Rise of DC Power for Homes in United States

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Abstract:
The widespread growth of direct current (DC) native devices, solar photovoltaic (PV) systems at residences, and battery-based energy storage is dramatically changing how electricity is distributed within U.S. residential structures. Approximately 76 percent of today's home-based internal DC usage are based on end-use. However, the prevailing AC distribution paradigm requires multiple conversions from DC to AC which incur 3-5 percent losses and total losses of 15-25 percent for solar-to-load pathways. In this paper we present an overall examination of DC power distribution in residential structures, examining the current DC appliance ecosystem, comparative efficiencies of DC vs. AC architectures, integration with Smart Home Energy Management Systems, Safety and Security concerns, Cost-Benefit Analysis, and Multi-Stakeholder Impact Assessments. Results from our literature review and quantitative modeling indicate that DC Microgrids will result in 5-15 percent efficiency improvements in homes equipped with solar PV and battery storage. Additionally, the results also indicate that possible savings could be as much as 58 percent in costs. We identify pathways to adoption, standards required for adoption, and recommend policies to advance DC powered residential infrastructure in the United States.

Keywords: DC power distribution, residential microgrids, energy efficiency, smart home energy management, solar photovoltaics, power electronic converters, direct current appliances

I. INTRODUCTION

The history of electrical power distribution is based upon the 'War of Currents' between Thomas Edison's direct current (DC) system and Nikola Tesla's alternating current (AC) system in the late 1880s. AC won out as it was easier to use voltage transformation via passive transformers to efficiently transmit power over long distances [1]. AC has been the unchallenged standard for residential power distribution in the U.S. and worldwide for well over 130 years. But there is a quiet revolution emerging that could dramatically change this paradigm.

The average American home now contains many appliances that use DC as their native power. There are light-emitting diodes (LED), computers, consumer electronics, smartphones, and many other electronic products and devices. These products and devices will continue to grow as they are used in virtually all aspects of our lives. In addition, with the growth of brushless DC (BLDC) motors in refrigerators, variable speed drives (VSD) compressors in heating ventilation and air conditioning (HVAC) units, and electronically controlled washing machines, we see an increase in DC internal appliances. Research conducted by Lawrence Berkeley National Laboratory shows that nearly all residential electricity end-use devices can be made DC compatible and are shown to be much more efficient than their AC counterpart [2].

At the same time, the United States is also seeing unprecedented growth in distributed DC energy generation and storage. Solar energy generated a record 83 Terawatt-hours (TWh) in 2025, representing an increase of 7.6% in total U.S. electricity production. Residential solar installation grew by 4,647 Megawatts DC (MWdc) in 2025 alone [4]. As battery energy storage systems and electric vehicles (EVs), both of which are inherently DC technologies that create a residential environment where DC sources and DC loads are connected through an AC-based infrastructure, we see additional unnecessary conversion loss occurring at each stage of the distribution process.

This paper gives an overview of the increasing presence of DC power in American households. This includes a review of the DC appliance landscape, a detailed analysis of the potential energy efficiency benefits of distributing power in DC form, an evaluation of how DC distribution may benefit smart home energy management, a discussion of the potential safety and security impacts associated with widespread DC distribution, a cost-benefit analysis of DC distribution, and an assessment of how the shift toward DC distribution will affect multiple stakeholder groups. This paper will identify viable pathways for the implementation of DC-based residential power distribution and provide recommendations to support the acceleration of this transition.

II. THE MODERN DC HOME: APPLIANCE LANDSCAPE

A. Classification of Residential Loads

Residential electrical loads can be categorized into three types, according to how they utilize power. First are the DC-native loads which use DC power exclusively and therefore require an outside source of DC power through a power adapter or internal converter. These loads represent nearly 38% of residential power consumption [2] and include LEDs, computers, televisions, gaming consoles, cell phones, tablets, smart phones, tablets and other USB accessory products.

Second, are DC-internal loads. These loads use AC power from the grid and then convert it to DC for operation. They also include electronically controlled appliances such as refrigerator compressors driven by brushless DC motors, variable speed drives (VSDs) used in HVAC applications, electronically controlled washers, and ceiling fans using DC motors. Studies have shown that DC-internal loads produce efficiencies of 20-30% over similar AC-internal loads due to the elimination of one AC-to-DC conversion step [5].

Third, are AC-only loads. These loads use resistance heating such as ovens, hot water heaters and space heaters. Legacy induction motors are also included in this category, and represent about 24% of residential energy consumption. Figure 1.1 represents these categories.

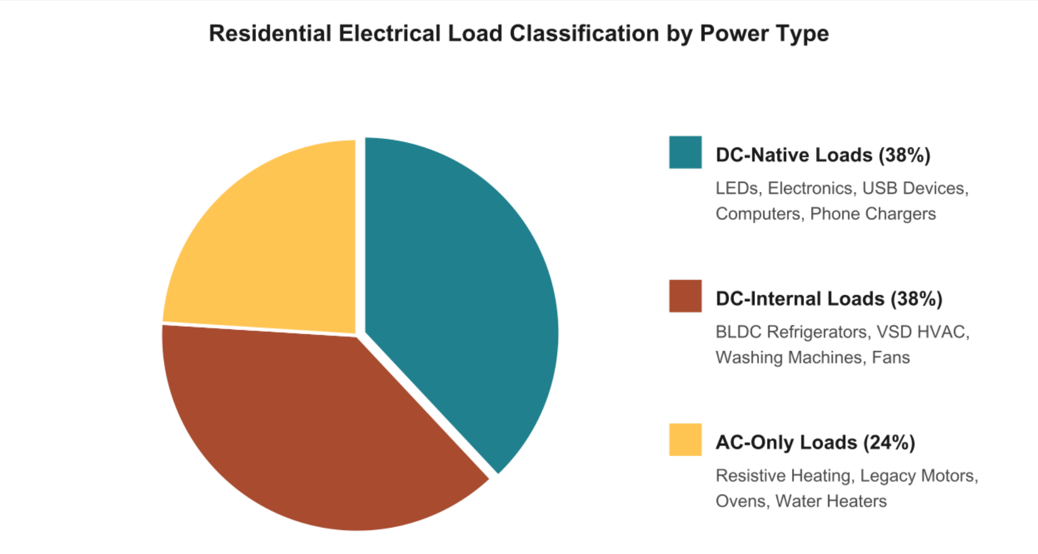

Fig. 1.1. Classification of residential electrical loads by internal power type. Approximately 76% of modern household loads operate internally on DC, creating a natural fit for DC power distribution architectures.

B. Emerging DC Standards and Interfaces

Residential DC distribution is being supported by an increasing number of emerging DC power interfaces that are making it easier for residential DC power to become widespread. The USB Type-C PD 3.1 standard now includes support for as much as 240 watts of power via a single connector, providing enough power for laptops, monitors, and many small appliances [6]. In addition to the Type-C PD 3.1 standard, there are two different voltage levels for DC Microgrid standards provided by the EMerge Alliance; 24 volts for low-power devices such as lights, sensors and Internet of Things (IoT) devices and 380 volts for higher-power distribution to be used for large appliances and building wide distribution [7]. PoE (Power Over Ethernet) or IEEE 802.3bt provides 48-volt DC power up to 90 watts per port, allowing for combined power and data for lighting, security cameras and access control systems via a single cable — significantly reducing installation time.

III. ENERGY EFFICIENCY ANALYSIS: AC VS. DC DISTRIBUTION

A. Conversion Loss Quantification

It is the cascade of energy conversions that creates the inefficiency at the heart of today's home power systems. Solar Photovoltaic and Battery Storage are examples of systems that follow this DC → AC → DC → AC conversion path. The first step is when the solar panel produces DC. Then the inverter converts it to AC (between 93% and 97% efficient). Next the battery converts it back to DC (again, 93% to 97%) so it can be stored. When you want to use the electricity again, it has to be inverted again to AC (between 90% and 95% efficient). Lastly, each device will have its own DC to AC converter as part of its power supply (and the quality of those converters can vary from 80% to 95%).

So if we take all of these conversions together, we get a total loss of 15% to 25% in the flow of energy from generation to consumption.

On the other hand, a DC MicroGrid will allow a one-step conversion from DC to DC. As such, the solar panels produce DC that goes to a DC-DC Charge Controller (with efficiencies ranging from 97% to 99%). The Charge Controller then provides the DC output to the battery which is distributed through the DC Bus to DC loads with only two steps of conversion (each being 97% to 99% efficient). This configuration will result in a 10-17 percent point reduction in overall conversion losses (from 15-25% to 3-8%) [1] [9].

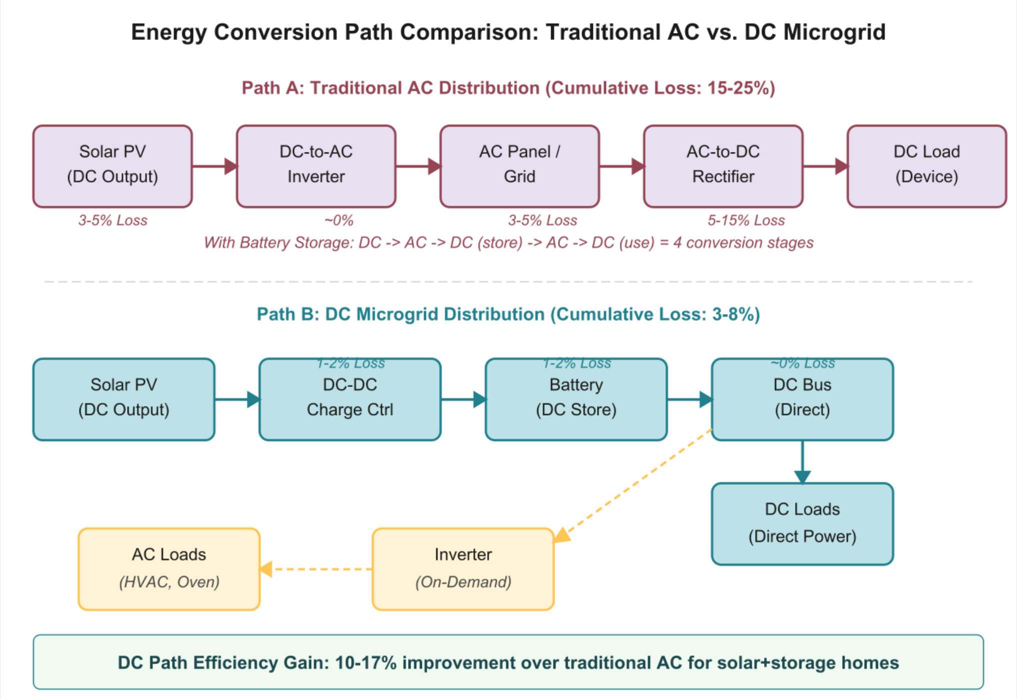

Fig. 1.2. Comparative energy conversion paths for residential power distribution. The traditional AC path (top) incurs 15-25% cumulative losses through four conversion stages, while the DC microgrid path (bottom) achieves 3-8% losses with direct DC coupling.

B. Comparative Efficiency Modeling

Ahmed et al. [8] evaluated several load scenarios and seasons as part of their comparative analysis of AC and DC distribution systems for a modern home in Bakersfield, CA. The results from Ahmed et al. show that the efficiency of DC distribution is highly influenced by the availability of solar power and the percentage of VSD-based loads (i.e. HVAC and Refrigeration) of total demand. In particular, when there are high levels of solar production and VSD loads make up a large portion of demand, DC distribution is shown to be approximately 5-15% more efficient than AC.

Markusson et al. [9] examined the geographic effects of using a DC distribution system for a single-family home. Markusson et al. found that PV self-consumption was increased by 19-46%, while PV utilization was increased by 3.9-7.4% with DC distribution over AC distribution. This resulted in an overall increase in the efficiency of the system of 1.3-8.8%. Additionally, DC distribution provides an advantage in terms of eliminating reactive power issues. While AC systems have to correct for power factor for all but the lowest of power loads, DC systems provide only active power, thus providing energy savings through reduced power loss as well as making power management easier.

TABLE I- COMPARATIVE EFFICIENCY: AC VS. DC DISTRIBUTION SYSTEMS

Parameter	AC System	DC System	Improvement
Solar-to-Load Efficiency	75-85%	92-97%	10-17%
Conversion Stages (PV+Battery)	4 stages	1-2 stages	2-3 fewer
PV Self-Consumption	Baseline	+19-46%	Significant
Reactive Power Losses	Present	Eliminated	100%
Net Residential Savings [2]	Baseline	Up to 30%	Substantial

IV. SMART HOME INTEGRATION AND ENERGY MANAGEMENT

A. Home Energy Management Systems

The integration of smart homes with dc distribution provides synergistic potential to optimize energy in the home. Home Energy Management Systems (HEMS) provide an intelligent control mechanism to monitor, schedule, and manage energy flow among generation, storage, and load in the home. The EPA's ENERGY STAR Smart Home Energy Management System (SHEMS) program is a recognition of total system solutions that integrate smart thermostats, smart lighting controls, and monitored smart plug loads to make it easier for homeowners to manage their energy usage [11].

Since dc distribution architectures are inherently simpler than ac distribution architectures, the HEMS will be easier to implement. The energy management controller does not have to consider the complexities associated with measuring and controlling ac power factors, ac harmonics, or phase synchronization to measure and control power flow because all devices are connected to a single dc bus. Real-time optimization algorithms may use information from solar generation forecasting, TOU tariffs, and battery SOC to schedule delayable loads and manage them through a single dc power distribution architecture. Research has shown that HEMS using reinforcement learning techniques to determine when to switch loads to maximize user comfort and minimize appliance wear have reduced overall costs by 7% compared to non-HEMS controlled systems [12].

B. DC-Enabled Smart Home Architecture

Figure 1.3 illustrates the DC-driven smart home system architecture that utilizes an intermediate DC bus as the common connection point for several energy generating sources and loads. High efficiency solar charge controllers are used to connect the solar photovoltaic arrays to the DC bus. This eliminates the need for the traditional DC – AC – DC conversion pathway. Battery banks and electric vehicle charging systems are native DC devices and therefore are able to be connected directly to the DC bus. Vehicle-to-Building (V2B) energy transfer is enabled due to this direct connection. Hybrid DC-AC systems utilizing V2B have demonstrated returns on investment (ROI) of over 180% when utilized in DC dominant building applications, according to research by Pradana et al. [13], as well as reduced conversion loss of up to 15%, resulting from the use of DC distribution.

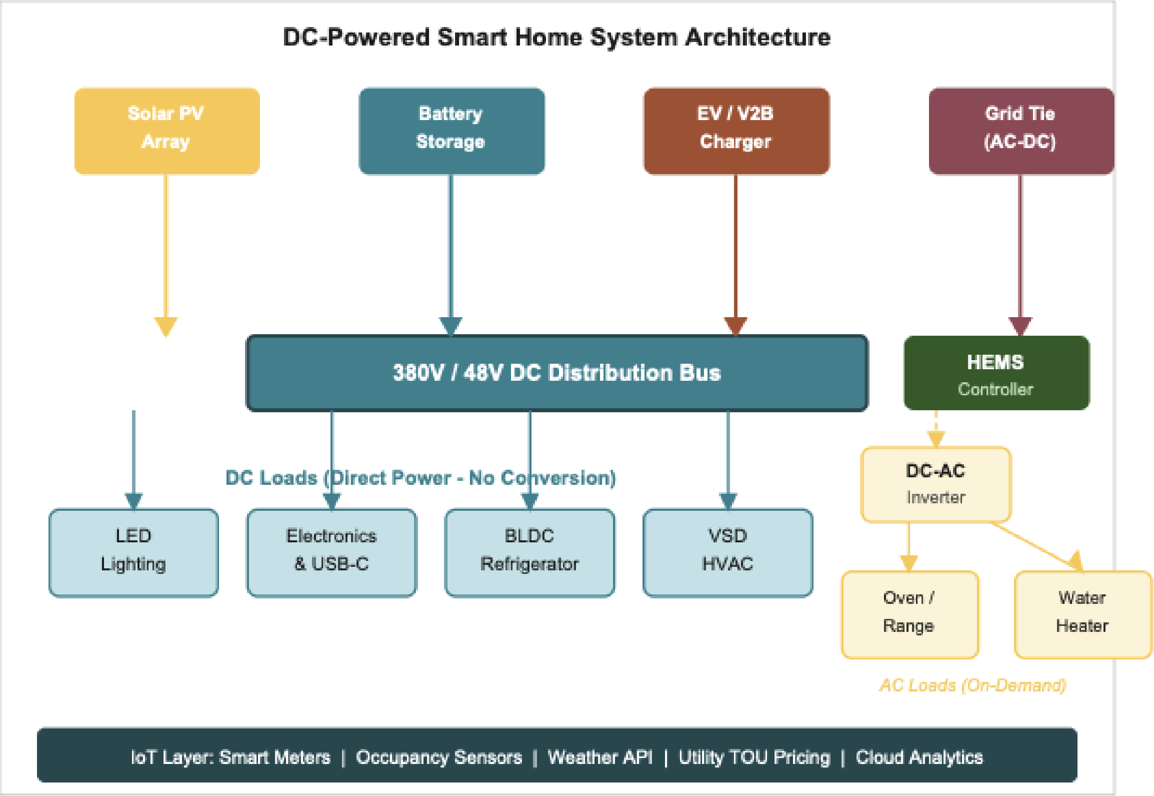

Fig. 1.3. System architecture of a DC-powered smart home integrating solar PV, battery storage, EV charging, and IoT-enabled energy management. DC loads connect directly to the 380V/48V DC bus, while legacy AC loads use an on-demand inverter.

The Internet of Things (IoT) layer provides a detailed view of the smart home system's energy usage through smart meters, occupancy sensors, weather APIs, and utility pricing information. Digital twins and edge computing provide the capability for predictive energy management. Studies have shown that operational cost savings of up to 10% can result from using digital twins to assist in the operation of the Home Energy Management Systems (HEMS), if the HEMS has a 15-minute scheduling resolution [14]. Non-intrusive load monitoring (NILM) provides the capability to perform appliance level energy disaggregation without having to place individual sensors on each appliance. This reduces the installation costs associated with NILM and allows for continued granularity in the management of energy usage.

V. SECURITY, SAFETY, AND RESILIENCE

A. Electrical Safety of DC Distribution

The low voltage DC distribution systems that use either 24V or 48V levels can be classified as SELV (Safety Extra Low Voltage) under international standards. DC is also generally regarded as being between 3-5 times safer than AC at the same voltage level because there are no repeating muscle contracting effects caused by AC [15].

Additionally, protocol level safety mechanisms, such as the PoE handshake requirements for power sourcing equipment to verify a valid powered device prior to delivering power; create an additional layer of safety that does not exist on traditional AC outlets which continue to supply power regardless of whether a device is connected.

However, high voltage DC (at 380V), represents a new set of safety issues. Unlike AC, DC fault currents do not naturally contain zero crossing points that allow arcs to extinguish using conventional circuit breaker technology. As a result, Aditya et al. [16] have designed and built a DC Circuit Breaker (DCCB) capable of interrupting bidirectional fault currents. The DCCB is rated at 350V / 10A and uses MOSFET based main conduction paths and controlled auxiliary branches with capacitor technology to manage the interruption of fault currents.

These advanced protection technologies coupled with the EMerge Alliance's development of standardized products and solutions for 380V DC building distribution [7] are working to address the safety concerns that have prevented the widespread adoption of DC at distribution-level voltages.

B. Cybersecurity and Grid Resilience

Cybersecurity for smart homes is a significant concern due to their reliance on networks. The use of smart meters, HEMS (Home Energy Management System) controllers and other connected Internet of Things (IoT)-enabled appliances creates additional points at which cyber attacks could occur and therefore requires a variety of actions including segmented networks, encrypted data transmissions and regular firmware upgrades. However, as compared to AC (Alternating Current), DC microgrids have a number of inherent advantages when it comes to resilience. When the utility grid fails, a smart home equipped with solar panels and batteries will be able to disconnect from the grid and continue to supply power to critical loads (e.g., LED lighting, communication equipment, computers and security systems) directly from its batteries. In this manner, DC loads are isolated from AC loads, thereby eliminating the "single point of failure" associated with the grid tie inverter used in conventional AC-based solar energy systems. As a result, all essential services within the smart home will continue to operate continuously during extended outages.

VI. COST ANALYSIS AND INSTALLATION BENEFITS

A. Market Growth and Capital Costs

The Residential Power Market in Washington D.C. has shown an increase in demand. The worldwide DC residential switchgear market was worth \$2.7 billion in 2024 and is expected to have a Compound Annual Growth Rate (CAGR) of 9.5% from 2024 to 2034 due to increased demand for renewable energy systems in residential markets [17]. In addition, the U.S. segment of the market is projected to exceed \$900 million by 2034. Simultaneously, the residential distribution panel market is expected to be valued at \$1.6 billion in 2025 and is growing at a CAGR of 8.3%, with modern distribution panels incorporating more smart monitoring, surge protection and load balancing capabilities [18].

B. Installation Simplification

DC power distribution offers several advantages during the installation process. Specifically, low voltage DC wiring (less than 60V) is classified as SELV and in many areas is installed without needing a licensed electrician; therefore, it saves on labor. With PoE (Power over Ethernet), lighting and devices can be installed using standard Ethernet cabling which combines power and data into a single cable run thereby eliminating the need to install separate electrical conduit. This approach eliminates approximately 30 – 50 percent of the materials used for installing AC wiring for lighting circuits and reduces the amount of time required to complete installations. Additionally, fewer conversion units, such as removing the need for AC/DC power supplies at every device that reduces equipment count, failure points and maintenance requirements.

C. Operational Cost Savings

Cost savings are demonstrated through techno-economic studies as a result of using DC distribution. Vossos et al. [1] determined that DC distribution systems were cost effective in all scenarios including large capacity batteries and/or on-site solar power, and that lifecycle cost savings increase as PV and battery capacity increases. Rashid et al. [19] determined that optimizing HEM in DC microgrids could potentially cut grid energy and expense by as much as 51% and 58% respectively when compared to current methods. Pradana et al. [13] reported ROIs of greater than 180% and payback times of less than 3 years for DC-dominant commercial buildings. Payback times for residential applications with solar PV and storage are expected to be in the range of 5-8 years with current technology costs and will decrease as DC component costs decrease as they are manufactured in higher volumes.

VII. STAKEHOLDER IMPACT ANALYSIS

The transition to dc power distribution affects multiple interest groups within the residential energy sector, as shown in Figure 1.4. Homeowners will benefit by lower electrical bills due to greater efficiencies, by having increased energy independence due to optimized use of their solar-plus-storage systems, by greater property values due to modern energy infrastructure, and by improved ability to be resilient when faced with grid outages. Studies indicate that homeowners may achieve 45% in cost savings through optimized dc microgrid energy management [20].

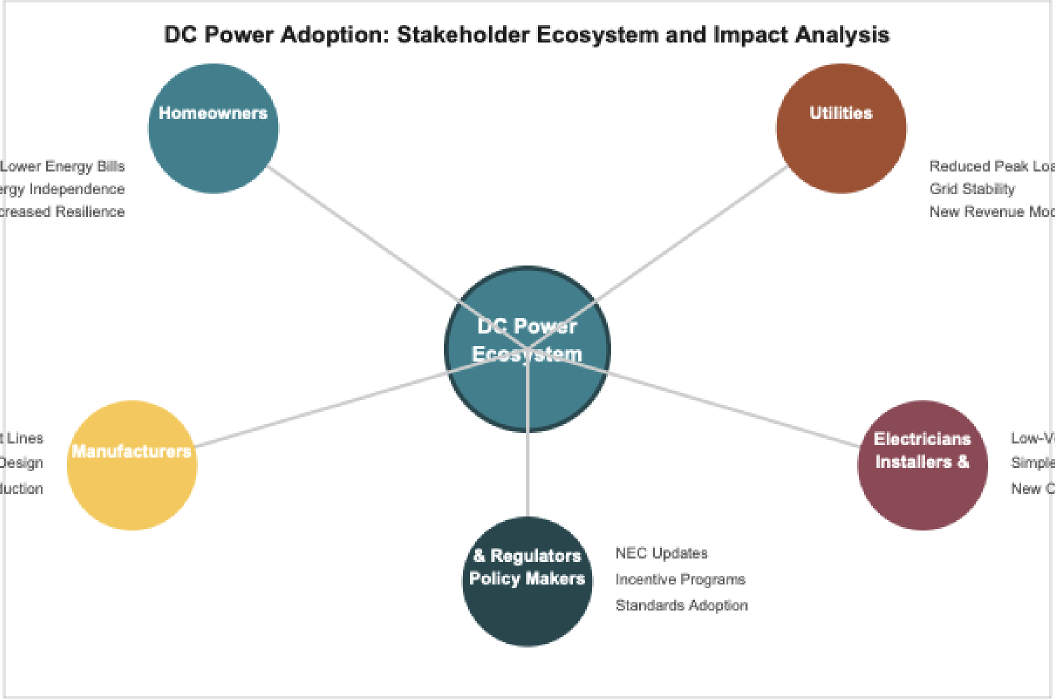

Fig. 1.4. Stakeholder ecosystem map for DC power adoption in residential settings, illustrating the interconnected impacts across homeowners, utilities, manufacturers, installers, and policy makers.

Utilities face both challenges and opportunities as they relate to dc storage located on the customer side of the meter. Residential battery banks, if aggregated together, can provide utility companies with a variety of grid services, such as peak demand reduction, frequency regulation and voltage support, allowing them to create new revenue streams through the creation of virtual power plants (vpp). Appliance manufacturers have new product lines available to them as well; since devices no longer require internal ac-dc converters, appliances can be made smaller, cooler, less prone to electromagnetic interference, have fewer components, be less expensive to manufacture, etc.

Installers and electricians will experience two different impacts: the need to learn new skills related to designing and protecting dc systems, but the simplicity of installing low-voltage dc systems will broaden the range of people who can perform work on poe and 24v/48v dc circuits. Policymakers and regulators must update the national electrical code (nec) to deal with protection issues specific to dc, develop similar incentive programs to those currently being used for solar and storage, and support industry-wide standards development through organizations such as the emerge alliance and ieee.

VIII. CHALLENGES AND FUTURE OUTLOOK

Although the reasons for adopting DC in homes are both technically sound and economically feasible, there are many factors that hinder the adoption of residential DC distribution. One of the biggest barriers to the wide-spread use of residential DC distribution is the lack of a unified residential DC standard. The different residential DC voltages being used today are; 12 volts, 24 volts, 48 volts and 380 volts. There is also no one type of residential DC connector format. The use of a single residential AC voltage (120V/240V) is well established. The amount of retrofitting required due to the fact that there are currently over 140 million homes in the United States makes it economically prohibitive for most homeowners to rewire their home for DC distribution [2]. Although advancements have been made in developing solid state circuit breakers for detecting DC faults, they have not reached the same level of maturity or cost effectiveness as AC fault detection and protection equipment [16].

The most likely path forward for the widespread adoption of residential DC distribution will be the hybrid AC/DC architecture. This will allow for the installation of dedicated DC circuits in all new construction and in homes undergoing major renovations. The hybrid AC/DC architecture will allow for the continued use of AC for legacy high-power resistive loads, while providing DC for the increasing number of DC loads such as lighting, electronics and heating, ventilation and air conditioning (HVAC). The rapid emergence of the USB-C PD 3.1, as a universal DC power interface, along with Power Over Ethernet (PoE) for lighting and Internet of Things (IoT), indicates that a de facto residential DC ecosystem is rapidly evolving through consumer electronics standards rather than through a mandate from utilities. As noted by Vossos et al. [1], specific paths for building-wide DC adoption can begin immediately using lighting, electronics and Electric Vehicle (EV) charging as initial entry points.

IX. CONCLUSION

This paper examines an important and developing trend in the built environment: the growth of DC Power Distribution (DCPD) in residential buildings across the United States. Specifically, this study focuses on the technical feasibility, economic viability, and stakeholders' interests relative to this emerging paradigm shift. A fundamental mismatch exists between the rapidly developing residential energy ecosystem, based upon increasing numbers of DC native devices (76% of residential loads), growing numbers of installed rooftop solar photovoltaic (PV) systems (estimated 387 TWh in 2025), expanding battery storage capabilities and growing numbers of electric vehicles (EVs) and the existing legacy AC power distribution infrastructure. Results of the quantitative analysis demonstrate that DC microgrids can increase overall efficiency by 5-15 percent compared to conventional AC-based residential energy systems, assuming that there are integrated solar PV and battery storage components; in addition, cumulative conversion losses are expected to decrease from 15-25 percent to 3-8 percent. In addition to increased efficiency, smart home energy management integration will provide additional benefits to consumers by providing intelligent load scheduling, predictive optimization, and vehicle-to-building energy exchange. Based on current costs, the payback period for transitioning to DC-powered homes is estimated to be in the range of 3-8 years, dependent upon building characteristics and DC load penetration; moreover, the authors estimate that ROI for DC-dominant installations will exceed 180 percent.

While the transition to DC-powered homes is not a matter of "if", it is a matter of "when" and "how". As such, the authors suggest that a hybrid AC/DC architectural approach may serve as a practical transitional pathway. Specifically, the authors suggest that a hybrid AC/DC architectural approach could include dedicated DC circuits for lighting, electronics, and EV charging as initial entry points. In order to realize the full potential of DCPD at the residential level, the authors believe that all relevant stakeholders must act in coordination. This includes the continuation of industry-wide standardization efforts through organizations such as the EMerge Alliance and IEEE, updates to the National Electric Code (NEC) related to DC protection, industry-wide commitments to design DC-native appliances, and policy incentives that acknowledge both the efficiency and resilience of DCPDs.

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