

CleanTech Blueprint for the Future



Coalition for Innovation, supported by LG NOVA

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The views and opinions expressed in the chapters and case studies that follow are those of the authors and do not necessarily reflect the views or positions of any entities they represent.

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October 2025



Preamble

The Coalition for Innovation is an initiative hosted by LG NOVA that creates the opportunity for innovators, entrepreneurs, and business leaders across sectors to come together to collaborate on important topics in technology to drive impact. The end goal: together we can leverage our collective knowledge to advance important work that drives positive impact in our communities and the world. The simple vision is that we can be stronger together and increase our individual and collective impact on the world through collaboration.

This “Blueprint for the Future” document (henceforth: “Blueprint”) defines a vision for the future through which technology innovation can improve the lives of people, their communities, and the planet. The goal is to lay out a vision and potentially provide the framework to start taking action in the areas of interest for the members of the Coalition. The chapters in this Blueprint are intended to be a “Big Tent” in which many diverse perspectives and interests and different approaches to impact can come together. Hence, the structure of the Blueprint is intended to be as inclusive as possible in which different chapters of the Blueprint focus on different topic areas, written by different authors with individual perspectives that may be less widely supported by the group.

Participation in the Coalition at large and authorship of the overall Blueprint document does not imply endorsement of the ideas of any specific chapter but rather acknowledges a contribution to the discussion and general engagement in the Coalition process that led to the publication of this Blueprint.

All contributors will be listed as “Authors” of the Blueprint in alphabetical order. The Co-Chairs for each Coalition will be listed as “Editors” also in alphabetical order. Authorship will include each individual author’s name along with optional title and optional organization at the author’s discretion.

Each chapter will list only the subset of participants that meaningfully contributed to that chapter. Authorship for chapters will be in rank order based on contribution: the first author(s) will have contributed the most, second author(s) second most, and so on. Equal contributions at each level will be listed as “Co-Authors”; if two or more authors contributed the most and contributed equally, they will be noted with an asterisk as “Co-First Authors”. If two authors contributed second-most and equally, they will be listed as “Co-Second Authors” and so on.

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The Coalition is intended to be a community-driven activity and where possible governance will be by majority vote of each domain group. Specifically, each Coalition will decide which topics are included as chapters by majority vote of the group. The approach is intended to be inclusive so we will ask that topics be included unless they are considered by the majority to be significantly out of scope.

We intend for the document to reach a broad, international audience, including:

- People involved in the three technology domains: CleanTech, AI, and HealthTech
- Researchers from academic and private institutions
- Investors
- Students
- Policy creators at the corporate level and all levels of government



Chapter 9:

Case Study: The Future is Direct – Shift to DC Power Systems

Author: Jiri Skopek

Introduction: The Future is Direct

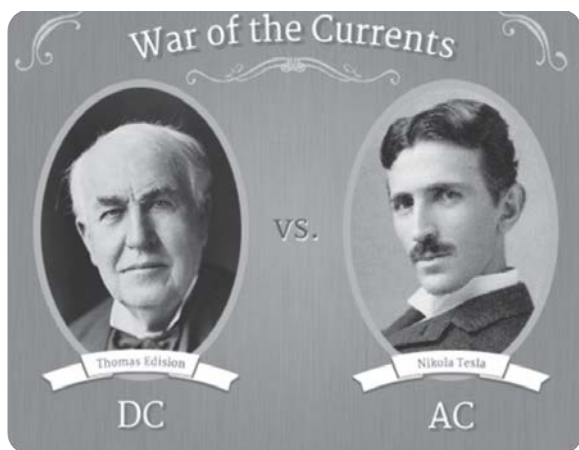


Figure 1: *The power struggle: more than a century after their iconic rivalry over AC and DC power, Tesla and Westinghouse emerged victorious. Now, as we need a more efficient and renewable energy future the time has arrived to reconsider the path we chose. [<https://princip.info/2014/03/12/tesla-protiv-edisona/>]. Public domain.]*

AC won the past, but DC is shaping the future.

For more than a century, alternating current (AC) has been the backbone of global power systems. Its ability to travel long distances efficiently secured its dominance during the 19th-century “War of Currents,” and it became the foundation of modern electrical infrastructure, supporting centralized

power plants, transmission lines, and city-wide grids.

But the way we generate and use electricity has changed dramatically.

Today, most modern devices, from smartphones and laptops to LED lighting, electric vehicles, and battery storage, run on direct current (DC). Solar panels also produce DC power. Yet, to integrate with the existing AC-based grid, this DC power must be converted to AC, transmitted, then often converted back to DC again for end-use. Each conversion wastes energy, often 5% to 20%, resulting in significant cumulative losses across the entire system.

The inefficiencies don’t end there. Our existing grid was built for centralized, predictable sources like coal, and nuclear plants. These sources provide stable “baseload” power but are slow to respond to fluctuations in demand. Quick adjustments typically come from gas-fired “peaker” plants, which are more flexible but less efficient and more carbon-intensive.

Meanwhile, the energy system is rapidly decentralizing. Rooftop solar, home batteries, electric vehicles, and smart appliances, most of them running on DC, are transforming homes and buildings into distributed power producers. Yet the grid still forces these technologies through layers of outdated AC infrastructure, creating friction and waste at nearly every turn.

This mismatch between how power is produced and how the grid is built introduces real costs. to homeowners, developers, businesses, and the environment. Our 20th-century grid was never designed for the solar panels, digital devices, and



electrified transportation systems of the 21st century.

The solution lies in grid-connected DC infrastructure that allows the direct use, storage, and distribution of DC power, cutting down on energy losses, reducing conversion costs, and improving overall system efficiency.

The Case for DC: Rethinking a Century-old Power Paradigm

Data centers are a clear example. These facilities, essential to cloud services, AI processing, and digital infrastructure, are among the most power-intensive buildings in the world. Despite running almost entirely on DC internally, they still receive AC power from the grid, requiring conversion at multiple stages. Each conversion layer introduces inefficiency, drives up operational costs, and increases heat load, requiring more cooling and further compounding energy use.

Switching to DC-based power architecture in data centers could cut conversion losses significantly, reduce infrastructure costs, and increase uptime through more efficient power management. Yet adoption remains limited, not because the technology is lacking, but because legacy infrastructure and outdated assumptions about AC compatibility still dominate engineering practice.

Utilities are under increasing strain from rising electricity demand. The electrification of transport, heating, and industrial processes, combined with widespread rooftop solar, has created new load patterns that the traditional grid wasn't designed to handle. Outages and reliability issues are already becoming more common in high-demand regions.

Building entirely new grid infrastructure is costly and time-consuming. In contrast, local DC systems reduce grid stress by allowing distributed resources, such as solar panels and batteries, to operate more efficiently, with fewer conversion losses and more flexible load management. These systems can be deployed at the building, campus, or neighborhood scale, reducing dependence on centralized infrastructure.

As reliability becomes a market differentiator, developers and energy users will increasingly prefer solutions that lower costs while enhancing energy autonomy. DC systems do both.

The Economic Impact for Developers and Businesses

Even when developers invest in renewable energy or smart infrastructure, much of the benefit is lost if systems are built on legacy AC assumptions.

For example:

- A new commercial development with rooftop solar may lose up to 20% of its generated energy through AC-DC-AC conversion before it reaches the building's LED lighting, HVAC controls, or server racks, all of which run on DC.
- A logistics hub installing EV chargers and battery storage may encounter higher-than-expected grid demand charges, due to inefficiencies in energy conversion and poor integration between systems.
- A corporate campus aiming for net-zero energy may fall short of targets, not because of inadequate generation, but because conversion losses and infrastructure constraints weren't accounted for in the original electrical design.

In each case, DC-based electrical systems could lower installation costs, reduce ongoing energy expenses, and enable smarter energy management, while supporting long-term sustainability and resilience goals.

A Strategic Infrastructure Shift

The transition to DC doesn't mean replacing the entire grid overnight. It starts with smart, modular integration such as:

- DC microgrids for buildings and campuses
- DC-ready zones in data centers, industrial sites, and transport hubs



- Plug-and-play integration of DC solar, batteries, and EV chargers without unnecessary conversion layers
- This approach is not only more efficient, it's more flexible, scalable, and future proof.

Energy Transmission

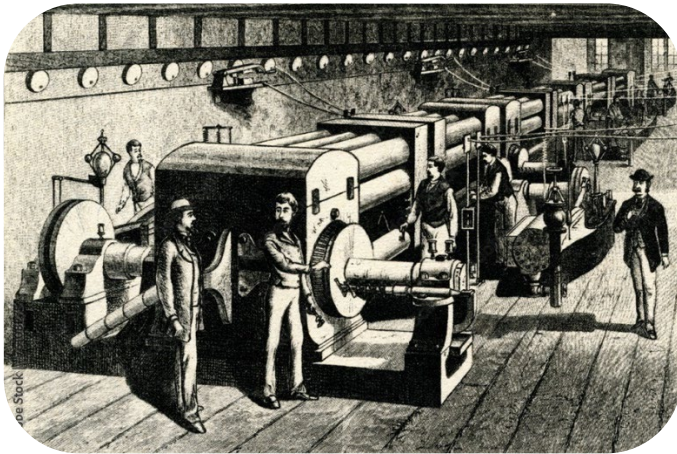


Figure 2: Pearl Street Station, was Thomas Edison's first commercial power plant. Opened in 1882 in Manhattan, it used coal-fueled dynamos. It initially powered 400 lamps for 82 customers expanding to 508 customers and over 10,000 lamps by 1884. [Wikicommons, Public Domain]

Early Transmission – The challenge was DISTANCE

In the early days of electricity use, the challenge was not just producing it, but how to effectively move it from central generation points to widespread users. With the growth of cities and industry, the need for centralized energy systems capable of supplying electricity across long distances became evident. This led to the birth of centralized energy systems, where large-scale power plants generated electricity and transmitted it via power lines to urban areas, factories, and households. As cities grew and industrialization demanded more power, the need for efficient transmission systems became urgent.

Both AC and DC used steam as their source, but DC was easier to generate from the steam than AC

because the dynamo generators used for DC were simpler. Generating AC required generators with alternators in order to oscillate the direction of the current, making AC generation more complicated and harder to set up at first.

Another key reason DC was initially chosen over AC, besides its comparative ease of generation, was its ability to provide steady, unidirectional current, which was ideal for applications like electric motors and early lighting systems. It could also be transmitted efficiently over short distances.

Meanwhile, AC's ability to generate and transmit power at higher voltages than DC was making it the ideal solution for emerging technologies like arc lamps for street lighting, industrial motors, and power plant alternators. Even before long-distance transmission was feasible, AC was powering localized grids, proving its scalability.

The real breakthrough, however, came with transformers, enabling efficient voltage conversion and securing AC's dominance in the 20th century.

AC Voltage Step-Up Won the Day by Solving the Problem of Distance

The solution to long-distance transmission was **AC's ability to change voltage levels using transformers**, which rely on oscillating electromagnetic induction to step-up or step-down voltage: something that wasn't possible with DC at the time.

By stepping up voltage for transmission, AC power could travel vast distances with minimal energy loss like using a high-pressure pipe to thrust a very narrow stream of water further with minimal friction. At the other end, transformers stepped the voltage back down to safe levels for homes and businesses, preventing electrical shock, equipment



damage, and fire hazards, while ensuring compatibility with everyday devices.

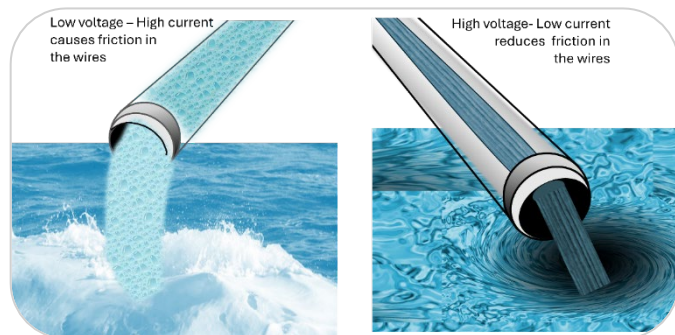
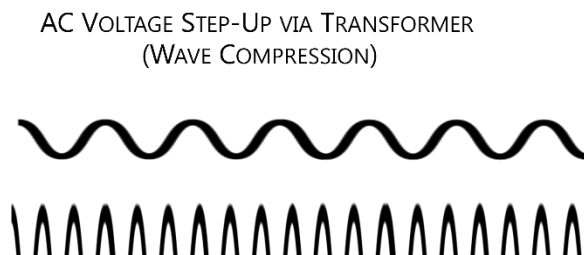


Figure 3: Power loss in electrical transmission occurs due to line resistance. To reduce losses, electricity is transformed and transmitted at high voltage and low current. A fluid dynamics analogy illustrates this:

A large, slow-moving water flow (high current, low voltage) in a pipe loses energy to friction, much like high-current transmission, where resistance causes heat losses. In contrast, a narrow, high-pressure jet (low current, high voltage) moves swiftly with minimal contact, retaining energy—akin to high-voltage transmission, which reduces resistive losses.

By increasing voltage and lowering current, long-distance transmission becomes more efficient, minimizing infrastructure needs and energy loss. This principle drives the use of high-voltage power lines in modern grids. [Image by J. Skopek]

Unlike high-voltage AC, which transmits power efficiently with lower current and minimal energy loss, DC suffered significant losses over long distances due to wire resistance. Westinghouse's development of the first commercially viable transformer in 1886 was a turning point, making



long-distance AC transmission practical and laying the foundation for the modern electrical grid.

AC has since become the standard for long-distance transmission. Passing through large transformers at substations, the high-voltage AC power from the transmission grid is then stepped down for distribution to homes and businesses.



Figure 4: Early transformer at the Amberley Chalk Pits Museum. The first Westinghouse step up voltage transformers were deployed at one of the earliest AC power plants, in Folsom, California in 1895. [Photo courtesy of David Blaikie on Flickr]

The Hum Problem: How Early Radios Revealed AC's Limitations

Despite its early success, AC was not without problems. AC's constantly reversing voltage was making it unsuitable for a growing list of applications that require a steady, uninterrupted current, such as modern electronics. This limitation first became evident in the early 20th century with

DC VOLTAGE STEP-UP VIA DC-DC CONVERTER
(PULSE CROWDING)



Figure 5: Two methods of voltage step-up. [Image by J. Skopek]



the advent of radio technology. Early vacuum tube radios required a steady power source, but when connected to AC, they produced an audible hum caused by the 50- or 60-Hertz oscillations that interfered with signal reception. Engineers developed rectifiers to convert AC into DC, a crucial innovation that paved the way for the widespread adoption of DC in electronics. Today, power adapters and internal circuits in most electronic devices still perform this conversion, highlighting the ongoing need for DC in a world powered primarily by AC grids.

DC-DC Converters: A Mid-20th Century Breakthrough in Efficient Voltage Control

For much of history, DC power could not be easily transformed to higher or lower voltages because traditional transformers rely on alternating magnetic fields requiring oscillating current that DC lacks. This limitation made AC the dominant choice for power transmission.

The breakthrough came in the mid-20th century with the development of **DC-DC converters**, which solved this problem by rapidly switching direct current **ON and OFF** at high frequencies. These pulses could then be manipulated using inductors, capacitors, and transistors to precisely step voltage up or down. Unlike traditional transformers, DC-DC converters were compact and offered fine-tuned control and high efficiency, making them essential for telecommunications, modern electronics, electric vehicles, and renewable energy systems.

Voltage Step-Up: How Transformers and DC-DC Converters Differ

AC Voltage Step-Up via Transformer (Wave Compression): The input AC waveform has a low amplitude and long wavelength. As it passes through a step-up transformer, electromagnetic induction increases the amplitude shortens the wavelength, thereby producing higher voltage,

DC Voltage Step-Up via DC-DC Converter (Pulse Crowding): The input DC is shown as a steady line. A DC-DC converter rapidly switches the current on and off, storing and releasing energy in bursts. This

results in an output with higher voltage, represented by closely spaced, taller pulses.

By enabling precise voltage regulation, DC-DC converters paved the way for compact, energy-efficient power supplies, reducing waste and enhancing performance across consumer, industrial, and aerospace applications. Their impact extended far beyond electronics supporting the rise of electric vehicles, solar energy, and battery storage, where voltage control is critical for system stability and efficiency.

Crucially, it is the increasing demand for DC power — from devices, vehicles, and distributed renewable systems — that will drive the gradual transformation of the electrical grid. Rather than a top-down shift led by supply and transmission institutions, the grid will evolve away from a centralized, high-voltage AC-dominated system towards a more flexible, distributed hybrid AC-DC network, better suited to modern energy needs.

Keeping the Grid in Sync: AC's Biggest Challenge

Despite AC's efficiency, for transmission from power station to consumer, it presents challenges, particularly in complex, long-distance grid systems. One major issue is **phase synchronization**. Since AC voltage reverses direction 50 or 60 times per second (Hertz), different sections of the grid can fall out of sync. This is akin to people pushing swings at different times; rather than maintaining smooth harmonized motion, their efforts interfere, which leads to energy loss and grid instability. To mitigate this, power systems rely on advanced grid management, substation synchronization technology, and phase correction equipment to maintain stability and efficiency.

High-voltage DC Has Solved the Problem of Long-distance Transmission and Cross-region Grid Integration

High Voltage Direct Current (HVDC) technology, developed in the 1950s, transformed long-distance



power transmission by overcoming the phase synchronization limitations of AC systems.

Unlike AC, HVDC transmits electricity as a steady, one-directional flow, eliminating phase synchronization issues. This is more efficient for long distances due to lower electrical losses compared to HVAC (High Voltage Alternating Current). It also allows for better control and stability of power flow, especially when integrating renewable energy sources.

HVDC is especially useful for connecting grids across regions or under oceans, where maintaining AC phase alignment would be nearly impossible. By minimizing energy losses, it has become the preferred choice for some of the world's longest transmission routes, shaping the future of global power distribution.



Figure 6 - Long distance High Voltage Direct Current (HVDC) lines carrying [hydroelectricity](#) from Canada's [Nelson River](#) to a [converter station](#) where it is converted to AC for use in southern [Manitoba's](#) grid. [Wikimedia. Photo by J. Lindsay, CC BY-SA 3.0]

The Future of DC: Driven by Demand, Not Utilities

Why Utilities Won't Lead the Shift to DC

Despite the increasing advantages of DC power, a large-scale transition to a DC-based grid is unlikely to be initiated by the power and transmission industry. The existing electrical grid is deeply entrenched in AC infrastructure and converting it to DC would require a complete overhaul from rewiring transmission lines to redesigning substations and replacing countless transformers. Such an endeavor would be prohibitively expensive, making it an unattractive proposition for utilities that prioritize cost-efficiency and grid stability.

Rather than spearheading a fundamental shift, utilities are more likely to maintain and optimize the AC grid they have already built. The financial and logistical challenges of converting an entire transmission system outweigh the potential benefits, at least from their perspective. For now, AC remains the backbone of large-scale power distribution, and there is little incentive for utilities to disrupt that model.

A Demand-Driven Evolution

Instead of being dictated from the top down, the shift toward DC power will come from the demand side. Grid challenges include balancing variable electricity supply (such as from wind, solar, or tidal energy), rising peak demand, and integrating climate-sensitive technologies. Peaks in supply and demand are getting more complicated, and the pace of change is too fast. Our old infrastructure is struggling to stay reliable, but power outages amplified by climate change are becoming a reality.

The evolution of energy needs, and the advent of new technologies are constantly challenging the status quo. As the demand for more efficient, reliable, and sustainable power systems grows, the potential for DC technology becomes more apparent. Industries and consumers that require stable, efficient power are already driving the change, prioritizing DC for its ability to eliminate energy losses from constant AC-DC conversion. Data centers, AI computing facilities, and industrial automation rely heavily on



DC power, and as these sectors grow, so too does the need for direct DC supply.

Electric vehicles add further momentum to this transition. Since EV batteries operate on DC, charging them directly without AC conversion is both more efficient and cost-effective. Meanwhile, the rise of renewable energy sources such as solar and battery storage—both of which naturally generate DC—reinforces the argument for broader DC adoption. The more these technologies expand, the more practical it becomes to integrate DC systems at a local level rather than converting everything to fit within an AC-dominated grid.

Rethinking the Grid: Centralized, Distributed, and Hybrid

Distributed Systems: Microgrids and Nanogrids

As the limitations of centralized power grids become more evident, distributed energy systems, such as microgrids and nanogrids are emerging as flexible and efficient alternatives, offering greater resilience, improved energy efficiency, and reduced reliance on large, centralized infrastructures.

Rather than attempting to replace the AC grid outright, the most viable path forward is likely to be through microgrids and nanogrids—localized energy networks that supply DC power where it is needed most.

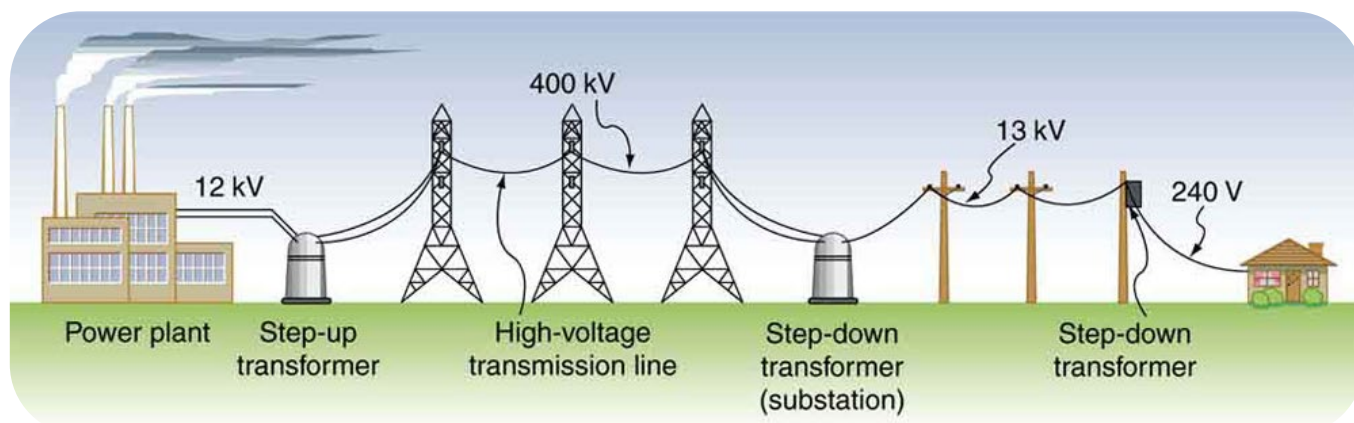


Figure 7: The Problem with AC: On the left is a power plant connected to a step-up transformer via a 12 kV line. The transformer links to a 400 kV high-voltage transmission line, which connects to a step-down transformer at a substation. From there, a 13 kV line goes to a further step-down transformer on an electric pole, and a 240 V line delivers power to a house. The high-voltage transmission line enables low-current transmission over long distances. However, each step-up and step-down introduces energy losses, making the overall system less efficient. Plus, the reliance on multiple transformers increases the complexity and cost of the infrastructure. [Imagine Public Domain <https://www.collegesidekick.com/study-guides/physics/23-7-transformers/>]



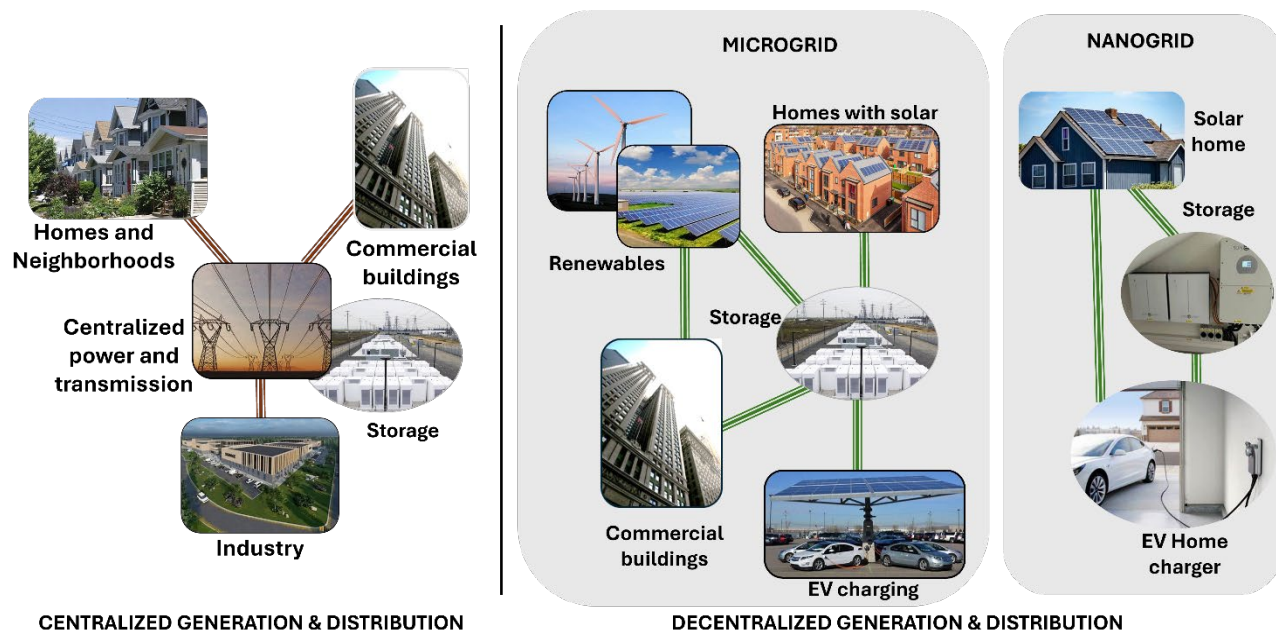


Figure 8: Showing the difference between Centralized and Distributed Systems [Image by J. Skopek]

Microgrids: Localized Power Solutions

Microgrids are self-contained energy systems that can operate independently or in tandem with the grid. These systems generate, store, and distribute electricity to specific areas such as communities, universities, and industrial sites. By integrating renewable energy sources like solar panels, wind turbines, and battery storage, microgrids enhance efficiency and reduce energy loss.

A notable advantage of microgrids is their ability to use both DC and alternating current (AC). Many modern devices—such as LED lights, computers, and electric vehicles—use DC power, and microgrids leverage this to minimize energy losses from AC-to-DC conversions. This dual approach increases the overall efficiency of the system.

Microgrids, integrate renewable energy and energy storage; they can serve industrial hubs, commercial centers, and even entire campuses, minimizing reliance on the traditional AC grid. They are particularly useful in areas where centralized grids are unstable or unavailable, such as remote communities, military bases, and rural regions. They also support urban grid stability by integrating

renewable sources and storing energy, which helps reduce peak demand

Nanogrids: Energy Control at the Individual Level

Nanogrids: DC power systems within buildings take the concept of distributed energy a step further by offering even more localized control, suitable for individual buildings. These systems allow users to generate, store, and manage their own electricity, often by incorporating renewable energy sources like solar panels and storage batteries and allow for direct connections to devices, eliminating inefficiencies associated with conversion.

Nanogrids, equipped with automated controls can manage consumers' energy usage, deciding when and where to use energy most efficiently, and providing them with greater autonomy and contributing to a broader shift toward distributed energy systems.

The Future Energy Landscape

While AC transmission will continue to dominate large-scale power distribution, the steady rise of



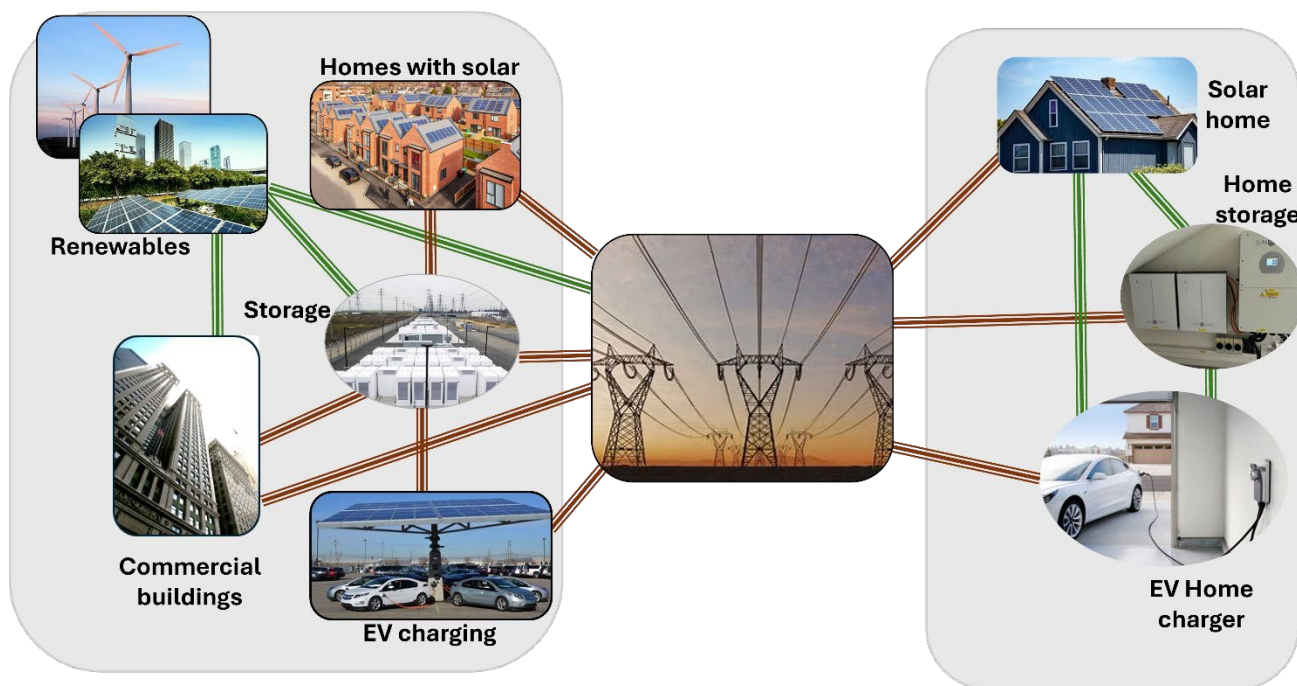


Figure 9: *Hybrid Centralized & Decentralized Generation & Distribution [Image by J. Skopek]*

microgrids and nanogrids will gradually reshape the energy landscape. More industries will turn to DC to meet their efficiency and stability requirements, and as adoption grows, it will become an increasingly integral part of modern energy systems. Engaging end users in grid operations can also enhance responsiveness and efficiency in energy consumption.

This transition will not happen overnight, nor will it be propelled by utilities. Instead, it will emerge organically, driven by industries and consumers seeking better power solutions. Over time, the energy sector will shift toward a hybrid model, where DC plays a significant role alongside AC, challenging the traditional dominance of alternating current and redefining how power is generated, distributed, and consumed.

The Hybrid Approach to Energy Transmission Offers Resilience and Sustainability

As distributed systems have gained momentum, they do not signal the end of centralized grids but rather the beginning of a hybrid approach. Digital grids, which use digital technology to monitor and optimize electricity distribution, are allowing for more efficient integration of both centralized and distributed systems. By using sensors, data analytics, and real-time communication, digital grids enable power to flow smoothly from both large plants and localized renewable sources.



Energy Storage: Stabilizing the Hybrid Grid and Introducing Flexibility

Energy storage technologies, such as long-term thermal storage systems (LTES) or large-scale batteries, are essential to hybrid grid systems. They store excess energy from renewable, nuclear or hydro generated surplus power during low-demand periods, making it available in response to peak demand or when renewable output is low. This balances supply and demand, ensuring that both distributed and centralized grids remain reliable and efficient.

As energy demands grow and the shift toward renewable sources accelerates, the grid must evolve into a more flexible, sustainable system. Technologies such as digital grids, energy storage, and distributed generation will work in concert to ensure reliability and resilience. The hybrid approach—combining centralized and distributed systems with advanced storage—will shape a future where energy is more accessible, efficient, and renewable.

From the early days of DC to the rise of AC, the technology enabling HVDC, distributed systems, and energy transmission has continually evolved. Now, integrating energy storage solutions into the grid will be key to building a resilient energy future, where consumers and producers collaborate to meet the challenges of the modern world.

The most common energy storage systems include battery storage, such as the Lithium-ion Batteries commonly used in electric vehicles, residential energy storage and grid-scale applications or Flow Batteries, that are typically used for grid-level storage due to their scalability, long lifespan, and capacity for deep cycling. Increasingly other energy storage systems are being used such as Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage (CAES) and Thermal Energy Storage (TES), which can store energy as heat or cold (molten salt or ice) and then convert the stored heat back to electricity.

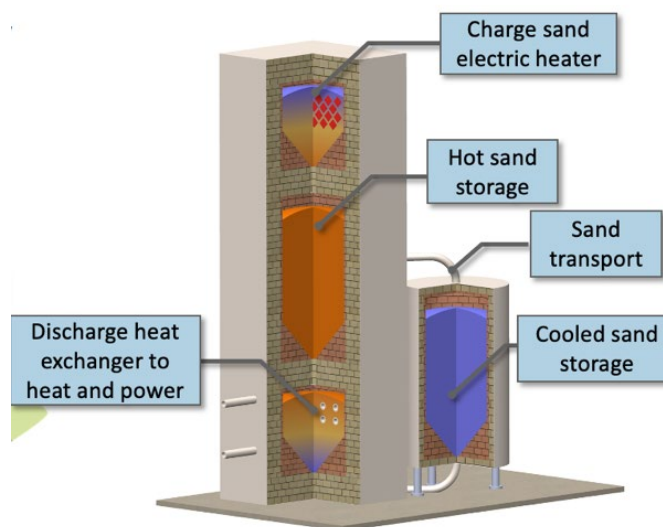


Figure 10: *Thermal Energy Storage: Drop-in modular (40' container) 1-10 Mwe heat/power, < 100 Mht storage for heat/power supply [Image courtesy of NREL]*

Energy storage systems can help stabilize the grid by reducing the strain during peak hours. By storing excess renewable energy—whether from solar, wind, or off-peak nuclear generation in their localized batteries—these systems can use that power when demand on the grid is at its highest. If large industries do this, they avoid drawing on the grid, which minimize the need for fossil-fuel-based peaking plants. This *load shifting* effect makes energy supply more predictable and cost-effective.

Enhancing Grid Resilience

Localized microgrids and nanogrids act as buffers against grid failures. In the event of power outages or disruptions, they can operate independently, ensuring critical facilities maintain power. By reducing reliance on long-distance transmission and providing backup capacity, they make the overall grid more adaptable to fluctuations in supply and demand.



A Smarter, More Adaptive Energy System

The future of energy will not be a choice between centralized and distributed systems but a hybrid model in which microgrids, nanogrids, and energy storage work in tandem with traditional infrastructure. This approach enhances efficiency, lowers costs, and makes the grid more resilient to both sudden demand spikes and long-term shifts in energy consumption.

Digital Grids

A **digital grid** is an advanced energy network that seamlessly integrates **electricity transmission and data communication**, making power distribution more efficient, reliable, and adaptable. Unlike traditional power grids, which deliver electricity in a one-way flow from power plants to consumers, digital grids **deliver electricity** with added layers of **digital intelligence, communication technologies, and automation** that make the system more **efficient, resilient, and responsive**. There are several advantages to digital grids:

Improved Efficiency: Smart grids allow for more efficient electricity distribution by enabling utilities to manage energy flow in real-time. For instance, if there is an issue with the transmission of power to a certain area, the smart grid can automatically reroute the electricity from other sources or alert utility operators to take corrective action. This reduces energy losses, which can occur during transmission and distribution, and ensures that energy is used where it is needed most.

Integration of Renewable Energy: One of the key advantages of smart grids is their ability to integrate renewable energy sources, such as wind and solar, into the grid. By using energy storage systems and dynamic load balancing, smart grids can help mitigate the challenges of intermittency that come with renewable energy generation. This not only helps in reducing dependency on fossil fuels but also accelerates the transition to a low-carbon economy.

Enhanced Reliability: Smart grids can improve the reliability of electricity supply by reducing the frequency and duration of power outages. They can detect faults in the system quickly and isolate the affected areas to prevent widespread disruptions. In some cases, smart grids can even automatically restore power to customers without requiring human intervention.

Cost Savings for Consumers: Through dynamic pricing and demand response programs, consumers can reduce their energy costs. Digital Grids enable real-time pricing, where electricity prices fluctuate based on demand and supply. Consumers who adjust their usage during off-peak hours can take advantage of lower rates. Additionally, the increased efficiency and reduced operational costs for utilities may result in lower electricity bills for consumers.

Environmental Benefits: By enabling more efficient use of energy and promoting the use of renewable sources, Digital Grids can help reduce greenhouse gas emissions. The ability to manage energy consumption more effectively means that power plants don't need to produce as much electricity from fossil fuels, leading to a cleaner, more sustainable energy system.

Consumer Empowerment: Digital Grids give consumers more control over their electricity usage. Through apps and smart devices, consumers can monitor and manage their energy consumption in real-time, allowing them to make informed decisions about when and how much electricity to use. This level of control can lead to greater energy conservation and lower overall costs.



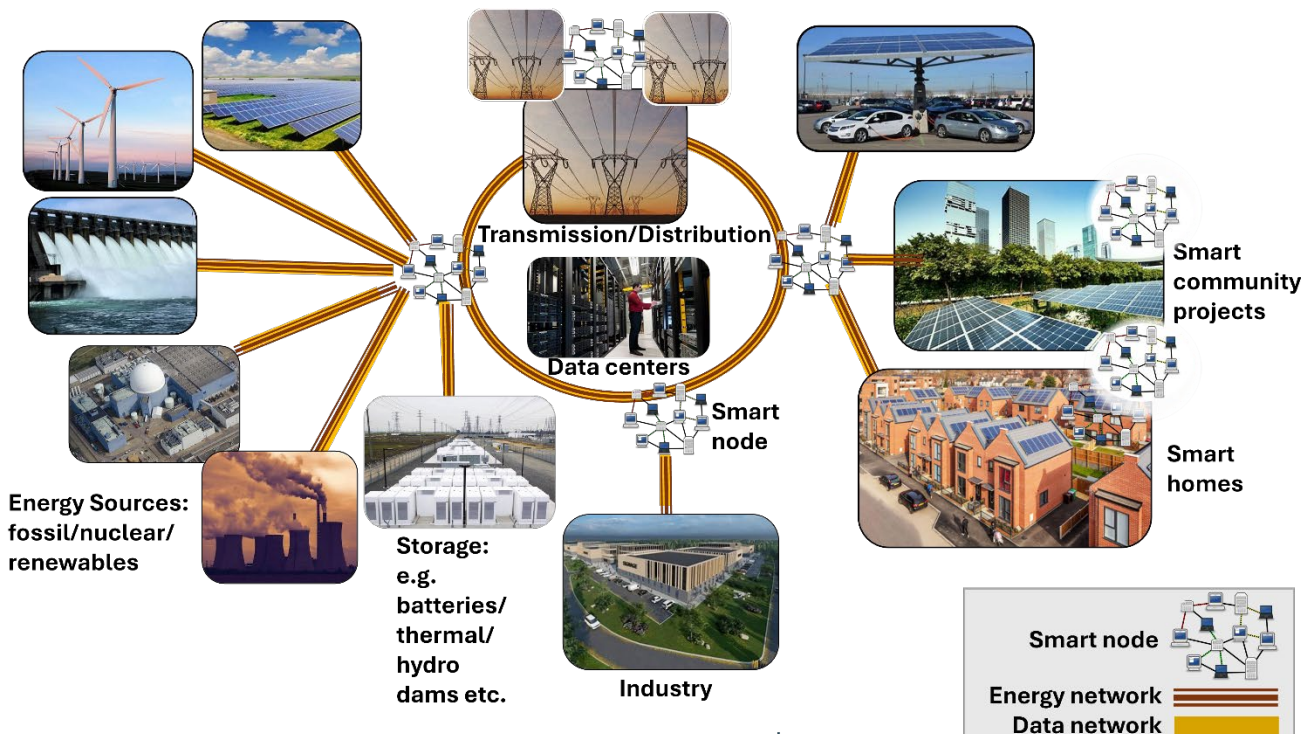


Figure 11: Digital Grids combine energy and data networks using smart nodes [Image by J. Skopek]

How Energy and Data are Transmitted

The Energy Network delivers electricity through transmission lines (either AC or DC) to homes, businesses, and devices

Data Networks transmit information about the grid, such as energy usage and system performance, using various technologies – both wired and wireless.

- **Wired methods** include fiber optic or Ethernet cables, which carry data over long distances. These physical cables offer fast, reliable connections, particularly in areas where wireless signals might not be ideal.
- **Wireless methods** include cellular networks (4G, 5G), Wi-Fi, and satellite communication. These technologies use radio waves to transmit data without the need for physical wires. They enable Digital Grids to efficiently manage energy use, monitor equipment, and exchange real-time data, all without the need for extensive (and potentially expensive) wiring.

- **Cellular networks** (such as 4G or 5G) send data via radio waves through mobile towers. These networks are ideal for long-distance communication, even in remote areas, with 5G offering faster speeds and better handling of multiple devices than 4G.
- **Wi-Fi** works for shorter distances, such as in homes or offices, providing local but reliable communication.
- **Satellite communication** is used for remote or off-grid areas where other wireless technologies may not reach. It transmits data via radio waves or microwave signals between ground stations and satellites in orbit, ensuring reliable data transfer across vast distances.

The Role of Data in Digital Grids

Digital Grids rely on real-time data exchange to balance supply and demand. Advanced smart meters in businesses and homes track energy usage



in minute intervals and communicate this data to utility companies. Grid operators also receive weather forecasts, solar and wind generation levels, grid congestion alerts, and power outage reports. For example:

- If solar power generation drops due to cloud cover, the grid automatically compensates by drawing energy from battery storage or ramping up fossil fuel plants.
- If a heatwave causes a surge in electricity demand, industries may receive an alert to temporarily reduce non-essential energy use, while stored energy from wind farms is directed to high-demand areas.
- During a power outage, the grid pinpoints the affected area and reroutes electricity from nearby substations, restoring power faster than conventional grids.

Demand Response & Consumer Participation

One of the Digital Grid's most powerful features is demand response, which actively manages consumption to prevent overloading. Consumers can opt into programs that adjust energy use based on grid conditions. For instance:

- Smart thermostats can lower heating or air conditioning use during peak hours, reducing strain on the grid.
- Electric vehicles (EVs) can be programmed to charge overnight when electricity demand is often lower.
- Operators of commercial buildings, factories and data centers can receive incentives to temporarily scale back energy-intensive operations during peak hours.

By integrating real-time monitoring, automated controls, and predictive **analytics**, Digital Grids create a resilient, cost-effective, and sustainable energy system, helping societies transition toward cleaner and smarter power solutions.

Power Meets Intelligence: Elements of Combined Energy-Data Networks

Energy Sources: The Backbone of the System

Energy networks rely on both renewable (solar, wind, hydro) and non-renewable (coal, gas, nuclear) sources to supply electricity. Renewable energy is gaining momentum, with projects like [Denmark's Energinet](#), which integrates wind and solar power with Digital Grids, reducing reliance on fossil fuels.

Transmission & Distribution: Keeping the Flow Steady

High-voltage transmission lines and local distribution networks ensure electricity moves efficiently. The alternative shift from AC (Alternating Current) to DC (Direct Current) transmission can be more efficient, especially for long-distance power transfer.

Data Centers: The Digital Powerhouses

Data centers require massive amount of power to process massive the enormous amounts of information from energy networks. Some, like [Google's Hamina Data Center in Finland](#), are powered by renewable energy and use seawater cooling to improve efficiency. Additionally, many data centers are increasingly adopting DC power systems, reducing conversion losses, and improving energy efficiency.

Smart Communities: The Local Energy Revolution

Cities and towns are becoming smarter by integrating energy-efficient buildings, shared solar projects, and AI-driven energy management. [The Fujisawa Smart Town](#) in Japan is a model, where homes, businesses, and infrastructure share solar energy and battery storage, creating a self-sustaining ecosystem. Many such smart communities are integrating DC microgrids,



allowing direct use of solar and battery-stored power without conversion losses.

Smart Homes: The Consumer's Role

Homeowners play a part by using smart meters, solar panels, and connected appliances to optimize energy consumption. In the Netherlands, the [PowerMatching City](#) project allows households to trade excess energy from one home to another automatically, reducing strain on the grid. With more DC-powered appliances and home battery systems, efficiency is further enhanced by reducing AC/DC conversion steps.

Large-Scale Storage: Balancing Supply and Demand

Energy storage solutions like batteries, pumped hydro, and thermal storage help balance fluctuations in renewable energy. [Hornsedale Power Reserve](#) in Australia, a giant battery storage facility, has significantly improved grid stability and lowered costs. Large-scale battery storage systems inherently operate on DC power, enabling seamless integration with renewable energy sources and DC microgrids.

Data Nodes: The System's Nervous System

Sensors and data nodes are spread throughout the network to track energy flow, predict demand, and detect outages. The UK's National Grid ESO uses AI-driven data analysis to balance supply and demand in real time, improving efficiency and preventing blackouts. Many of these monitoring and control systems are now powered by DC microgrids, reducing energy waste, and increasing resilience.

A Future of Intelligent Energy

By merging energy and data networks, we create a resilient, efficient, and sustainable power system. With real-time monitoring, smart distribution, and data-driven decision-making, the future of energy is not just renewable; it's intelligent and increasingly DC-powered, ensuring minimal energy loss and optimal efficiency.

Where Digital Grids Are Used:

Digital Grids are being deployed worldwide, with many countries and regions investing in the technology to modernize their aging power infrastructure. The United States, Europe, and China are among the leaders in implementing Digital Grid technologies, but smaller regions and developing nations are also adopting them as part of their efforts to build more sustainable and resilient energy systems.

In the U.S., the Department of Energy has provided funding to accelerate the [deployment of Digital Grids](#), particularly in cities and states looking to reduce carbon emissions and integrate more renewable energy. Cities like San Diego, New York, and [Chattanooga](#) have implemented Digital Grid technologies with varying degrees of success. San Diego, for example, uses Digital Grid technology to integrate solar power with the grid, while New York focuses on improving the resilience of the electrical network to reduce outages during storms.

In Europe, countries like Denmark, Germany, and the Netherlands have made significant investments in Digital Grid technologies, using them to integrate wind energy and create a more efficient and sustainable energy network. Germany's [Energiewende](#) (Energy Transition) policy is an example of a national strategy that incorporates Digital Grids to reduce carbon emissions and promote renewable energy.

The most recent innovations in digital grid technology reflect a convergence of AI, real-time analytics, modular hardware, and regulatory momentum, altogether driving smarter, safer, and more flexible energy systems. By integrating advanced communication technologies, renewable energy sources, and real-time data analytics, Digital



Grids are reshaping how electricity is distributed, consumed, and managed. The benefits are clear: from enhanced reliability and cost savings to environmental sustainability and consumer empowerment, Digital Grids are poised to play a crucial role in the future. Whether in North America, Europe, or Australia, the smart, digital grid revolution is in motion.

Commercial Buildings in the Era of DC

High-Performance Buildings: The Shift to Smarter, DC-Powered Spaces

Buildings today must do more than provide shelter; they must be energy-efficient, resilient, intelligent, and secure. The drive for high-performance buildings is accelerating, fueled by global challenges and technological advancements:

- Combating climate change
- Achieving sustainability and net-zero targets
- Ensuring reliable, resilient power
- Strengthening cybersecurity and energy security
- Enhancing occupant wellness and productivity

DC Power - A Key Innovation in the Transition to Smart Buildings

With more buildings integrating solar panels, battery storage, and energy-efficient systems like LED lighting and smart controls—all of which natively use DC—there's an alternative to traditional AC grids. By reducing the need for AC-DC conversions, buildings can achieve greater energy efficiency, lower costs, and improved reliability. Smart buildings leveraging DC microgrids are paving the way for a more sustainable, flexible, and future proof-built environment.



Figure 12: Sinclair Digital contributed to improving the energy efficiency of the Sinclair Hotel in Fort Worth by utilizing DC power and Ethernet cable technology instead of traditional electrical cords and wiring to connect devices such as lights, smart mirrors, and mini refrigerators. [Courtesy of Sinclair Digital]

Beyond Automation: The INTELLIGENCE of Smart Buildings

A Building Automation System (BAS), aka Building Management System (BMS), traditionally controls mechanical and electrical systems such as HVAC, lighting, and security. However, true smart buildings go beyond automation:

System of Systems & DC Integration –A smart building's foundation lies in its interconnected systems—lighting, HVAC, security, and power—designed to work with common protocols. DC microgrids are emerging as a core component, reducing conversion losses in integrating solar power, battery storage, and DC-powered devices.

Seamless Connectivity – Web-based middleware enables systems to share real-time data, allowing intelligent decision-making. DC-based power distribution simplifies wiring and enhances the efficiency of connected systems.

Enterprise-Level Management – Occupants can personalize environments, such as adjusting lighting or temperature via apps. Energy-efficient



DC systems provide greater flexibility, enabling dynamic load management and cost savings.

Key Components of a Smart Building

Advancements in sensor technology and IoT-driven analytics have transformed building management. With more devices natively operating on DC, reducing AC-DC conversion steps leads to measurable energy savings. Smart buildings typically integrate:

- **DC-powered LED lighting** with sensors that adjust brightness based on occupancy and daylight levels.
- **HVAC systems** optimized with machine learning to predict usage patterns.
- **On-site renewable energy**—such as solar PV panels—delivering DC power directly to devices, bypassing inefficient AC conversion.
- **Battery or thermal storage** that smooth power demand and reduce reliance on the grid.
- **Building-wide data networks** supporting energy-efficient DC loads, reducing energy waste.

Safeguarding AC and DC Grids from Cyber Threats

The security of electrical grids — whether using AC or DC — remains a critical concern as power systems become increasingly digitized and interconnected. Recent reports indicate a 70% surge in cyberattacks on U.S. utilities in 2024, attributed to the rapid expansion and digitalization of the power grid

Industrial control systems (ICS) manage power plants, substations, and renewable energy infrastructure. These systems are particularly vulnerable to cyberattacks that can disrupt electricity supply, damage equipment, and pose significant physical risks. For instance, the FBI has highlighted that malicious actors could target operational technology (OT) software and hardware, such as inverters in solar panel systems, to gain unauthorized control.

AC grids, predominant in long-distance power transmission, rely on precise synchronization between substations. Cyberattacks manipulating frequency regulation or phase synchronization could trigger cascading failures, leading to extensive blackouts. Conversely, DC power systems, employed in HVDC transmission, battery storage, and renewable energy applications, face risks from software vulnerabilities in power management systems and targeted attacks on inverters that convert DC to AC power.

To safeguard these systems, a proactive cybersecurity strategy is essential, incorporating measures such as network segmentation, encryption, and robust authentication protocols.

Key Security Measures for Power Systems

Network Segmentation: Traditional power grids operate as extensive, interconnected networks. A breach in one segment can allow attackers to move laterally to adjacent segment, causing widespread disruptions. Implementing network segmentation divides the grid into smaller, isolated sections separated by firewalls and access controls. This compartmentalization ensures that even if one segment is compromised, the rest of the system remains secure. Critical infrastructure control systems, such as those for transformers and substations, should be isolated from less critical systems to prevent unauthorized access to core operations.

Encryption: Power systems depend on continuous data flow between substations, sensors, and control centers. Intercepted or altered data can be exploited to manipulate grid performance, shut down substations, or induce unsafe power fluctuations. Employing strong encryption protocols, like the Advanced Encryption Standard (AES), secures data transmission and storage, ensuring that only authorized entities can access and interpret critical information.

Robust Authentication Protocols: Traditional username-password authentication methods are inadequate for modern power networks. Implementing multi-factor authentication (MFA) requires multiple verification forms before granting



access. For example, a technician might need to enter a password as well as provide biometric verification, or a one-time code sent to a secure device. Certificate-based authentication, where users and devices present cryptographic certificates before system access, further reduces the risk of identity theft and unauthorized entry into critical grid components.

Securing Distributed Power Systems

Microgrids — small, localized energy networks often relying on DC power — are gaining popularity due to their resilience and ability to operate independently from the main grid. While they enhance energy security and facilitate greater renewable energy adoption, they also introduce unique cybersecurity challenges. Many microgrids incorporate smart controllers, IoT-connected sensors, and energy storage systems, all potential targets for cyberattacks.

To bolster microgrid security, the following measures are essential:

Zero-Trust Architecture: In a zero-trust model, every user and device must be authenticated and verified before receiving access, regardless of their network location. This approach ensures that even if an attacker breaches one segment, they cannot move laterally to access critical infrastructure.

Secure Communication Channels: Implementing encrypted communication protocols safeguards data exchanges between energy management systems, battery storage units, and inverters. Encrypted channels prevent attackers from intercepting or manipulating operational data.

Automated Threat Detection: Utilizing artificial intelligence (AI) and machine learning algorithms enables real-time monitoring of microgrid operations, detecting anomalies such as unauthorized access attempts or unexpected power flow changes. These automated systems can respond swiftly to potential threats, mitigating damage before escalation.

Physical Security Measures: Microgrid infrastructure, often located in accessible areas, is susceptible to physical tampering. Implementing

security measures such as surveillance cameras, biometric access controls, and tamper-proof enclosures help protect critical hardware from physical attacks.

Regular Software Updates and Patching: Many cyberattacks exploit known vulnerabilities in outdated software. Regularly updating and patching microgrid controllers, IoT devices, and energy management systems is crucial to close security gaps and protect against evolving threats.

As power systems continue to evolve, integrating these security measures is vital to safeguarding both large-scale grids and smaller, distributed energy networks. Adopting a multi-layered defense strategy enables utilities and operators to enhance the safety, reliability, and resilience of the electrical infrastructure upon which modern society depends.

Powering the Future: Industrial and Commercial Microgrids



Figure 13: U.S. Department of Energy Microgrid Workshop with Micro Grid demo in the NREL's ESIF Control room: January 2019 [Flicker Public domain. Image by NREL]

As energy demands rise across industries, large-scale facilities are turning to microgrids to ensure resilience, efficiency, and sustainability. While microgrids are most prevalent in industrial settings — where energy independence and cost savings are critical — they are also gaining traction in data



centers, which require uninterrupted, high-density power.

Industries that benefit most from DC microgrids include:

- **Data centers**, where servers, cooling systems, and backup batteries all operate on DC power.
- **Semiconductor manufacturing**, which requires ultra-stable, high-quality power
- **Electric vehicle (EV) manufacturing and charging stations**, as EVs run on DC power.
- **Aerospace and defense facilities**, where uninterrupted, high-efficiency power is mission-critical.
- **Advanced manufacturing plants**, especially those using robotics and automation, which are often DC-powered.

Examples of Microgrids in Industrial and Hi-Tech Installations

Some industrial sites are in remote areas with unreliable grid access. Combined heat and power (CHP) systems or renewable microgrids can enhance efficiency and reduce operational costs. Some governments incentivize industrial microgrids, especially in heavy manufacturing and mining, which helps drive adoption. From automotive logistics hubs to hyperscale data centers, the following are notable case studies of microgrids in industrial and commercial installations, that show their growing role in ensuring a reliable and sustainable energy future.

Mining & Natural Resources

Rio Tinto (Australia) – Uses [renewable microgrids](#) to power remote mining operations, reducing reliance on diesel generators.

BHP (Australia) – Implemented [microgrids with solar and battery storage](#) at several mines to cut emissions and improve energy security.

Newmont Corporation (U.S.) – [Uses solar microgrids in off-grid mining locations](#) to lower costs and carbon footprints.

Oil & Gas

Shell – Deploys [microgrids at refineries and offshore drilling sites](#) to reduce emissions and improve operational efficiency.

ExxonMobil – Uses [wind power and microgrids at remote production sites](#) to ensure reliable power supply.

Manufacturing & Heavy Industry

ArcelorMittal – Integrated [microgrids into steel production facilities](#) to optimize energy use and increase sustainability.

Schneider Electric – While a microgrid solutions provider, it also [uses them at its own manufacturing plants](#) for energy resilience.

Tesla – [Runs its Gigafactories on renewable microgrids](#), reducing dependence on traditional grid.

Commercial & Retail

Walmart – Uses [microgrids with solar and battery storage](#) at several locations to reduce energy costs and provide backup power.

IKEA – Implemented [microgrids at distribution centers and stores](#) to align with its renewable energy goals.

Transportation & Logistics

Port of Los Angeles – Uses [microgrids to power operations](#) with clean energy and reduce emissions from shipping activities.

UPS – Invested in [microgrids for logistics hubs](#) to support electric vehicle (EV) charging and operational resilience

Honda's North American Parts Distribution Center, one of [North America's largest DC microgrids](#), supplies 300 kW of solar power directly to LED lighting, ventilation systems, and forklift charging stations, reducing conversion losses and improving operational efficiency.



Tech Companies

As data centers consume vast amounts of energy and require **24/7 power reliability** major tech companies are turning to microgrids for added protection against grid failures. While they still rely on **grid power with fossil fuel backup**, the rising use of **renewable energy sources** in hyperscale data centers and the shift toward **sustainability goals** among cloud and colocation providers is marking a gradual shift. Some of the most ambitious projects are led by industry giants, each with a unique approach to integrating renewable energy.

Google has entered a \$20 billion partnership with Intersect Power and TPG Rise Climate to develop [gigawatts of data center capacity powered by adjacent renewable energy plants](#). This initiative, aimed at supporting AI-driven workloads, reflects Google's long-term commitment to clean energy. Notably, Google's Hamina data center in Finland runs on wind energy and is cooled by seawater from the Baltic, reducing both its carbon footprint and cooling costs.

Amazon Web Services (AWS) is taking a different approach by [proposing direct connections between its data centers and power plants](#). One key example is its plan to source energy from the Susquehanna nuclear plant in Pennsylvania. This ensures grid independence and reliable energy access, particularly as AI and cloud computing increase energy demands.

Microsoft has been [experimenting with microgrids](#) at various sites, including its Quincy, Washington, facility, which integrates fuel cells and battery storage. The company has also tested underwater data centers, such as Project Natick, to reduce energy use and cooling costs.

Meta (formerly Facebook) has [committed to fully renewable-powered data centers](#), such as its facility in Prineville, Oregon, that operates on a microgrid combining solar and wind energy with advanced battery storage.

Apple has long been a leader in sustainability, [powering its data centers with on-site solar farms and battery storage](#). Its Reno, Nevada, facility is one of the largest to operate entirely on renewable

energy, reinforcing Apple's goal of achieving carbon neutrality across its operations.

Switch's Citadel Campus in Nevada boasts one of the [world's largest data center microgrids](#), drawing power from a massive solar array. This facility, designed to withstand natural disasters, showcases how microgrids can provide both resilience and sustainability.

These case studies illustrate the diverse strategies employed by tech giants to secure reliable, independent, and sustainable power for their data centers.

DC Power in Homes

Pilot projects, such as Purdue University's nano-grid home, demonstrate how a full-DC setup can function efficiently with solar power and battery storage. The growing adoption of EVs further strengthens the case for DC, as fast-charging stations rely on DC power, which makes a direct DC-based grid an optimal solution. One challenge with nanogrids is system integration. Advanced technologies, such as buck-boost converters, can help regulate DC voltage to ensure compatibility with a variety of appliances and storage systems.



Figure 14: Purdue University Nano-grid home runs solely on DC power. [Photo courtesy of Purdue University]

As smart homes evolve, the integration of hybrid energy systems is gaining prominence. Traditional homes rely on AC power grids, but the rise of



renewable energy sources such as solar panels along with battery storage has increased interest in DC-based power distribution. While a full-scale transition to DC power will not happen overnight, a hybrid approach combining AC and DC systems is a practical step forward. High-power appliances like air conditioners and stoves can remain on AC grids, while low-power devices, EV chargers, and lighting systems operate on DC. This strategy balances efficiency gains with practical implementation, making it increasingly feasible. As technology advances and more devices become DC-compatible, the shift towards grid-connected DC systems will become not just an option, but a necessity for energy sustainability. There are several models to integrate DC distribution into homes.

Scenario 1: A Traditional Home AC System with Solar and Battery Storage

This approach keeps things conventional, relying entirely on standard AC wiring while integrating solar panels and battery storage. Power from the rooftop solar panels flows through an AC inverter, then into the home or to charge the battery bank. All existing household appliances continue to operate on AC power. The result: resilience, modest efficiency gains, and a degree of energy independence.

It's a familiar model with minimal disruption—no rewiring, no new circuits—just added solar panels, inverters, and battery storage layered onto existing infrastructure.

Costs and Installation

The largest cost is equipment. A complete system—including solar panels, an inverter, and lithium-ion batteries—typically ranges from \$15,000 to \$25,000, depending on system size and storage capacity.

Since the existing AC wiring stays in place, infrastructure costs are relatively low. Labor and installation usually run between \$5,000 and \$10,000, influenced by factors such as roof configuration, panel orientation, and the complexity of connecting battery storage.

Expect battery replacement every 10 to 15 years, at a cost of \$7,000 to \$10,000 depending on battery quality and usage.

Efficiency and Maintenance

While this configuration is reliable, it's not the most efficient. Solar panels produce DC power, which is converted to AC for home use only to be re-converted back to DC inside many modern devices like laptops and LED lights. These conversion steps introduce 5–10% energy loss over time.

Maintenance needs are moderate and mainly involve monitoring inverter performance and planning for battery replacement. The system's simplicity contributes to its long-term durability.

Pros and Considerations

This setup delivers grid resilience, emergency backup, and lower monthly electricity bills—particularly in areas with time-of-use pricing or frequent outages. It's well-suited to households looking for greater energy independence without changing their existing electrical infrastructure.

However, since all power is routed through the AC system, conversion losses remain. There's no opportunity to make use of direct DC power from solar panels or batteries.

In short, this is the most conservative and straightforward way to integrate solar and storage reliable, widely supported, and low-risk, though less efficient than hybrid or DC-optimized alternatives.

Scenario 2: AC-Based Home with Selective AC-to-DC Wall Converters

This setup retains the home's standard AC wiring, but upgrades select wall outlets with built-in AC-to-DC converters. It's a subtle yet effective enhancement. Devices that usually rely on inefficient adapters can now plug into high-efficiency outlets, reducing energy waste and cord clutter.



There's no need to open up walls or overhaul existing wiring just add smarter outlets in key locations. This makes it an appealing option for both retrofits and new builds.

Costs and Installation

Specialty outlets with built-in converters typically cost \$100 to \$300 each. Installation is relatively simple. In retrofit applications, labor and infrastructure expenses range from \$500 to \$2,000, depending on how many outlets are upgraded. In new construction, these costs are much lower when integrated during the initial wiring phase.

In some cases, small upgrades to breakers or circuits may be needed, but disruption is minimal.

Efficiency and Maintenance

This setup excels in energy performance. High-quality wall-mounted converters operate at 90–95% efficiency, compared to the 60–80% efficiency of many plug-in adapters. Centralizing power conversion at the wall reduces cumulative energy loss and helps eliminate phantom loads.

Advanced outlets can shut down idle circuits, further lowering energy consumption.

Maintenance is simple: most converter units are modular and can be replaced without opening walls or calling a specialist.

Pros and Considerations

This is an excellent middle-ground solution. It avoids the complexity of full DC rewiring while capturing meaningful efficiency gains particularly in homes with lots of low-voltage electronics like laptops, smart hubs, or gaming setups.

Benefits include improved energy efficiency, lower operational costs, and straightforward maintenance. The main limitation is that appliances still draw power from an AC-based system, with batteries in electronic devices playing a supporting rather than primary role.

Still, for homes looking to boost performance without a major renovation, this scenario is flexible, affordable, and easy to scale.

Scenario 3: Hybrid AC-DC Home with Partial DC Wiring

This scenario introduces dedicated DC circuits into the home to support USB-C outlets, high-efficiency lighting, or an EV charger while keeping standard AC outlets for most appliances. It's a balanced approach, blending traditional infrastructure with modern upgrades to increase overall efficiency.

Here, power from solar panels and batteries can travel directly to certain devices without the need for constant conversion between AC and DC.

Costs and Installation

Upfront costs, not including the cost of solar system and batteries, depend on whether the system is installed during new construction or as a retrofit. New builds may incur \$1,500 to \$4,000 for DC equipment, while retrofitting an existing home typically costs \$3,000 to \$6,000 due to the need to open walls and modify circuits.

Wiring and infrastructure upgrades can run from \$5,000 to \$15,000 for retrofits but are far lower when installed from the outset in a new build.

Labor costs are higher than usual, as DC systems require electricians trained in DC safety standards. Custom setups—for example, integrating solar charging for an EV—also add complexity.

Efficiency and Maintenance

The benefits are significant. Devices running directly on DC—such as LEDs, fans, and many electronics—can be 10–20% more efficient, than AC-powered devices for the same function. If solar production aligns with usage, this can dramatically boost energy savings.

Maintenance is minimal. With fewer conversions, components generate less heat and experience less wear. Occasional checks and basic replacements



(e.g., fuses or connectors) are typically all that's required.

Pros and Considerations

For homeowners who want better energy performance without giving up AC appliances, this hybrid model offers a strong compromise. It supports smart tech, reduces energy waste, and lowers long-term electricity costs. However, it's a larger investment—especially for retrofits—and requires appliances compatible with DC power, along with professionals familiar with hybrid installations.

Overall, this is a forward-looking option for those planning a major energy upgrade or building a new home with efficiency in mind.

Scenario 4: Full DC Nanogrid Home (Off-Grid Capable)

This is the most advanced and transformative option: a completely DC-powered home, fully independent of the traditional AC grid. Solar panels generate DC power, which is stored in batteries and delivered directly to appliances, eliminating conversion losses almost entirely.

This model supports full energy autonomy and exceptional efficiency.

Wiring and Appliances

The home is wired entirely for DC, which means all appliances—from refrigerators and HVAC systems to lighting and electronics—must be compatible with DC power. Energy flows directly from solar panels and batteries to these devices, without routing through an inverter. The result is minimal energy loss and a highly optimized, self-contained power system.

Costs and Installation

This is the most expensive and complex option. Costs vary widely depending on home size, energy needs, and system design. All wiring, outlets, and appliances must be purpose-built or adapted for DC

use. Specialized labor is essential, as DC systems follow different standards and safety requirements than AC. However, new developments in modular nanogrid systems are beginning to reduce barriers, making this model more accessible than in the past.

Efficiency and Maintenance

With nearly all conversion steps eliminated, efficiency is outstanding. Direct DC-to-DC transmission minimizes losses, and the system can be fine-tuned for specific usage patterns. Maintenance is relatively low, focused mainly on battery health and periodic system diagnostics. Because there's less heat and electrical stress, components tend to last longer.

Pros and Considerations

This approach is ideal for those seeking full energy independence, whether for sustainability, resilience, or off-grid living. It offers unmatched efficiency and long-term cost savings once installed.

However, it requires full commitment to DC infrastructure and careful planning. Compatible appliances can be harder to source, and until the market acceptance of DC power devices develops, the initial cost is likely to be higher than for other traditional AC configurations.

For the right homeowner — especially those building from scratch — this represents the most forward-thinking, future-ready option in home energy.

Scenario 5: Smart, AI-Optimized Nanogrid Home with Grid Interaction

This is the most sophisticated and adaptable model: a home energy system where solar panels, batteries, appliances, and the grid interact in real time under the guidance of artificial intelligence. Within this hybrid environment, DC is used in a wide range of specific systems which are increasingly common— smart lighting networks powered by DC for ultra-efficient, automated lighting control; solar integration with battery systems; DC appliances for streamlined power use;



home security (cameras, locks, sensors) running on low-voltage DC circuits; remote energy monitoring via mobile apps that offer visibility into household consumption and solar output and climate control systems using DC-powered fans and compressors to regulate temperature based on occupancy and outdoor conditions.

The system continuously analyzes usage patterns, forecasts weather, tracks energy prices, and coordinates how power is generated, stored, and consumed.

Wiring and Appliances

Like Scenario 3, this setup features a hybrid AC/DC infrastructure, but it adds a new layer: predictive controls, data cabling, and IoT-connected devices. DC zones power efficient lighting, fans, and smart appliances, while AC circuits handle legacy systems. Smart devices are coordinated through centralized platforms that distribute energy intelligently across lighting, HVAC, security, and entertainment systems.

Appliances and systems respond dynamically—lights dim during peak pricing, washers delay cycles until solar output rises, and thermostats pre-cool or pre-heat based on occupancy and time-of-use rates. AI bridges these decisions without user input.

Infrastructure and Labor Costs

Initial hardware costs range from \$30,000 to \$60,000, covering AI-enabled inverters, solar-plus-storage systems, DC wiring, sensors, and smart appliances. Infrastructure also includes data and control systems, with wiring for mesh networks and automated device integration.

Installation costs can exceed \$15,000, especially when systems integrators and software technicians

are involved. These specialists ensure communication protocols (such as BACnet, KNX, or Modbus) work across subsystems. They also program control logic and design user interfaces for monitoring performance, ensuring that all components—from lighting to energy storage—operate as a unified, intelligent ecosystem.

Performance and Maintenance

The efficiency of this system lies in its intelligence. AI minimizes idle loads, schedules energy use for off-peak hours, and avoids demand spikes. Operational costs are significantly reduced, and surplus solar power can be sold to the grid during high-value periods.

Maintenance is primarily software-based: firmware updates, diagnostics, and performance tuning, which are often handled remotely. System alerts and energy performance data can be accessed via smartphone apps or dashboards.

This scenario combines cutting-edge hardware with intelligent orchestration, resulting in an energy system that continuously adapts, saves money, and enhances resilience. While upfront costs are high and technical complexity requires expert design, the payoff is a home that learns and responds, seamlessly balancing comfort, efficiency, and autonomy.

Regulatory and Grid Interaction

These homes maintain a grid connection but do so intelligently. Advanced inverters comply with interconnection standards (such as IEEE 1547 in North America) and can feed power back into the grid under utility or local energy market programs. In some jurisdictions, such systems qualify for feed-in tariffs, dynamic pricing programs, or demand response incentives.



	Scenario 1 <i>Traditional AC Home with Battery Storage</i>	Scenario 2 <i>AC Home with AC-DC Wall Converters</i>	Scenario 3 <i>Hybrid AC-DC Home with Partial DC Wiring</i>	Scenario 4 <i>Fully DC Home with Centralized DC Power Supply</i>	Scenario 5 <i>Smart DC Home with Predictive Controls</i>
Equipment Costs	\$8,000–\$15,000 (solar + battery + inverter)	\$200–\$500 per outlet (retrofit)	\$10,000–\$20,000 (solar, battery, DC outlets)	\$15,000–\$25,000 (includes solar, centralized battery, DC panel)	\$20,000–\$30,000 (includes smart systems, sensors, battery)
Wiring & Infrastructure Costs	Minimal if AC wiring is existing	Minimal; uses existing AC wiring	\$3,000–\$10,000 (partial rewiring, USB-C ports)	\$5,000–\$12,000 (dedicated DC wiring, breakers)	Mirrors Scenario 4, plus layered data cables
Labor & Installation Costs	\$2,000–\$5,000	\$2,000–\$4,000 (10–15 upgraded outlets)	\$5,000–\$8,000	\$7,000–\$10,000 (DC specialists, electricians)	\$10,000–\$15,000+ (adds integrators and software technicians)
Operational Costs	Moderate (conversion losses)	Lower than Scenario 1 (fewer conversion losses)	Low (reduced conversions)	Very low (minimal conversion losses)	Lowest (predictive load management)
Maintenance	Low to moderate (battery service every 5–10 years)	Low (occasional outlet unit replacement)	Moderate (more systems to monitor and service)	Moderate (newer systems, fewer parts to fail)	Higher complexity, but self-diagnostics reduce downtime



Efficiency Gains	Low – due to dual conversion (DC→AC→DC)	Moderate – more efficient than device-level conversion	High – DC directly powers many loads		
Grid Interconnection & Compliance	Fully grid-compliant; minimal permitting issues	Fully compliant; no change to grid connection	May require inspection/approval for DC circuits		

Notes:

- **Equipment Costs** include solar panels, batteries, inverters, smart devices, and DC-compatible appliances where applicable.
- **Wiring & Infrastructure** accounts for new cabling, outlets (USB-C/DC), circuit panels, and in some cases, entire DC loops.
- **Labor & Installation** reflects licensed electrical work, integration of smart systems, and the complexity of the retrofit or new build.
- **Operational Costs** are lower in DC-based systems due to minimized conversion losses and optimized energy flow.
- **Maintenance** increases with system complexity, particularly in smart or fully off-grid homes.
- **Efficiency Gains** are highest when DC generation and consumption are matched without multiple conversion stages.
- **Grid Interconnection & Compliance** is simplest for hybrid AC/DC systems and most complex for full off-grid nanogrids.

DC in Action: How Efficiency Gains Translate into Dollars

Let's consider a typical residential HVAC setup in Toronto. The home is equipped with a 2-ton heating and cooling system (such as Goodman 48v DC-Direct Hybrid Solar Air Conditioning & Heating 28 SEER 24000 BTU - 7200 Watts - 3 HP), which corresponds to a power draw of approximately 7

kilowatts (kW). On an average day during the heating or cooling season, the system runs for about eight hours to maintain a comfortable indoor environment. Over the course of a month—assuming 30 days of consistent operation—this results in a total energy consumption of approximately 1,680 kilowatt-hours (kWh) based on 56 kWh per day multiplied by 30 days.



Electricity in Ontario is billed using a tiered rate structure. As of 2025, the first 1,000 kWh used in a billing cycle are charged at a rate of 9.3 cents per kWh. Any consumption beyond that threshold is billed at a higher Tier 2 rate of 11.0 cents per kWh. Given that the HVAC system alone exceeds the Tier 1 limit, a portion of the monthly usage will fall into the higher-priced bracket—raising the overall energy cost for the household.

Cost for \$1,680 kWh per month

- First tier: 1,000 kWh × \$0.093 = **\$93.00**
- Second tier: 680 kWh × \$0.11 = **\$74.80**

Total: \$167.80/month

Now let’s look at the impact of upgrading to a DC-coupled HVAC system. Unlike traditional setups, a DC-coupled system connects directly to solar panels and battery storage. This streamlined design avoids multiple power conversions between AC and direct current (DC), which typically cause energy losses. This means they require less electricity to deliver the same level of heating or cooling.

Applying a conservative 15% efficiency gain to our earlier example, monthly energy consumption drops from 1,680 kWh to approximately 1,428 kWh.

Cost for \$1,680 kWh per month

- First tier: 1,000 kWh × \$0.093 = **\$93.00**
- Second tier: 428 kWh × \$0.11 = **\$47.08**

Total: \$140.08/month

Under Ontario’s tiered electricity pricing in 2025, the first 1,000 kWh are billed at 9.3 cents per kWh, and the remaining 428 kWh fall under the Tier 2 rate of 11.0 cents. This translates to a total monthly cost of approximately \$140.08.

Here’s how the two systems compare over time:

System Type	Monthly Energy Use	Monthly Cost	Annual Cost
Traditional HVAC	1,680 kWh	\$167.80	\$2,013.60
DC-Coupled HVAC	1,428 kWh	\$140.08	\$1,680.96
Annual Savings	—	—	\$332.64

This example highlights how a DC-coupled HVAC system can deliver meaningful long-term savings—not only by reducing energy consumption but also by lowering operating costs.

Calculating the savings from using DC power for HVAC is a straightforward approach that can be extended to a wide range of home systems from lighting and refrigeration to entertainment and computing equipment.

For more complex residential setups with on-site renewable generation, the potential gains grow substantially. Let’s explore this through a narrative case study of a Toronto home equipped with both a ground-source (geothermal) heat pump along with solar PV, and a DC coupled system in which solar panels, a battery storage unit, and a geothermal heat pump all operate directly on DC power

Geothermal

In this scenario, let’s first examine the operational energy costs of heating and cooling a typical residential property using a geothermal heat pump, comparing the performance and cost between conventional AC-powered and DC-coupled systems. Geothermal (or ground-source) systems are especially efficient in Canada’s cold climate because they rely on stable underground temperatures



rather than fluctuating outdoor air temperatures. With a coefficient of performance (COP) of approximately 4.5, the geothermal heat pump delivers 4.5 units of heat for every unit of electricity consumed to operate the compressor, pumps, fans and control systems. By comparison, an air-source heat pump has a COP closer to 3.0. This roughly 33% improvement in efficiency means that, for the same heating and cooling output, a geothermal system consumes significantly less electricity.

Let's say this Toronto home typically uses about 6 kW of power for heating and cooling for six hours a day over a month during peak operation hours. **A ground-source system would use 720 kWh (compared to an air-source heat pump that would consume about 1,080 kWh monthly for the same output).**

Add in lighting (about 18 kWh/month for 10 LED bulbs used six hours per day) and appliances like refrigerators and laundry machines (roughly 90 kWh/month), and the total monthly electricity consumption for the home with a ground-source system comes to approximately 828 kWh.

Heating/Cooling (geothermal): 720 kWh

Lighting: 18 kWh

Appliances: 90 kWh

Total = 720 + 18 + 90 = 828 kWh/month

Under Ontario's tiered electricity pricing (at 9.3 cents per kWh for the first 1,000 kWh), this adds up to a monthly energy bill of about \$77, or \$924 per year.

Solar PV

Now let's consider the impact of integrating solar photovoltaic (PV) panels. In Toronto, each installed kW of solar capacity produces around 100 kWh of electricity per month. To cover the 704 kWh monthly demand of the DC-coupled geothermal system, a 7.04 kW solar array would suffice. That's roughly a 7 kW system. At current rates, the installation cost for such a system is about \$17,500 CAD before any federal or provincial incentives.

If we look at heating alone, the solar system would save about \$785.64 per year – roughly the amount needed to supply the geothermal heat pump. That implies a basic payback period of around 22 years. However, this estimate is conservative. It doesn't account for government rebate programs or potential tax credits, both of which can reduce the upfront cost significantly. Moreover, if the solar array is sized appropriately, it can also supply lighting, appliances, and water heating, which shortens the payback period considerably.

DC-coupled system

Switching to a DC-coupled system, which in this case might consist of solar panels, a battery storage unit, and a geothermal heat pump designed to operate directly on DC power, offers a significant improvement. By eliminating the AC-to-DC and back again conversion losses that come with typical home electrical infrastructure, a DC-based heat pump system operates about 15% more efficiently. Applying this gain, the monthly energy consumption drops from 828 to 704 kWh. At the same electricity rate, the monthly bill would fall to \$65.47, or \$785.64 annually.

The savings from switching to a DC-coupled system alone amount to around 124 kWh per month, translating to \$11.53 in monthly cost savings or roughly \$138 per year. While not life-changing in isolation, these savings are cumulative and open the door to even greater efficiencies when paired with on-site renewable energy.

This example shows how pairing on-site renewables, battery storage, and DC power with efficient HVAC and appliances boosts efficiency.

A well-designed system in Toronto, where both cold winters and meaningful solar potential exist, can reach net-zero heating energy costs and begin to recoup its installation costs well within the system's lifespan. As electricity rates rise and solar technologies improve, the case for DC-coupled renewables continues to strengthen especially for homeowners ready to invest in long-term resilience and energy independence.

However, accurately assessing costs and savings requires consideration of several key factors.



Savings ultimately depend on the system's efficiency and the household's specific usage patterns.

One major variable is time-of-use (TOU) pricing, which can significantly impact monthly costs. In many large jurisdictions across North America, Europe, and beyond, TOU tariffs are widely used to encourage off-peak electricity use. For instance, running a system during On-Peak hours—when rates can reach 15.8¢/kWh—can drive up costs. In contrast, shifting usage to Off-Peak periods, priced at 7.6¢/kWh, or to Ultra-Low Overnight windows, where rates drop to just 2.8¢/kWh, can lead to substantial savings.

As smart homes evolve, the integration of hybrid energy systems is gaining prominence.

While a full-scale transition to DC power will not happen overnight, a hybrid approach combining AC and DC systems is a practical step forward. High-power appliances like air conditioners and stoves can remain on AC grids, while low-power devices, EV chargers, and lighting systems operate on DC. This strategy balances efficiency gains with practical implementation, making it increasingly feasible. As technology advances and more devices become DC-compatible, the shift towards grid-connected DC systems will become not just an option, but a necessity for energy sustainability.

DC-Compatible Domestic Devices and Appliances

As we move towards more sustainable energy systems, the importance of DC-compatible devices is growing. DC systems are now at the forefront of energy-efficient living, driven by advances in technology and the increasing integration of renewable energy. In modern households and industries, appliances and electronics designed to operate on DC are transforming the way energy is consumed, helping reduce conversion losses and promoting a cleaner, more sustainable ecosystem.

LED Lighting

LED lighting is a prime example of DC-compatible, energy-efficient technology. LEDs inherently run on DC power, making them ideal for solar and renewable setups. In AC systems, they require a converter to transform grid electricity into DC, causing energy losses. By running directly on DC, LEDs avoid conversion losses, improving efficiency. In homes, businesses, and outdoor spaces, DC-compatible LEDs support a more sustainable energy system.

Household Electronics: Computers, Televisions, and More

Many household electronics, such as computers, televisions, and audio equipment, rely on DC power. Traditionally, these devices have been designed to run on AC power, requiring a rectifier to convert AC electricity into the DC power they need. This conversion process is inefficient. By transitioning to DC-powered electronics, the need for conversion is eliminated. As the adoption of DC technology grows, more household devices—such as laptops, televisions, and sound systems—will be designed to operate directly on DC power. This trend is particularly evident in off-grid and renewable energy setups, where appliances powered by DC can function more efficiently and integrate better with battery storage systems.

HVAC Systems

Heating, ventilation, and air conditioning (HVAC) systems are some of the largest energy consumers in households and commercial buildings. Traditionally, HVAC systems have relied on AC power to run their compressors and motors. However, modern HVAC units are increasingly adopting DC-compatible motors, which offer smoother operation, reduced energy consumption, and better integration with renewable energy sources. DC-compatible HVAC systems can operate more efficiently, with less energy waste, than their AC counterparts. They also integrate better with solar power systems, which generate DC electricity, further reducing the need for energy conversions. As the demand for energy-efficient climate control



solutions grows, the adoption of DC motors in HVAC systems is likely to become more widespread.

Home Battery Storage

Home battery storage has evolved rapidly, driven by advances in technology, lower costs, and growing demand for energy independence. Companies like Tesla, LG, and Enphase are leading the way with more efficient, scalable, and user-friendly systems that integrate seamlessly with solar power. Technological innovations, including solid-state batteries and advanced lithium-ion technology, have significantly reduced costs and extended battery lifespans, making energy storage more accessible and efficient for homeowners.

Modern batteries offer higher capacity, faster charging, and smart energy management, allowing homeowners to store excess solar energy, reduce reliance on the grid, and maintain power during outages. Innovations in lithium-ion and solid-state batteries are further improving performance and longevity. As the market expands, home energy storage is becoming more accessible, making renewable energy a more practical and resilient choice for households worldwide. For example, in Texas, innovative business models offer homeowners discounted or free solar panels and battery systems in exchange for participation in programs that support the grid during peak times. In Australia, the adoption of home batteries has surged, with one in five new solar panel owners now installing a battery, a significant increase from previous years.

Electric Vehicle (EV) Chargers: A More Efficient Charging Process

EVs represent another significant application of DC technology. EVs store energy in their batteries as DC, bypassing the need for the energy-intensive AC-to-DC conversion. This not only speeds up the charging process but also reduces energy loss, making EV charging more efficient and environmentally friendly.

In addition to reducing conversion losses, DC chargers are more compatible with renewable energy sources, such as solar power, which also

generates DC electricity. This alignment with renewable energy systems enhances the overall efficiency of both the EV charging process and the broader energy infrastructure. Furthermore, the advent of vehicle-to-grid (V2G) technology, where EVs can supply stored DC energy back to the grid or to homes, further boosts energy efficiency and resilience.

DC in Home Appliances

The adoption of DC technology is not limited to small electronics. Several major home appliances are making the switch to DC-powered systems, with significant benefits for energy efficiency and system integration.

DC-Powered Refrigerators and Freezers are increasingly popular, particularly in off-grid and renewable energy setups. GE Appliances, for example, has introduced 12V DC refrigerators designed specifically for recreational vehicles (RVs). These DC-powered fridges operate directly on solar power or battery storage, eliminating the need for inverters and minimizing energy losses. By running on DC, these refrigerators can maintain food at a consistent temperature using significantly less energy than traditional AC-powered units.

DC-Powered Washing Machines, especially those with DC motors, are becoming more energy-efficient. These appliances typically convert AC from the grid into DC for the motor, but in some newer models, the motor operates directly on DC. This eliminates conversion losses and improves energy efficiency. However, fully DC-powered washing machines are still rare, as most models continue to rely on AC for certain functions.

Heat Pump Clothes Dryers are a more energy-efficient alternative to traditional dryers. These appliances use a DC motor to drive the heat pump, improving performance and reducing energy consumption. Unlike traditional dryers, which vent hot air outdoors, heat pump dryers recycle warm air, reducing energy waste and improving airtightness in the home.

Solar DC Air Conditioners represent an exciting development in energy-efficient cooling. These air conditioners operate directly on DC power supplied



by solar panels, eliminating the need for inverters and improving overall efficiency. Solar DC air conditioners are especially useful in off-grid or energy-efficient homes, where minimizing energy losses and operating costs is a priority.

Innovative Applications of DC Power

Several novel appliances and systems are being developed to run on DC power, demonstrating the growing versatility of this energy source. Some of these include:

Electrochromic Windows: These windows, which change transparency or tint in response to voltage changes, typically operate on low-voltage DC. They are part of smart building systems that integrate renewable energy sources and enhance energy efficiency.

Smart Faucets: DC-powered smart faucets offer precise control over water flow and temperature, often integrating features like motion sensors, touch sensors, and smart connectivity. These faucets reduce water waste and improve convenience in modern homes.

USB Wall Outlets: USB outlets, which provide direct DC power for charging devices, are becoming more common in homes. These outlets reduce the need for AC-to-DC adapters, saving energy and improving convenience for charging devices like smartphones and tablets.

Future Outlook

As renewable energy adoption increases and technology advances, the range of DC-powered appliances will likely expand. While high-power devices like ovens and cookers are not yet widely available in DC versions, ongoing developments in DC technology suggest that these appliances may become more common in the future.

The integration of DC motors in appliances like washing machines and air conditioning units is already improving energy efficiency, and we can expect further advancements in this area. For off-grid homes, DC-powered appliances offer an efficient and seamless way to operate energy

systems without the need for inverters, providing a more sustainable and cost-effective solution.

In conclusion, the rise of DC-compatible devices represents a vital step toward achieving greater energy efficiency and sustainability in both domestic and industrial settings. These technologies not only reduce conversion losses but also align perfectly with the increasing use of renewable energy sources, helping to create a cleaner, more resilient energy ecosystem. With continued advancements in DC technology, we can look forward to a future where energy-efficient, sustainable living becomes the norm.

The Business Case for DC Technology and KPIs

The transition to DC energy systems presents a compelling business case for homeowners, building owners, and investors seeking cost savings, energy efficiency, and resilience. DC microgrids, which support on-site renewable energy generation and storage, reduce reliance on the traditional AC grid and minimize energy losses from conversion. The result is lower electricity costs and improved energy security.

Summary of the Advantages of DC Energy

Reduced “First Cost” A DC-coupled system has a lower first cost due to fewer components, simpler wiring, reduced labor, and greater efficiency. However, if retrofitting an existing AC-based system, AC-coupling may be preferable despite the higher first cost.



Overall First Cost Comparison:

Factor	AC-Coupled	DC-Coupled	Cost Impact
Inverter Costs	Multiple inverters	Single hybrid inverter	DC is cheaper
Wiring & Hardware	More wiring & components	Simpler infrastructure	DC is cheaper
Installation	Complex & labor-intensive	Easier, fewer components	DC is cheaper
Efficiency	~5-10% losses	Minimal conversion losses	DC is more cost-effective
Grid Compliance	Additional protections needed	Simpler integration	DC is cheaper

Lower Operational Costs: DC-powered lighting, HVAC, and IT systems reduce maintenance and energy expenses over time. Switching to DC-coupled HVAC systems can significantly reduce operational energy costs in buildings, especially in solar-powered applications. The exact savings depend on the system design, energy tariffs, and load profiles.

Differences in “Operational Maintenance Cost”. While the **Operational Maintenance Cost (OMC)** of **AC** vs. **DC** systems differs due to inherent differences in system complexity, conversion losses, equipment lifespans, and component requirements, the DC-based systems typically tend to have **lower** OMC.

Increase in productive energy available with reduced losses. Combined **Total Gain in Productive Energy Use** is roughly **15%–35%** more in productive energy available, depending on configuration, load profile, and system size.

Reduced Energy Waste: DC-powered systems eliminate conversion losses between AC and DC, leading to significant energy savings.

Seamless Integration with Renewables: Solar panels and battery storage operate on DC power, making DC microgrids a natural fit for maximizing renewable energy usage.

Resilience and Reliability: With DC microgrids and energy storage, buildings can maintain power during grid outages or peak demand periods, ensuring continuous operation.

Incremental Investments with Rapid ROI

The transition to DC power does not require an all-at-once overhaul. Businesses and homeowners can make incremental upgrades to realize immediate benefits:

DC-Powered LED Lighting: Reduces electricity use while providing superior lighting quality and longevity.

Power over Ethernet (PoE) Systems: Streamline energy distribution for lighting, sensors, and communications.

Hybrid AC/DC Systems: Allow gradual integration of DC power without disrupting existing infrastructure.

These investments offer rapid returns, often achieving payback within a few years through energy savings and reduced maintenance costs.



Key Performance Indicators for DC or Hybrid AC-DC Microgrids and Nanogrids

To effectively measure the performance of DC or hybrid AC-DC powered microgrids and nanogrids, a variety of tools are required, including energy meters, power analyzers, efficiency monitors, and data logging systems. These tools help track the system's effectiveness and sustainability through key performance indicators (KPIs).

One important KPI is Energy Efficiency (kWh per kWh consumed), which evaluates overall system efficiency by measuring losses from conversion, transmission, and distribution. It tracks how much energy is wasted during the conversion process, especially between AC-DC and DC-AC. More efficient systems minimize these losses, leading to better performance. Power meters, efficiency analyzers, and load testing equipment are needed to measure this.

Another key metric is Renewable Energy Utilization (%). This KPI tracks the percentage of total energy demand met by renewable sources such as solar and wind. A higher percentage reflects a system's ability to reduce reliance on external power sources and contribute to sustainability goals. Monitoring renewable energy generation requires energy production meters, weather data integration tools, and renewable energy generation trackers.

Grid Independence (%) is another crucial measure, assessing how much of the energy demand is met without drawing from the main utility grid. This KPI is important for ensuring resilience and self-sufficiency in microgrids and nanogrids, especially during emergencies. Tools for measuring grid independence include grid connection monitoring tools, energy consumption meters, and load balancing systems.

Power Conversion Losses (%) measures the energy lost during the conversion process between AC-DC and DC-AC. Minimizing these losses is key to improving system efficiency. Power analyzers, voltage and current measurement devices, and efficiency monitoring equipment are necessary to accurately track these losses.

The Battery Storage Utilization KPI, which includes cycle life and efficiency, tracks the performance of the energy storage system. It measures parameters like the depth of discharge, cycle count, and overall storage efficiency, determining how long and effectively the batteries can operate. Tools needed for this KPI include battery management systems (BMS), charge/discharge testers, and cycle life measurement tools.

For ensuring the system is operating properly, Power Quality is critical. This KPI monitors voltage stability and minimizes harmonic distortions, which can cause instability and affect the performance of sensitive equipment. Power quality analyzers, harmonic analyzers, and voltage stability monitoring equipment are necessary to maintain these standards.

Cost Savings (OPEX and CAPEX Reduction) is a financial KPI that compares the operational and capital expenses before and after the microgrid's installation. By evaluating the reduction in costs, this measure helps determine the system's financial viability and return on investment. Financial analysis software, cost comparison tools, and accounting systems are used to track these savings.

The Carbon Footprint Reduction (CO₂ Emissions Avoided) KPI tracks the reduction in greenhouse gas emissions due to the use of renewable energy sources and improved system efficiency. This is an essential metric for any sustainability-driven project. Emissions monitoring systems, carbon calculators, and environmental impact assessment tools help quantify these reductions.

System Reliability (Uptime %) evaluates the system's reliability by tracking downtime and overall availability. A higher uptime percentage indicates a more reliable system, ensuring service continuity. This KPI requires system monitoring software, uptime tracking tools, and fault detection systems.

Finally, Demand Response Efficiency (%) measures how well the system responds to fluctuating load demands or grid signals. Efficient demand response is crucial for managing peak loads and supporting grid stability. This KPI is monitored using demand response management software, real-



time load monitoring tools, and communication systems for grid signals.

DC Power: Challenges, Opportunities and Future Outlook

DC power systems provide notable advantages, including improved energy efficiency, better integration with renewable energy sources, and lower operational costs. However, there are significant challenges that must be overcome to enable their widespread adoption, especially as part of hybrid AC-DC solutions.

Challenges

One of the primary challenges is infrastructure compatibility. Most buildings are designed for AC power, which requires significant retrofitting for the integration of DC systems. This includes updating electrical panels, wiring, and outlets, which adds complexity and costs to the transition. Hybrid systems, which incorporate both AC and DC, can partially address this issue, but they still necessitate additional components like inverters.

A major issue in the DC power adoption process is the lack of standardization. The absence of universal standards for residential and commercial DC systems creates compatibility challenges between devices, making it difficult for systems to work together seamlessly. This lack of standardization can also discourage investment in DC solutions, as potential adopters may be uncertain about the long-term viability of their equipment.

Another obstacle is the high initial cost of implementing DC microgrids and hybrid systems. While the long-term operational savings can offset these costs, the upfront expenses, including for inverters, energy storage solutions, and wiring, can be a barrier. Additionally, few financial incentives are available for consumers, particularly in regions where the technology is not yet widespread, slowing down the transition.

One further challenge is the need for workforce training. As DC power systems and hybrid technologies become more common, there is a growing need for specialized skills. Electricians, engineers, and contractors will need to be trained in the installation and maintenance of DC-based systems. Existing workforce expertise must be updated to keep pace with these changes, ensuring that the workforce is prepared to meet the growing demand for DC solutions.

Opportunities

Despite these challenges, several opportunities lie ahead for DC power.

The increased adoption of DC appliances is a key driver. As more devices are designed to operate directly on DC power, such as LED lights, computers, and certain heating systems, the demand for DC-powered systems will grow. These DC appliances benefit from reduced energy losses compared to AC systems. This results in higher efficiency and lower operational costs.

Additionally, advancements in power electronics offer significant potential. New technologies in inverters and power management systems are improving the efficiency and affordability of hybrid AC-DC grids. These advancements will help make DC systems more cost-competitive with traditional AC systems and reduce energy conversion losses. More efficient and cheaper components will make it easier for homes and businesses to implement DC systems without significant upfront investment.

Policies and regulatory support can move the needle. Governments are beginning to recognize the benefits of DC power in terms of energy efficiency and sustainability. Policies such as tax credits, rebates, and grants can help offset the initial investment costs for consumers. As governments push for lower carbon emissions and more sustainable energy practices, DC power is poised to play an increasingly important role in achieving these goals.

Smart building technologies present another area of opportunity. As smart cities and buildings evolve, DC microgrids and Power over Ethernet (PoE) devices are becoming integral. These solutions allow



for cost-effective modernization of infrastructure while reducing overall energy consumption. DC-powered smart buildings, which are already in use in some commercial settings like office buildings and university campuses, demonstrate that the transition to DC is not only possible but is already underway.

Adoption of DC Devices by Category

Load Type	DC Compatibility	Likely Adoption	Notes
LED Lighting	High	Immediate	Already prevalent
Batteries	High	Early	Emerging
Batteries +Solar	High	Early	Emerging
Fans	High	Early	Used in off-grid DC homes
Home Appliances	Medium	Early	Induction cooktops
HVAC Components	Medium	Mid-term	DC compressors emerging
IT Equipment	High	Immediate	Data centers already moving to 380V DC
EV Chargers	High (DCFC)	Growing	DC charging more efficient
Elevators	Medium	Mid-term	Regenerative systems

			standard in new builds
EVs (V2X)	High	Mid/Long-term	Regulation dependent

Future Developments

The future of DC power looks promising, with several key developments on the horizon. As DC appliances become more widespread, the demand for DC systems in residential and commercial buildings will increase. The shift to DC will be driven by both the increased availability of compatible devices and the growing recognition of the efficiency benefits offered by DC power.

Perhaps the greatest potential for adoption are battery systems, such as **Tesla Powerwall** or **LG Chem** in residential buildings. They offer several advantages, including backup power during outages, reduced energy costs through peak shaving and load shifting, and enhanced grid stability. They also facilitate the integration of renewable energy sources, potentially leading to a smaller carbon footprint. Additionally, battery systems can increase energy independence and provide peace of mind during grid failures or extreme weather events.

Advancements in power electronics will continue to make DC systems more affordable and efficient. Innovations in inverters, energy storage solutions, and power management technologies will reduce the cost and complexity of installing and maintaining hybrid AC-DC systems. These innovations will also improve the overall reliability and performance of DC systems, making them more accessible to a broader range of consumers.

Integrating DC-coupled and AC-coupled equipment in a hybrid/mixed environment is becoming increasingly relevant, especially in advanced residential and commercial energy systems. The goal is to maximize system efficiency, flexibility, and reliability while managing the differences in voltage types.

Workforce development will be crucial to the future success of DC power. As demand for DC systems



grows, so too will the need for a skilled workforce. Training programs for electricians, engineers, and building designers will help ensure that professionals are equipped to design, install, and maintain DC-based systems. Investment in workforce development will be necessary to meet the rising demand for DC infrastructure and ensure a smooth transition to this new energy paradigm.

Lastly, regulatory support will continue to grow as governments worldwide seek to meet energy efficiency and sustainability targets. Policies that incentivize the adoption of DC and hybrid systems, such as rebates, grants, and tax credits, will help accelerate the transition. As more governments recognize the potential of DC power to reduce emissions and improve energy efficiency, the

regulatory landscape will evolve to support its wider adoption.

The business case for DC power is compelling: lower costs, higher efficiency, and greater energy resilience. While there are significant challenges to overcome, including infrastructure compatibility, standardization, initial costs, and workforce training, ongoing advancements in technology and regulatory support will accelerate the adoption of DC systems. As these challenges are addressed, DC power will play a vital role in the future of energy, driving a more sustainable, efficient, and resilient energy landscape.

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