuits inside buildings over the next decade.

The values provided here provide only a rough estimate of the current and future costs of DC distribution
systems in buildings. While these results are only rough estimates, they show that most experts believe that these systems have the potential to provide slight cost savings compared to a traditional AC system. Alternatively, they could also be significantly more expensive over the next ten years.

4.4. Standards
Referencing the same hypothetical commercial office building, experts were asked to identify the voltage levels and current forms most likely to be seen in future buildings wired with DC circuits. Figure 5 shows experts’ responses. The figure on the left shows the voltage levels and current forms chosen by each expert, and the figure on the right shows the number of times each combination was selected.

The two most common voltage levels chosen were 48VDC and 380VDC, followed by 24VDC, 120VAC, and 480VAC. 48VDC was described as a replacement for the 120AC standard. It would serve similarly sized loads, not suffer as much line loss as lower proposed replacements, and be accessible at the plug level without safety concern. 380VDC was cited for larger loads, and convergence to this level was due to its promotion and existing use in data centers that would easily transition to other buildings and loads. 24VDC was described for serving smaller electronics and lighting, with industry promotion cited as the reason for convergence on this level. Maintaining a 120VAC distribution circuit was often mentioned to give the option to continue using existing devices in future hybrid buildings. And finally, 480VAC was described for large loads such as HVAC equipment where a DC alternative may not be readily available.

Five experts described flexible voltage circuits, most commonly at low voltage levels to serve small loads. Similar to the USB Power Delivery specification, these circuits were described as having the ability to provide various DC voltages to devices that communicate their required voltage to the circuit. Thus, these types of circuits are capable of serving electronic devices with varying voltage levels on a common circuit.

Next, the experts were asked if they had any concerns about the systems they described as most likely to be adopted. If they identified any such issues, they were asked to describe the system architecture that should be adopted. There were two common responses to this question: that the 24VDC standard that industry appears to be converging toward is too low, and that higher voltages would have benefits when onsite generation is available. 24VDC was seen as generating too much line loss and 48VDC would reduce that and be similarly safe. 48VDC also has the benefit of having been used in the telecom industry for decades, meaning that expertise and some componentry already exist and have been proven safe and reliable. For higher voltages, experts cited 760VDC to 1000VDC distribution buses for collecting power from solar arrays. These would be stepped down before being distributed throughout the microgrid at the voltages identified above.

4.5. Long-term viability
As the experts identified above, one of the primary benefits cited of DC circuits in buildings is the energy savings generated by reducing the number of power conversions required to serve DC-internal end uses. However, as power electronic conversions become more efficient, the savings generated by eliminating those conversions will diminish over time. Of the 17 experts interviewed, eight said that this trend will not change the outlook of DC systems in the future and six said that it could. Most experts cited other positive characteristics of DC systems as being the real drivers of future adoption.

Another trend relevant to adoption of DC relates to raw material supplies. Central in most analyses of DC circuits in buildings is an assumption that efficient DC appliances will be adopted. Many such appliances replace traditional electric motors with permanent magnet motors. Beginning in 2011, due to a
combination of increased demand from electric vehicles and Chinese production quotas, magnetic material prices increased rapidly for several years before falling back to close to their original price. Experts were asked how the outlook of DC systems would change if a similar price fluctuation increased magnetic material prices by 20%. Nearly half of experts were unsure, and only one expert expected this to significantly change the outlook of DC systems in the future.

4.6. Disruptive technologies

Next, experts were asked to describe any technologies that could potentially change—positively or negatively—the trajectory of DC power distribution, DC microgrids, or DC appliances in buildings. Responses showed optimism about developments in related technologies that would positively influence adoption of DC.

Most commonly cited was increased adoption of battery storage—either as a dedicated system or as part of vehicle-to-grid storage architectures—and pairing that storage with increasingly affordable and accessible solar PV arrays. Experts thought that as more homes and buildings began installing these systems to reduce their reliance on grid power, the better the case became to distribute generated power to the batteries and internal loads as DC. Thus, any developments that would increase adoption of batteries, EVs, or distributed generation sources producing DC would also positively influence adoption of DC.

Also commonly cited were advances in digital power delivery or combined communication and power delivery systems like Power over Ethernet. Such systems allow end uses to be controlled and powered over a common line, while simultaneously allowing end uses to communicate back to a central hub. This kind of power delivery inherently operates over DC lines, often at low voltages, so these systems deliver the same reliability, space flexibility, easy installation, and low shock risk benefits. As existing trends continue to increase the automation, connectivity, control, and overall intelligence of buildings, the case for distributing power as DC will only improve.

4.7. Research priorities

Finally, we asked the experts to reflect on their roles, their knowledge of the state of the industry and technology, and the questions we posed during the rest of the elicitation and identify what they consider to be the top research priorities going forward. Table 1 summarizes these responses.

| Research objective | Mentions (Qty) |
|--------------------|---------------|
| Understanding use cases where DC has a clear advantage over AC | 6 |
| Developing devices and components for DC systems | 5 |
| Integrating communication and power delivery | 4 |
| Building demonstration projects | 3 |
| Better understanding energy and cost savings potential | 3 |
| Better understanding power quality issues | 2 |
| Better understanding the potential for implementing DC as a retrofit | 1 |
| Better understanding transactive power potential of DC | 1 |
| Better understanding resilience benefits of DC | 1 |
| Training and educating professionals | 1 |
| Better understanding power scavenging | 1 |
| Developing voltage, metering, safety, and other standards | 1 |
| Building demonstration projects | 1 |

5. Discussion

In this study we present 17 experts’ judgments on the barriers and opportunities to more widespread use of direct current power systems in buildings in the United States. While there are major hurdles that need to be overcome to see them more widely deployed, there are fundamental advantages that make these systems better suited than our existing AC building infrastructure to meet the needs of future buildings. Similar hurdles and advantages likely exist in other countries, but the experts and context of this paper are limited to the existing markets, technologies, and regulatory environments in the US.

One main focus of research into the prospect of DC circuits in buildings to this point has focused on the potential energy savings generated by centralizing and reducing the number of power conversions required to supply building loads. While experts thought this was a major determinant of the success of these systems so far, the long-term viability of DC power systems is less dependent on energy savings than existing literature suggests. While there are fairly clear and significant energy savings to be generated, experts were not confident that these savings alone are enough to drive adoption.

Instead, experts cited a number of other known benefits of DC as promoting adoption. These are related to ongoing trends that are already driving adoption of other technologies such as increasing attention to resilience and increasing demand for centralized control of end uses. The direction and strength of these trends suggest that DC power systems are better technically suited to serve the increasingly DC-internal loads in modern buildings.

Finally, the biggest challenges to DC were identified as being the small markets for these systems and professionals unfamiliar with them. To address these, experts proposed training engineers and technicians on DC systems, and identifying niche use cases where DC power distribution holds a clear advantage over AC and building pilot projects to further prove the technology is safe and reliable. Efforts in Japan and South Korea are already making progress on overcoming these barriers through the construction of large-scale demonstration projects. Similar efforts in the United States can build on these experiences,
advance understanding of the challenges and opportunities of these systems, and continue development towards adoption of what appears to be a promising technology.

Acknowledgments

This work is supported by the Center for Climate and Energy Decision Making (CEDM) through a cooperative agreement between Carnegie Mellon University and the National Science Foundation [grant number SES-1463492]. Additional funding was provided by the Phillips and Huang Family Fellowship in Energy.

ORCID iDs

Brock Glasgo  https://orcid.org/0000-0002-2192-9279
Inês Lima Azevedo  https://orcid.org/0000-0002-4755-8656

References

[1] Thomas B A, Azevedo I L and Morgan G 2012 Edison revisited: should we use DC circuits for lighting in commercial buildings? Energy Policy 43 399–411
[2] Vossos V, Garbesi K and Shen H 2014 Energy savings from direct-DC in US residential buildings Energy Build 68 223–31
[3] Glasgo B, Azevedo I L and Hendrickson C 2016 How much electricity can we save by using direct current circuits in homes? Understanding the potential for electricity savings and assessing feasibility of a transition towards DC powered buildings Appl. Energy 180 66–75
[4] Puko T 2013 Pitt Ohio opts to use revived electric technology (TriB Live) (http://triblive.com/business/headlines/5048061-74/power-current-direct)
[5] Abdelhamid A 2013 Bosch building DC microgrid at California Honda plant Clean Tech (https://cleantechnica.com/2015/04/13/bosch-building-dc-microgrid-california-honda-plant/) (Accessed: 5 December 2016)
[6] Emerge Alliance Public Overview of the EMerge Alliance Data/Telecom Center Standard Version 1.1 2014 (www.emearealliance.org/Standards/OccupiedSpace/Overview.aspx)
[7] Alliance for Sustainable Colorado 2017 The Alliance Center DC Project (www.sustainablecolorado.org/what-we-do/building-innovation/dc-project/)
[8] Garbesi K, Vossos V and Shen H 2011 Catalog of DC Appliances and Power Systems (Berkeley, CA: Lawrence Berkeley National Laboratory)
[9] Savage P, Nordhaus R and Jamieson S 2010 DC Microgrids: Benefits and Barriers. Silos to Syst Issues Clean Energy Clim Change (New Haven, CT: Yale School of Forestry and Environmental Studies)
[10] DTI 2002 The use of direct current output from PV systems in buildings DTI Sustain Energy Program (http://webarchive.nationalarchives.gov.uk/) (www.berr.gov.uk/files/file17277.pdf)
[11] Kakigano H, Miura Y and Isac T 2010 Low voltage bipolar type DC microgrid for super high quality distribution IEEE Trans. Power Electron. 25 3066–75
[12] Fantauzzi M, Iannuzzi D, Pagani M, Sclafati A and Roscia M 2015 Building DC microgrids: planning of an experimental platform with power hardware in the loop features IEEE Int. Conf. Renew. Energy Res. Appl. 2015 1507–12
[13] Salomonsson D, Soder L and Sannino A 2007 An adaptive control system for a DC microgrid for data centers Ind. Appl. Conf. (Piscataway, NJ: IEEE) (https://doi.org/10.1109/IAS.2007.364)
[14] Planas E, Andreu J, Gárate J I, De Aelegria I M and Ibarra E 2015 AC and DC technology in microgrids: a review Renew. Sustain. Energy Rev. 43 726–49
[15] Papadimitriou C, N. Zontouridou E I and Hatziangriou N D 2015 Review of hierarchical control in DC microgrids Electr. Power Syst. Res. 122 159–67
[16] Curtright A E, Morgan M G and Keith D W 2008 Expert assessments of future photovoltaic technologies Environ. Sci. Technol. 42 9031–8
[17] Rao A B, Rubin E S and Keith D W 2006 Evaluation of potential cost reductions from improved amine-based CO2 capture systems Energy Policy 34 3765–72
[18] Abdulla A, Azevedo I L and Morgan M G 2013 Expert assessments of the cost of light water small modular reactors Proc. Natl Acad. Sci. USA 110 9686–91
[19] Prasad S, Abdulla A, Morgan M G and Azevedo I L 2015 Nonproliferation improvements and challenges presented by small modular reactors Prog. Nucl. Energy 80 102–9
[20] Dalziel C F and Massoglia F P 1956 Let-go currents and voltages Trans. Am. Inst. Electr. Eng. Part II Appl. Ind. 75 49–56
[21] National Fire Protection Association 2016 NFPA 70: National Electrical Code
[22] National Fire Protection Association 2018 NFPA 70 E: Standard for Electrical Safety in the Workplace
[23] Stallcup J S 2000 Classifying and using class 1, 2, and 3 circuits EC&M (http://ecmweb.com/code-basics/classifying-and-using-class-1-2-and-3-circuits/) (Accessed: 5 August 2017)
[24] ABB 2007 ABB low voltage circuit-breakers for direct current applications (Bergamo, Italy) ABB Technical Application Papers 2007
[25] Goodsen M 2017 GIs and Fire Investigation Interfire (www.interfire.org/features/gi.asp)
[26] Raimi K T and Carrico A R 2016 Understanding and beliefs about smart energy technology Energy Res. Soc. Sci. 12 68–74
[27] Tom M, Fortenbery B and Tschudi W 2008 DC Power for Improved Data Center Efficiency (Berkeley, CA: Lawrence Berkeley National Laboratory)
[28] Intel 2009 US Environmental Protection Agency ENERGY STAR 5.0 System Implementation
[29] Sannino A, Postiglione G and Bollen M H J 2003 Feasibility of a DC network for commercial facilities IEEE Trans. Ind. Appl. 39 1499–507
[30] Whaite S, Grainger B and Kwasinski A 2015 Power quality in DC power distribution systems and microgrids Energies 8 4378–99
[31] International Association of Electrical Inspectors 2016 US Electrical Codes and Regulations by State (www.iaei.org/web/Online/Regulations/usregulations.aspx)
[32] Lam L, Azevedo I and Branstetter L 2018 A sunny future? Expert elicitation of Chinese photovoltaic technologies Energy Res. Lett. 13 aaa170
[33] Reed Construction Data LLC 2014 RSMeans Square Foot Costs (Norwell, MA: Construction Publishers and Consultants)