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The Case for DC: Motivation of Modern Topologies, DC-Powered Solutions, and Applications within Residential Environments

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ABSTRACT

The more than a century-old debate between AC and DC has its roots in an electrical distribution challenge, tackled by rival inventors Nikola Tesla and Thomas Edison during the late 1800s. Although originally collaborating on the improvements of Edison's work, the pair eventually parted ways due to conflicts in their personalities and business pursuits. Edison's direct current (DC) system leveraged a constant voltage and current to supply electricity, which was initially sufficient for small locales and geographical regions. However, DC encountered a major obstacle when longer-range transmission was required; there was simply no way to easily convert it between higher and lower voltages. These step-up and step-down conversions were critical for transmission, as power line losses are reduced significantly when proportionally increasing voltage levels. Tesla's alternating current (AC), on the other hand, was readily compatible with the newly christened *transformer*, a device which possessed the ability to effectively adjust AC voltages on demand. With more and more entities investing into the AC-based distribution scheme, it seemed that the war of currents had been firmly decided in favor of Tesla's solution. However, a century later has revealed an outmoded and fragile electrical ecosystem, with new energy sources and infrastructures that reposition DC as a primary contender for distribution and consumption. This paper will outline these current challenges, and explore the implementation of practical DC solutions across both the larger power grid and within residential applications.

1. INTRODUCTION

The U.S. power grid is one of the most complex engineering systems in the world, involving highly convoluted nonlinear behaviors, tens of thousands of individual nodes, and scores of intricate power electronics throughout. Its construction and historical progression hold far-reaching implications on the advancement of modern society, and ultimately the sustainability of the global environment. Insights into transportation and distribution mechanisms, the electrical needs of contemporary appliances and devices, and the revolution of renewable energy resources are paramount for discerning the path forward of electricity and the next generation of its development. More than a century ago, engineering heavyweights Nikola Tesla, George Westinghouse, and Thomas Edison battled over what would become the foundation for present-day electricity distribution. A major asset of Tesla's Alternating Current (AC) at the time was its ability to be converted to higher and lower voltages, giving it a critical advantage over Edison's Direct Current (DC). The battle was clinched during the Chicago World's Fair in 1893, during which Westinghouse successfully underbid Edison to supply power to the Fair. This demonstration of AC power consequently resulted in the Niagara Falls Power Company awarding Westinghouse a major contract to construct a power generator for the falls. In 1896, the Niagara Fall's hydroelectric power plant was successfully launched, providing power to the Buffalo, NY area. Following this success, General Electric and a multitude of other firms shifted their investment into AC power, securing AC as the predominant means of power distribution in the U.S (U.S. Department of Energy, 2014).

The war between AC and DC ultimately concluded in favor of AC, owing to its capability to be transformed to higher voltages and thus minimize power losses over longer transmission distances. This feature is a direct corollary of Ohm's law and the Joule-Lenz law, in which electrical power lost decreases quadratically with respect to current. Since by

Ohm’s law, current can be reduced by a corresponding increase in voltage over a constant resistance, the flexibility of AC voltage to be modulated by the newly christened transformer of the late 1800s gave it a distinct advantage over the competing DC option (Gómez-Expósito *et al.*, 2018).

In parallel fashion to the U.S.’s geographical development, the overall power grid, or *macrogrid*, has evolved in a bottom-up regional fashion across the country, resulting in three primary interconnections defined by the North American Electric Reliability Corporation (NERC): The Eastern Interconnection, Western Interconnection, and Texas Interconnection (NERC, 2019). Each system maintains its own AC frequency and experiences unique load shapes, power flows, and stability challenges. The macrogrid is a composite of transmission and distribution networks, which directly contribute to the control and stability challenges surrounding it. Increasing energy demands and greater dependence on the macrogrid have fostered a delicate balance between satisfaction of consumer needs and reliability of operations. The spatial layout of the power grid in North America makes it especially vulnerable to cascading failures, with the Federal Energy Regulatory Commission (FERC) explaining that a loss of merely nine key substations out of 55,000 could result in a country-wide blackout (Smith, 2014). Compounding this, in 2017 the American Society of Civil Engineers (ASCE) scored the U.S. energy system with a grade of a *D+* for overall reliability, citing aging distribution lines, capacity bottlenecks, and climate impacts as leading factors in their evaluation (ASCE, 2017). In short, the urgency for a plausible strategy toward improvement and upgrade is clear, but to better appreciate the direction it should take, an understanding of the requirements at the end point of use must be considered.

2. REEVALUATING THE GRID

2.1 Power Transmission

According to the U.S. Energy Information Administration (EIA), approximately 5% of electricity transmitted is lost due to grid inefficiencies. Between 2000 and 2015, more than 172 quads of electricity were transferred through the U.S. electrical grid, equivalent to approximately 50 trillion kWh. From distribution losses alone, the amount of energy dissipated would be sufficient to power 306,000 houses over the same time period, assuming an average consumption of 914 kWh per house per month (EIA, 2019). An individual study in New York identified utility transmission losses of up to 5.8% and distribution losses of up to 4.6%; however, these values were obtained *after* utilities had enacted a variety of improvements to reduce losses in the distribution system. Ultimately, AC transmission and distribution schemes must contend with an array of loss-mechanisms, including but not limited to (a) ohmic losses, (b) corona losses, and (c) other distribution losses (Jackson *et al.*, 2015).

A little over a century from its induction, DC no longer faces the same challenges with respect to voltage transformation. In fact, similar to high voltage AC, high voltage DC (HVDC) can also be employed to transfer power over long distances while minimizing electrical losses. The first HVDC transmission lines were enacted in the 1950's in both Sweden and Italy, with dozens of new projects presently under construction or completed (Arrillaga, 1998). In 2019, China demonstrated an HVDC link using a 1,100 kV transmission line over a span of 3,300 km, supporting a maximum bulk power transfer of 12 GW (Ying *et al.*, 2019). With installations such as these, both intra- and intercontinental networks are feasible, with a host of benefits in contrast to AC equivalent systems.

Costs for transmission lines are associated with a variety of parameters, including occupied space for transmission line towers (referred to as right-of-way (ROW)), physical cost of towers, conduction line costs, electrical equipment and terminators, and other necessary power electronics. DC transmission has the immediate benefit over AC via its conductor real-estate needs; while AC requires three conductors to carry power (hot, line, and neutral), DC only requires two (positive and negative). Since high voltage transmission lines require a minimum amount of spacing between conductors to avoid ground-faults and arcing, HVDC transmission also benefits from requiring a smaller ROW through spacing management between its two conductors as opposed to three, as illustrated in Figure 1. The reduced amount of conduction material also affords smaller conductor losses, such as ohmic losses discussed in the previous section, and the avoidance of other AC-specific losses, such as the skin effect (Rashid, 2011).

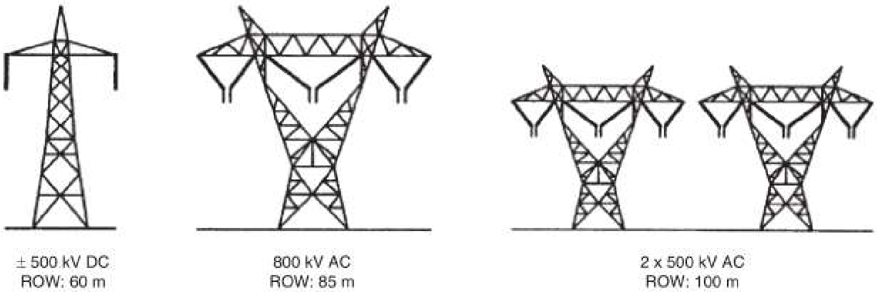

Figure 1: Equivalent DC vs AC ROW for long distance power transmission (Rashid, 2011)

An economic analysis of high voltage AC and DC transmission can be performed in consideration of the specific costs associated with each system configuration. A break-even distance occurs where the capital investment for an HVDC system is more cost-effective than the corresponding AC system. Several studies have determined this distance to be approximately 500 km, but there are some caveats with this calculation (Rashid, 2011). When directly compared to HVDC, more AC transmission lines are often required to provide sufficient stability between endpoints, thereby increasing overall cost. In addition, AC transmission lines must contend with complex power consumption and generation, and therefore require switching stations along a transmission path to appropriately manage power distribution (Bahrman, 2008). As a result, the true benefit of utilizing HVDC is underappreciated when performing a pure comparison in transmission and equipment costs. From a top-down perspective of the macrogrid, HVDC affords more opportunities for efficient energy transmission, practical long-distance transportation, and distinct economic and structural benefits as compared to conventional AC transmission.

2.2 Characterization of Energy Consumption

In a survey of 24 countries representing 92% of energy consumed worldwide during 2018, the International Energy Agency (IEA) determined that residential consumers represented up to 20% of the end-use of energy, as illustrated in Figure 2. Of this sector, space heating and cooling accounted for more than half of energy consumed as shown in Figure 3, positioning HVAC systems as key points of interest for analysis. Appliance energy consumption followed in second, accounting for another one-fifth of residential net energy consumed.

Owing in part to their significant partition of total energy consumption and homogeneity of specific load types, residential spaces occupy a pivotal juncture in the path toward the future architecture of the electrical grid. Many studies have evaluated the individual characteristics of residential loads, such as Anzar *et al.* (2017), Chauhan *et al.* (2017), Gerber *et al.* (2019), and Luo *et al.* (2019), for the purposes of assessing both demand side management and the opportunity for retrofit suitable with DC power. In particular, Gerber *et al.* (2019), classified common residential electrical loads as either (a) lighting, (b) electronics, (c) heating elements, or (d) motor loads. Of these, all but the heating elements were surmised to benefit from a direct-DC supply or suitable DC-retrofit compared to the baseline AC versions. In order to distribute DC power to these endpoints in such a setting, however, innovative and modernized electrical architectures must first be formulated, prefixed with the SI names corresponding to their relative size. These are known as the *microgrid*, *nanogrid*, *picogrid*, and so on.

2.3 State of the Art Topologies

As defined by the Lawrence Berkeley National Laboratory (LBNL), a microgrid is represented by a group of loads and distributed energy resources (DERs), which have a defined electrical boundary from other entities, can be controlled as a single body, and maintain the ability to either interact with the grid, or disconnect and operate independently in an islanding mode (Black, 2021). The International Council on Large Electric Systems (CIGRÉ, 2010) provides a similar interpretation, further specifying that DERs include all manner of energy generation in the microgrid (e.g., fossil fuels, combined heat and power (CHP), photovoltaics, wind, etc.), and that storage devices can possess a diverse collection of implementations (e.g., electrical, mechanical, gravitational, thermal, chemical, etc.). To this end, a microgrid is a unit which can coexist alongside conventional electrical distribution mechanisms, but affords the capability to operate on its own if necessary. Furthermore, the microgrid can distribute energy back to the macrogrid if required, offering an additional advantage to stability.

Figure 2: End-use energy consumption by sector during the 2018 year (IEA, 2018).

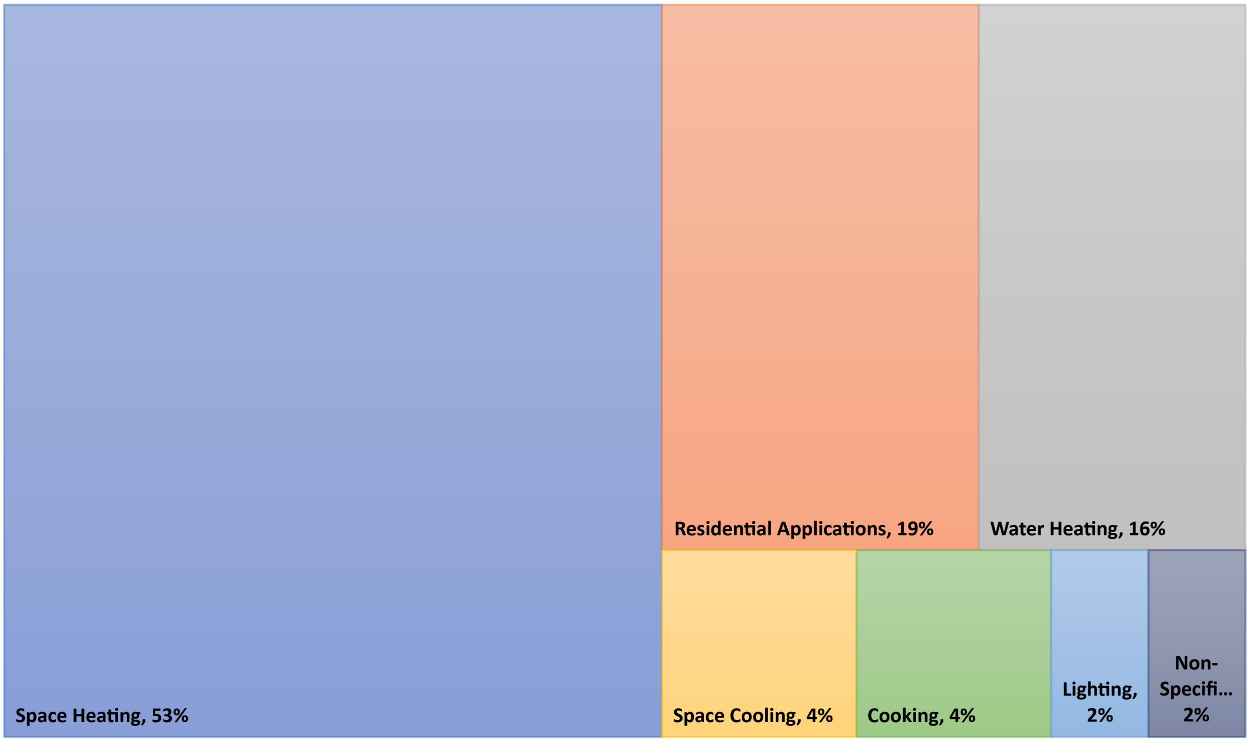

Figure 3: End-use energy consumption breakdown in residential environments during the 2018 year (IEA, 2018)

Similar to microgrids, nanogrids offer much of the same benefits on a smaller scale. While a microgrid might encompass an entire neighborhood of interconnected houses, a power plant, and local energy storage, a nanogrid could be comprised of a single home with a solar installation. Nordman (2010) defines a nanogrid to represent a single controllable entity with at least one load, and at least one connection to external grids (e.g., a larger microgrid, the overall macrogrid, etc.). A critical difference from the microgrid, however, is the requirement for storage; a nanogrid may or may not have energy storage integrated into its design. As a result, by its formal definition a nanogrid is not required to support islanding operation.

Microgrids and nanogrids are not required to stipulate a specific voltage type for distribution, although DC and other hybrid combinations are common. These systems benefit from their flexibility to integrate into a panoply of applications, ranging from industrial facilities, commercial buildings, cul-de-sacs, individual homes, and many other structures. Microgrids and nanogrids offer a bottom-up solution to transmission and distribution challenges, requiring minimal coordination and the flexibility to function alongside the existing AC infrastructure. With integrated battery storage, these topologies offer resiliency to grid disruptions, load-balancing opportunities, and ready-compatibility with DC-power producing renewable energy sources. Nanogrids advocate these benefits another step further, yielding configurations with reduced conversions between distribution and devices, and increasing the potential for energy savings. Combining these systems with DC-compatible devices and furthering retrofit-research into additional appliances capable of supporting DC could render AC the minority in power distribution, rather than the predominant entity.

Two possible microgrid topologies are demonstrated in Figure 4, with the left side indicating an AC/DC hybrid structure, and the right side presenting a pure DC structure. In these diagrams, darkened circles represent a switch, open circles represent power electronics, and arrows represent the direction of power flow. Under both schemes, the electrical storage could be removed without affecting the overarching integrity of the design. The hybrid structure affords some of the benefits of the microgrid architecture without fundamentally altering the common distribution mechanism. The right style, however, yields an ideal configuration for a DC-based solution. In this case, all conversions from AC to DC have been eliminated (with the exception of the primary grid-tie), and renewable energy generation, energy storage, and loads can benefit from direct-DC supplies with minimal and highly efficient DC-DC conversions. These topologies illuminate one of the most critical elements for the motivation of innovative grid layouts: the integration of DERs.

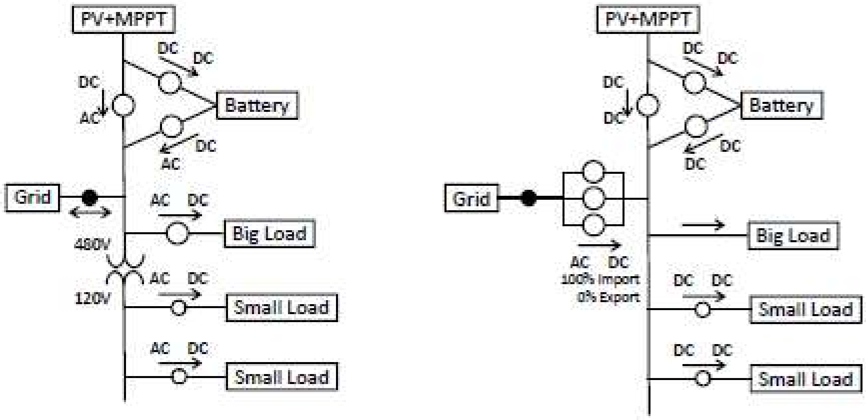

Figure 4: Sample AC and DC microgrid/nanogrid topology reference layouts (Backhaus *et al*., 2015)

2.4 Distributed Energy Resources

As the macrogrid increases in size and throughput, so do its stability challenges and supply requirements. In addition, higher instantaneous power demands can lead to cascading failures during disruptions, as evidenced by the 2003 blackout resulting in over 50,000,000 impacted customers, and many other similar backout events during the past decade (Minkel, 2008). These obstacles can be overcome with the help of a newly emerging asset – DERs.

According to NERC, a DER is, “any resource on the distribution system that produces electricity and is not otherwise included in the formal NERC definition of the Bulk Electric System (BES)” (NERC, 2017, p. 1). As a result, DERs occupy a broad range of resources, including energy storage, renewable energy generation, electric vehicle (EV) charging stations, back-up generators, and even microgrids themselves. Fundamentally, to be classified formally as a DER an entity must be capable of producing electricity, thus supporting the inclusion of energy storage systems.

Interestingly, individual equipment and devices which maintain their own storage may also function as a DER (such as an EV) if the electrical connection is bidirectional (NERC, 2017).

With the acceleration in deployment of renewable energy generation, especially that of solar photovoltaics (PV) and wind power, the macrogrid is presented with an increasingly diverse supply of energy resources. Unlike traditional base load power plants, such as coal and nuclear, renewable resources are frequently volatile and therefore unsuitable for satisfaction of base load power demands. Instead, these systems are far more effective for responding to transient shifts in demand, such as intermediate loads arising during the daytime in winter and summer seasons. If these sources are coupled with energy storage systems, such as compressed air energy storage (CAES), pumped heat energy storage, or other conventional battery storage systems, the variability of energy generation can be significantly mitigated. In addition, storage systems within the macrogrid provide a relaxation to the demands on other generation processes, and bolster the stability of the neighboring grid elements.

Opponents to the integration of renewable energy sources and the larger composite of DERs have argued that due to their inherently unstable nature, these resources are unreliable and thus incapable of replacing established fossil-fuel based power generation sources. Contrary to this suggestion, multiple studies have recognized the considerable benefit of incorporating sources such as wind and solar PV, as Miller *et al.* (2014) confirmed in their multiphase Western Wind and Solar Integration Study (WWSIS). The WWSIS report sought to understand whether the macrogrid (specifically the Western Interconnection) could withstand the inclusion of extensive amounts of wind and solar energy generation without inducing instabilities and resulting in undesirable strain to the overall system. Far from any unfavorable impact, the WWSIS's first phase determined that up to 35% of the region's power production could be substituted by wind and power generation without requiring significant restructuring of the grid. Furthermore, the same modification would also provide an equivalent benefit to the environment roughly similar to removing up to 36 million cars off the road (compared to the existing system operation). Utility and operation costs were also discovered to decrease under the addition of these renewable resources, and transmission segments could provide better utilization due to the locality of energy generation. Finally, distributing the points of energy generation geographically was also recognized to reduce variability in production, as the prevalence of wind and solar conditions becomes proportionally more consistent as the spatial size of the region considered increases (Miller *et al*., 2014).

3. RESIDENTIAL APPLICATIONS

3.1 The Residential Nanogrid

Owing to the explosion of growth in renewable energy generation in residential locations, and the aforementioned benefits from the inclusion of DERs within the existing macrogrid infrastructure, the application of DC-based architectures within residential spaces has become a compelling topic. In its *2020 World Energy Outlook* publication, the IEA (2020a) states that, "for projects with low-cost financing that tap high-quality resources, solar PV is now the cheapest source of electricity in history" (para. 5). Even while global electricity demand curtailed due to the COVID-19 pandemic, renewables maintained a year-over-year growth of nearly 7% during the 2020 year (IEA, 2020b). According to Solar Energy Industry Associates (SEIA), this international advancement was fueled in-part by a 43% increase in new electricity production of solar PV within the U.S. in the same year, and incidentally was also the single largest increase of that category during the previous decade. Contributions to new production included a 14% increase in residential solar installations between the second and third quarters of 2020 within the U.S., and new residential solar capacity additions of approximately 3 GWdc during the same year (SEIA, 2020).

From the perspective of consumption, the majority of modern devices and appliances consume DC power either directly or indirectly, yielding further credence to DC-based topologies. In a residential setting where DERs are present, maintaining conventional AC distribution results in a multitude of potentially dissipative AC to DC and DC to AC conversions, which diminish the capacity for micro/nanogrid benefits. As a result, a centralized DC-distribution architecture affords the capability to mitigate these impacts, reducing the need for complex and expensive power electronics, and offering viable high efficiency DC-DC conversions. Hybrid structures of the layouts previously described in Figure 4 can also be attainable, where DERs and DC-compatible loads can share a common DC bus, while conventional AC loads and DC-indifferent loads can remain on a traditional AC infrastructure. As Backhaus *et al.* (2015) enumerates, there are nine key performance indicators (KPIs) that can be applied to analyze an electrical architecture's benefit:

1. Safety and Protection
2. Reliability
3. Capital Costs
4. Energy Efficiency
5. Operating Costs
6. Engineering Costs
7. Environmental Impact
8. Power Quality
9. Resilience (p. 2).

After reviewing numerous studies for evidence and implementation details, including Vossos *et al*. (2014), Wang and Jain (2010), Burmester *et al*. (2017), Garbesi *et al*. (2011), and many others, these nine KPIs were summarized over various AC and DC topologies to reveal distinct advantages of DC designs for categories (3), (4), (6), and (8), and neutral or marginal benefits for the remaining categories (Backhaus *et al.*, 2015). As a result, architectures including significant DC composition certainly merit additional investigation.

3.1.1 Conversion Efficiencies

The losses associated with various AC and DC conversion and inversion processes is a prime mover for the topic of modern electrical topologies, but continues to persist as a significant topic of contention surrounding the explicit degree of benefit. Challenges to clarifying and simplifying these issues include the vast array of converter technologies and types, continuing developments from novel research efforts, manufacturer specifications versus actual performance, and the use-cases and scenarios under which findings are reported. As an example, Backhaus *et al.* (2015) reported peak load conversion efficiencies from high voltage AC to low voltage DC of approximately 95%. However, several common household devices studied by Santos *et al*. (2018) described conversion efficiencies for devices such as a laptop, LED, phone charger, fan, and 1 kW inverter as low as 87%, 49%, 71%, 60%, and 65%, respectively. Similarly, Burmester *et al*. (2017) indicated typical AC to DC conversion efficiencies of common appliances, including refrigerators, computers, televisions, lighting, and water heaters of approximately 87%, 80%, 85%, 82%, and 88%, respectively. As a result, although peak conversion efficiency studies frequently record values in the high 90 percentile range for all manner of conversion combinations (i.e., AC-AC, AC-DC, DC-AC, DC-DC), ordinary devices usually fall significantly short of this range.

An intrinsic aspect of the various conversion mechanisms and their impact on the overall electrical architecture's benefit encompasses the specific location where the conversion needs to occur. Figure 5 provides an illustration of common conversion placements and values in both an AC and DC-based micro/nanogrid layout employing local energy generation and storage elements. Under an AC scheme, energy generated from renewable sources is fundamentally DC in nature (even from wind turbines) but must be converted to AC to be distributed within the home. Multiple studies have indicated potential improvements through the use of a DC-based architecture ranging from 14% (Vossos *et al*., 2014), 18% (Gerber *et al*., 2018), and even as high as 30% (Hofer *et al*., 2017) over AC-equivalent counterparts. These achievements are made feasible in part by (a) isolating primary AC-DC inversion processes to one central, highly specialized and efficient module, (b) instituting multiple high-efficiency DC-DC conversion devices driven by a principal DC bus, and (c) eliminating multiple conversion losses from energy generation and storage elements. In the case of an AC-based micro/nanogrid, the potential utilization path for wind power generation could include as many as six or more conversions (e.g., AC-DC (from generation), DC-AC (for distribution), AC-DC (for initial storage), DC-AC (for subsequent distribution), AC-DC (for appliance rectification stages), and DC-AC (for motor consumption)).

3.1.2 The DC House Project

The Purdue DC Nanogrid House project is a research effort located within a residential home in West Lafayette, IN, with the ultimate objective to retrofit the entire building and all appliances and devices from AC to DC power. The home is a two-story 1920's era structure, which functions as a legitimate *living-laboratory*, and houses three graduate students who live and work within the dwelling. Total floor space of the building is approximately 208 m^2, the exterior of which includes a detached garage and a property lot occupying 595 m^2. Each of the house's 32 individual circuits have been instrumented with current transformers (CTs), voltage clamps, and Wi-Fi circuit breakers to monitor historical and real-time energy and power consumption, and to serve as a baseline of comparison against the planned

DC retrofits. Currently, the nanogrid architecture outlined by Ore and Groll (2020) is under construction, with an intent to commission early in the 2021 year. Included in this design is a 14.3 kW rooftop solar installation, 20 kWh LiFePO4 battery system, and novel Energy Management System (EMS) and Building Management System (BMS) for optimal control of the nanogrid and individual loads. Following successful energization of the completed nanogrid, the first DC loads to be investigated include a retrofitted-hybrid heat pump system, capable of operating on either 380 VDC or 230 VAC, and a PoE-based LED lighting system. During the life of the system, additional loads will be added and compared against the previous years of AC baseline data to thoroughly report on observed energy efficiency improvement, system benefits and challenges, and potential for reproducibility in other locations.

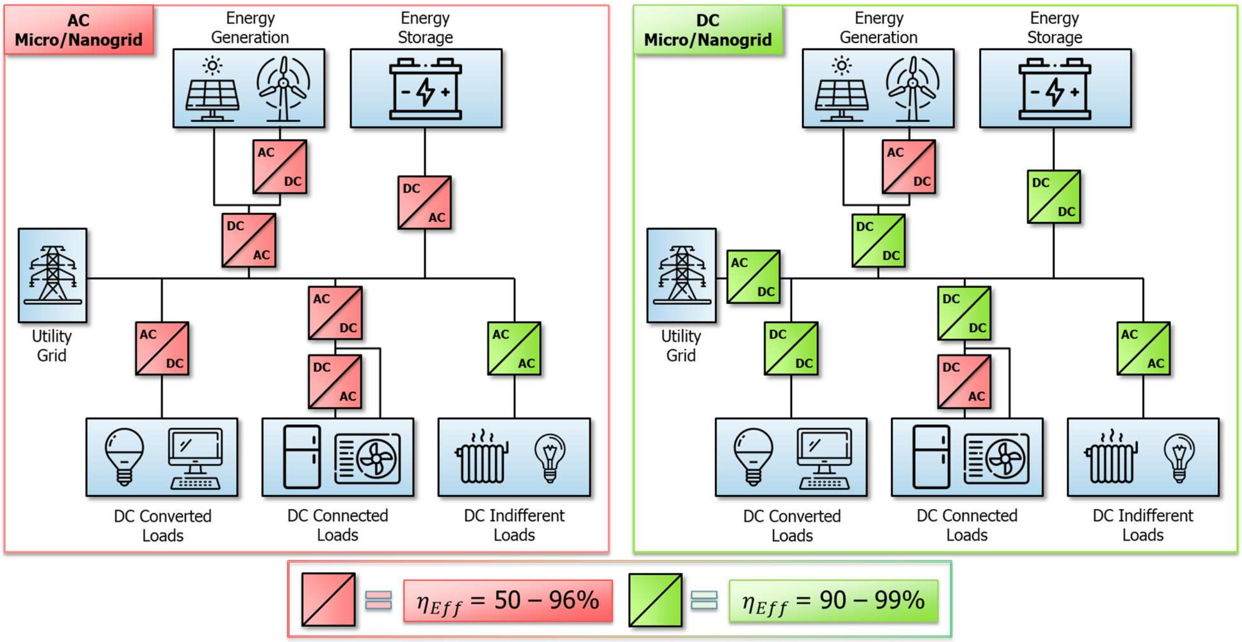

Figure 5: DC vs AC micro/nanogrid architectural depiction highlighting relative conversion efficiencies

4. CONCLUSIONS

A wealth of previous studies and research endeavors have reiterated the pressing necessity to evaluate DC and hybrid AC/DC based electrical topologies to satisfy the ever-increasing demands of the modern power grid. Though many articles frame this issue as a dilemma of proper choice between AC or DC, or even Tesla versus Edison, the reality is more fundamental to simply *using the right tool for the job*. In the same way obsolete wooden waterwheels are viewed today, doubtlessly too will fossil fuels and other similar power sources seem primitive to those of the coming centuries. However, the present time must commit to continual examination of constructive and propitious distribution strategies, independent from political or commercial inclinations, and remain focused on the ultimate goal of preserving the environment and promoting sustainability. As the well-known anthropologist Joseph Tainter (1988) wrote in his book, *The Collapse of Complex Societies*, "sociopolitical systems require energy for their maintenance, [and] increased complexity carries with it increased costs per capita…a new energy subsidy is necessary if a declining standard of living and a future global collapse are to be averted." (pp. 194–215). This admonition has held true through the ages, and continues through today; for the survival of both our individual societies and world as a whole, we must ceaselessly seek practical and effective means of leveraging our available resources to supply our civilization.

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