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Executive Summary

As buildings are transitioning towards modernization and facing stricter sustainability goals, traditional electrical systems are reaching their limits. Hybrid AC/DC installations offer a smarter way forward combining the strengths of both AC and DC to deliver greater efficiency, flexibility, and resilience.

By directly connecting renewable energy like PV, batteries, and modern devices to DC networks, hybrid systems reduce energy losses, lower operational costs, and simplify future upgrades.

This approach supports EV charging and native DC loads, seamless integration of solar power, and reliable operation even during grid congestion.

Co-authored by Schneider Electric, Nexans, Vinci Energies, and Tridonic, this white paper shows how hybrid AC/DC solutions can help building owners and managers cut energy losses, improve system efficiency, and prepare for tomorrow's energy needs driving new energy landscape.

Authors

Schneider Electric

Mili Anand –
Power Systems Expert, Energy Management

Santhosh Sambandan –
Global Cluster Leader, Energy Management

Stéphane Follic –
Senior Systems Architect, Energy Management

Nexans

Assane Ndour – *R&D Electrical Engineer*

Nidhal Ben Mbarek – *DC Electrical Grid Engineer*

Chencho Dorji – *R&D Electrical Engineer*

Nicolas Rousselet – *Standardization Director*

Lina Ruiz – *LVDC & MVDC Techno-platform Manager*

Tridonic

Dietmar Klein –
Domain Expert, Power Electronics

Dr. Norbert Linder –
Director, Global Technology & Innovation

VINCI Energies Building Solutions

Mame Thiedel Thiongane –
Project Manager

Romain SCOLAN -
Senior Project Manager

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1. Introduction

The accelerating global shift toward electrification and modernization is reshaping energy consumption patterns across industrial, commercial, and residential sectors. Rising adoption of electric vehicles, advanced IT infrastructure, and smart building technologies is driving unprecedented demand for reliable and flexible power supply. At the same time, public grids are facing increasing pressure from congestion and the growing integration of distributed energy resources (DERs), including renewable energy sources such as solar photovoltaic (PV) generation, creating new challenges for grid stability and energy management.

Modern commercial facilities exemplify this transformation, requiring high levels of energy availability and efficiency to support critical systems like HVAC, lighting, and IT equipment.

Traditional AC-based distribution remains the backbone of electrical systems but struggles with the increasing prevalence of native DC loads and sources, including LED lighting, IT equipment, photovoltaic panels, and battery storage. Multiple AC-DC conversions may lead to energy losses, added complexity, and higher operational costs. To address these potential challenges, hybrid AC–DC distribution architectures are increasingly being explored as a possible solution, as they enable more efficient energy flow, help reduce conversion losses, and simplify DER integration.

This white paper explores the role of hybrid AC-DC architectures in modern office buildings, comparing them with traditional AC systems. It provides data-driven insights and practical guidance for facility managers, developers, and stakeholders seeking to enhance building performance, reduce operational costs, improve reliability, and meet sustainability standards such as LEED, BREEAM, and net-zero energy objectives. By outlining technical benefits, economic implications, and implementation strategies, this paper aims to serve as a roadmap for creating resilient, efficient, and future-ready commercial facilities.

2. Acronyms

Acronyms	Definitions
AC	Alternating Current
BSRIA	Building Services Research and Information Association
CIBSE	Chartered Institution of Building Services Engineers
DC	Direct Current
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
PV	Photovoltaic
BESS	Battery Energy Storage System
EMS	Energy Management System
BIPV	Building Integrated Photovoltaics
DER	Distributed Energy Resources
MDB	Main Distribution Board
ILC	Interlink Converter
OBC	On-Board Charger
MPPT	Maximum Power Point Tracking
CSA	Cross-Sectional Area
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
ROI	Return on Investment

Acronyms	Definitions
IRR	Internal Rate of Return
RCM	Residual Current Monitoring
RCD	Residual Current Device
SPD	Surge Protection Device
OCPD	Overcurrent Protective Device
TN-S	Terre Neutral-Separate (a type of earthing system)
SCCB	Semiconductor Circuit Breaker
TM-DC	Thermal Magnetic Trip Unit for DC
LVAC	Low Voltage Alternating Current
LVDC	Low Voltage Direct Current
LV	Low Voltage
SE	Schneider Electric

3. Relevant Standards and Regulations

Current/OS	Current/OS is a non-profit, open partnership dedicated to ensuring reliable and sustainable hybrid AC/DC power distributions in buildings and other installations.
CIBSE	Chartered Institution of Building Services Engineers is a professional body that sets standards and provides guidance for building services engineering, covering areas such as energy efficiency, sustainability, and occupant comfort.
BSRIA	Building Services Research and Information Association is an industry association delivering research, testing, and practical guidance to improve the design, installation, and operation of building services.
IEC 60364-8-1	Low Voltage electrical installations – Functional aspects – Energy Efficiency
IEC 60364-8-82	Low-voltage electrical installations - Part 8-82: Functional aspects - Prosumer's low-voltage electrical installations
IEC 61851-21-1	Electric vehicle conductive charging system - Part 21-1 Electric vehicle on-board charger EMC requirements for conductive connection to AC/DC supply
IEC 60364-5-52	Deals with the selection and erection of wiring systems.
IEC 60502-1	Specifies the construction, dimensions and test requirements of power cables with extruded solid insulation for rated AC voltages of 1 kV (Um = 1,2 kV) and 3 kV (Um = 3,6 kV) for fixed installations such as distribution networks or industrial installations.
IEC 60502-2	Specifies the construction, dimensions and test requirements of power cables with extruded solid insulation from 6 kV up to 30 kV for fixed installations such as distribution networks or industrial installations.
UL 1699 B	Photovoltaic (PV) DC Arc-Fault Circuit Protection
UL 2202	DC Charging Equipment for Electric Vehicles
IEEE 1562-2007	IEEE Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems
IEEE 2030.1.1-2015	IEEE Standard Technical Specifications of a DC Quick Charger for Use with Electric Vehicles
IEC 61851-23:2014	Electric vehicle conductive charging system - Part 23: DC electric vehicle charging station.
NF C 15-100	Low Voltage Electrical Installations is the principal French standard covering low-voltage installations (≤ 1 kV AC / 1.5 kV DC) in residential, commercial, and certain industrial contexts. It defines requirements for design, protection against overcurrent and electric shock, circuit organization, verification, and maintenance.
NF C 14-100	Low Voltage Service Connections regulates the interface between customer premises and the public low-voltage distribution network. It specifies service entry configurations, metering arrangements, and protective devices at the point of supply.
IEC 60598-1	Specifies general requirements for luminaires, incorporating electric light sources for operation from supply voltages up to 1 000 V. The requirements and related tests of this document cover: classification, marking, mechanical construction, electrical construction and photobiological safety.

4. Partners' Perspectives

This white paper is uniquely differentiated by the complementary strengths of Schneider Electric, Vinci, Tridonic, and Nexans, combining expertise in system design, facility infrastructure, lighting and cable technology. Together, we are not just delivering solutions, we are shaping a disruptive vision for the future electrical distribution. By working closely with our partners and customers, we ensure our innovations are grounded in real-world needs and deliver lasting value. The partnership reflects a shared commitment to build more resilient solutions for buildings by aligning innovation, engineering excellence and end-to-end delivery capabilities.

Schneider Electric
At Schneider Electric, our purpose is to empower all to make the most of our energy and resources, bridging progress and sustainability for all, through our vision of "Your Energy Technology Partner" We strive to be the trusted digital partner for Sustainability and Efficiency.

As buildings evolve to integrate more DC-native loads, Schneider Electric leads the way in hybrid AC/DC power distribution. Our solutions minimize energy losses, simplify integration of renewables and storage, and enable direct, efficient use of on-site energy.

Hybrid AC/DC architectures developed by Schneider help buildings reduce grid dependence, lower peak demand, and support features like flexibility, demand response and load shifting. This accelerates progress toward net-zero goals while enhancing operational resilience.

With decades of experience in electrification, automation, and digital transformation, Schneider supports customers from design to operation, ensuring every building is resilient, sustainable, and ready for the future.

Nexans
Cables are a foundational element of any building's electrical infrastructure. As the energy landscape evolves, they are becoming a key enabler in the shift toward DC-powered architectures.

Nexans is actively supporting this transformation by designing and manufacturing cable systems specifically engineered for DC applications. Beyond product innovation, Nexans is also deeply engaged in shaping the future of DC-powered buildings through strategic partnerships and active participation in industry working groups.

Nexans strategically targets these segments with dedicated offerings. Our PWR Grid & PWR Connect empower DC cable for: solar power rooftop, EV grids, energy storage, and building power. The potential doesn't stop here, emerging opportunities include:

- Off-grid microgrids,
- Fast vehicle charging infrastructure,
- Commercial buildings,
- Data centers and beyond Nexans electrify the building of tomorrow with innovative DC Technology: Smart cable for DC infrastructures to ensure efficiency, reliability, safety and durability

VINCI Energies – Building Solution
Building Solutions is VINCI Energies business line dedicated to buildings. Buildings are at the heart of the major transformations underway: environmental transition, economic challenges, and sovereignty, particularly digital, demographic and societal changes. VINCI Energies Building Solutions contributes to their adaptation by making them more sustainable, live able and performant through customized multi-technical solutions and services, throughout their life cycle. For more than two years, we have been investing in the development and experimentation of building-scale direct current (DC) distribution.

This approach is part of a clear logic: prepare tertiary infrastructure for new electrical uses, optimize the integration of renewable energies and reduce losses related to AC/DC conversions.

Our commitment has materialized with the commissioning of the first building in France patiently powered by direct current: Wave, the North-East headquarters of VINCI Energies.

Tridonic
Tridonic, a global leader in sustainable lighting technology, is equally committed to pioneering advancements in direct current solutions for commercial environments. With an emphasis on intelligent lighting systems, Tridonic provides DC-based components that not only enhance energy efficiency but also enable seamless integration with renewable sources and storage.

Tridonic offers sustainable lighting solutions, including LED drivers and LED modules with industry-leading energy efficiencies. Its smart light management systems combine energy savings with user comfort through advanced sensors and control algorithms. Maintenance can be precisely scheduled with lifetime data, minimizing waste and service efforts. Energy usage data from Tridonic's LED drivers supports building energy monitoring and optimization and ensures compliance with future standards.

With its ongoing commitment to sustainability, Tridonic is teaming up with strong partners, demonstrating how a collaborative ecosystem of manufacturers, integrators and technology innovators is accelerating the adoption of DC power in the built environment.

These collaborations among key industrial leaders are essential to accelerate the adoption of DC technologies and establishing the standards that will guide the next generation of building design.

5. Use Case Definition

This study focuses on a typical large, multi-storey office building in Europe, with 10 floors, covering an area of 46,000 square meters and capable of accommodating 2000 people, to illustrate the challenges and innovation opportunities of implementing hybrid AC-DC distribution systems at scale. The high-rise structure introduces additional challenges such as increased and diverse energy demands across multiple floors, limited rooftop space for solar PV, and complex cable routing, making them an ideal case for evaluating strategies to optimize system efficiency, reduce conversion losses, and optimize power sharing between onsite generation, storage and load. While the focus is on large buildings, the findings are also relevant for mid-size buildings.

The white paper examines two configurations for an office building's electrical system. The first represents the present scenario: AC distribution integrated with distributed energy resources (DER) and electric vehicle (EV) charging, as shown in Figure 1. The second scenario explores an advanced hybrid AC-DC distribution architecture combined with DER and EV integration, in which a dedicated DC bus powers DC loads and connects directly to renewable DC energy generation and storage, as shown in Figure 2.

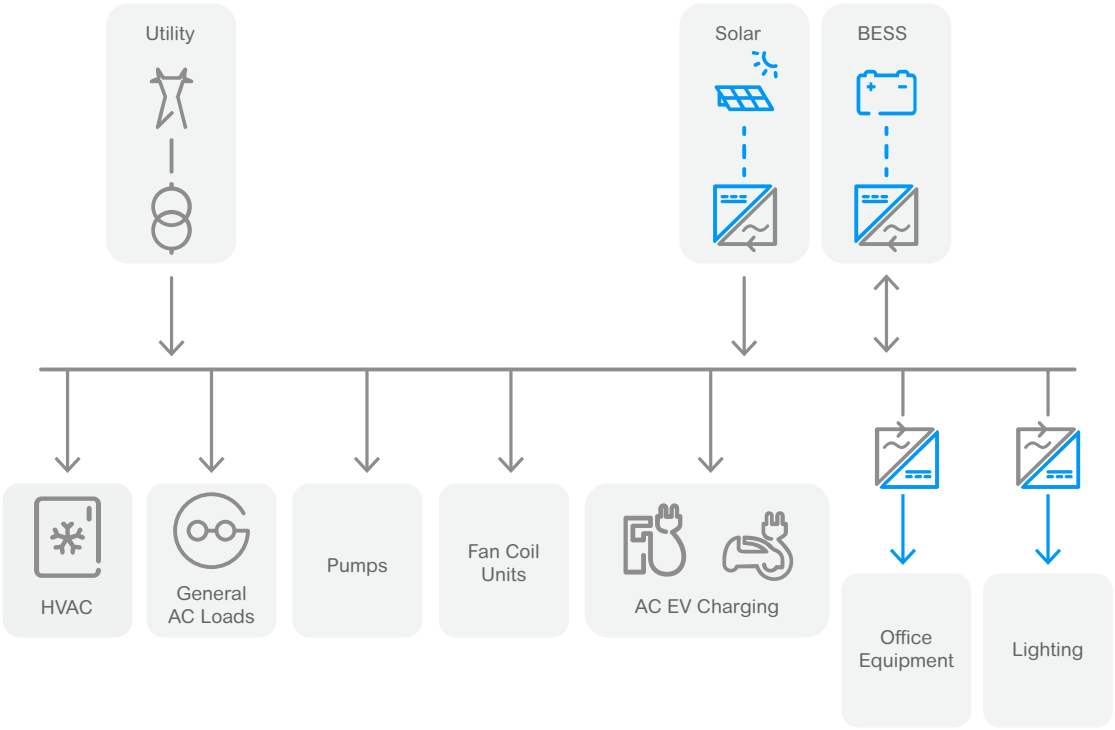


Figure 1: AC Architecture

In an AC-based configuration, DC native elements such as solar PV system, and the BESS must be converted to AC using an inverter. Supplying this energy to a DC load like an electric vehicle battery requires an additional conversion stage. In the case of AC EV charging, vehicle's onboard charger converts the AC supply back into DC to charge the battery, while the external AC charger primarily functions as a conduit for power delivery. To ensure that grid interaction remains within the defined capacity, an energy management system should be implemented.

Figure 2 illustrates a representative hybrid AC–DC architecture for an office building. Unlike a conventional AC-only distribution system, this configuration integrates both AC and DC networks, enabling greater efficiency and flexibility. Since battery energy storage systems (BESS) and solar PV inherently operate in direct current (DC), connecting these DERs directly to the DC network eliminates the multiple DC–AC and AC–DC conversion stages typically required in fully AC-based systems when supplying DC loads such as electric vehicle charging. DC-native loads can then be supplied through dedicated DC–DC converters for voltage adaptation and regulation within the DC network, enabling efficient power delivery across different voltage levels. The DC-to-DC charger further minimizes repeated power conversions and allows energy to bypass the onboard charger (OBC), delivering DC power straight to the electric vehicle battery.

It is to be noted that some of the native DC loads may require a DC-DC converter to adapt the system voltage to its rated voltage.

The hybrid system operates within the specified grid capacity limits for both export and import of power through an Interlink Converter (ILC). This converter facilitates bidirectional power flow and ensures that the building's interaction with the grid remains within contractual capacity. In the hybrid building scenario, the voltage droop control strategy automatically balances power flows between multiple sources and loads that are connected to the DC backbone.

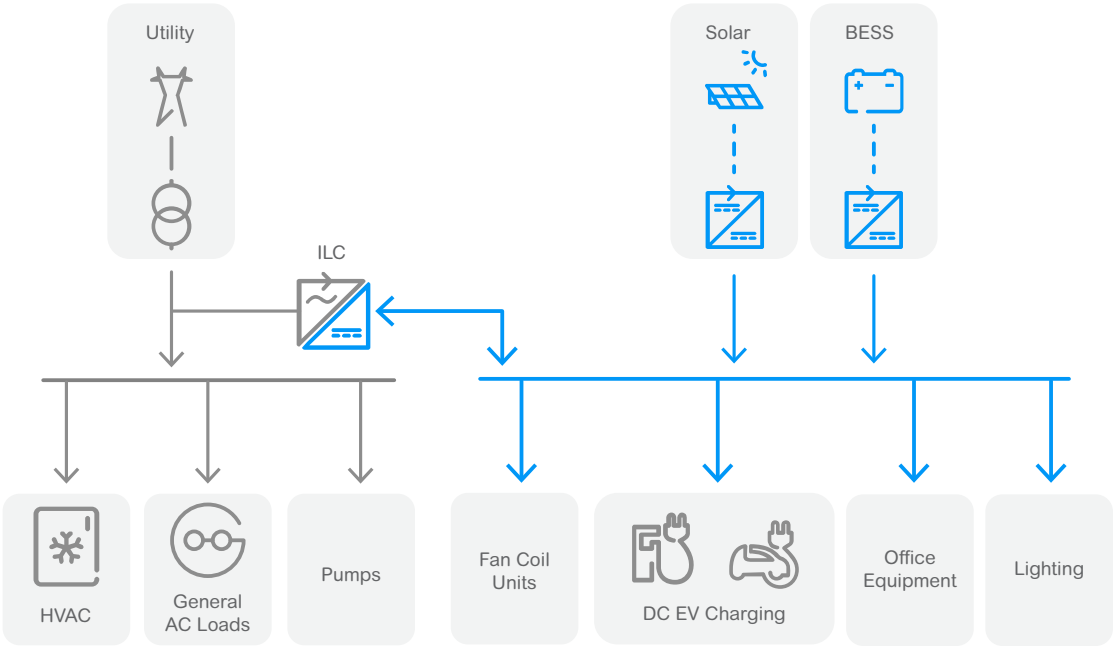


Figure 2: Hybrid AC-DC Architecture

Design Considerations

Table 1 presents the key design considerations for the office building case that is considered for this whitepaper. The design approach follows CIBSE and BSRIA guidelines, which provide standardized methods for estimating energy demand, load density, and diversity factors. By adhering to these guidelines, the study ensures that baseline calculations for the building's energy requirements are aligned with best practices for office buildings in Europe, while considering the constraints of typical building structures and infrastructure.

Parameter	Value
Building area	46000m²
Number of levels	10
Transformer capacity	2x2MVA (operating in parallel)
EV charging spaces	16
Rooftop Solar	300kWp
BIPV	200kWp
Carport Solar PV	100kWp
Carport Solar PV	120kWp

Table 1: Building Characteristics

Building Characteristics

Typical Office Layout: The spatial layout of the office building is distributed across multiple levels, each designated for specific functions. Levels 1- 8 primarily accommodate office-related spaces, including meeting rooms, work areas, and support facilities. Level 9 is configured for collaborative and technical operations, featuring larger meeting rooms, computer areas, and dining facilities. The ground floor is allocated for public-facing and utility functions such as reception, retail, dining, parking, and essential services. For detailed information on area allocations, layout is shown in Figure 3 and 4.

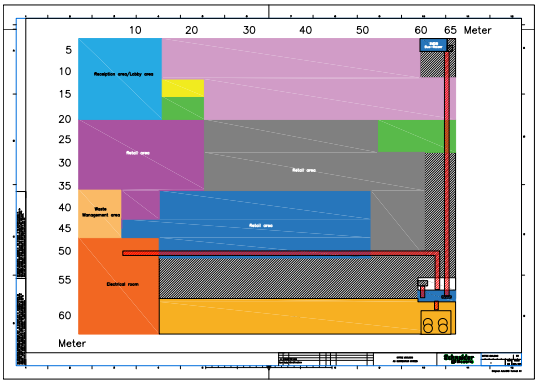


Figure 3 Layout of Ground Floor

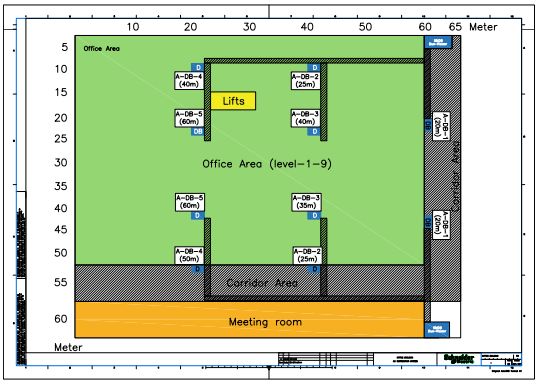


Figure 4 Layout of Level 1 to Level 9

Typical Electrical Loads in Office Building: For this study, the electrical loads for an office building are estimated with typical shares referenced from CIBSE guidelines and BSRIA Rules of Thumb. The HVAC systems including chillers and air handling units, typically represent the largest portion of demand, followed by office equipment and lighting systems. Secondary categories such as vertical transport, water pumps, and kitchen services contribute to additional demand, while integration of electrical vehicle infrastructure can introduce variable loads depending on charging capacity and utilization. Understanding these load categories is essential for accurate system sizing and energy modelling. Table 2 Represents the type of loads considered for the office building.

S.No.	Type of Loads	Power (KW)
1	Lighting	227
2	Office Equipment/ Plug Loads	824
3	Air Handling Unit	554
4	EV Charging	176
5	Chiller	1536
6	Vertical Transport	88
7	Kitchen Equipment	50
8	Water Pump	50

Table 2 Electrical loads and Power rating

6. Comparison of AC vs Hybrid AC-DC

Table 3 shows a comparative study conducted to evaluate conventional AC and Hybrid AC-DC electrical systems from an architectural and systems integration perspective. The analysis considers the electrical architecture of office buildings and examines how each system influences equipment sizing, cables and installation requirements.

Parameter	AC Architecture	Hybrid AC-DC Architecture
Distribution Architecture	Single AC network	Integrated AC and DC networks
Supply Configuration	Two 2 MVA transformers feeding AC distribution	Dedicated 2 MVA AC and 2 MVA DC distribution sections
Distribution Voltage	400/230 V AC	400 V AC, 700 V DC, 350 V DC, 48 V DC
PV Integration	PV connected through AC network	PV connected directly to DC bus
Battery Storage	300 kW / 450 kWh connected to AC system	300 kW / 450 kWh connected to DC system
Load Allocation	All loads supplied via AC	AC loads remain on AC; lighting, FCUs, EV chargers, and part of plug loads supplied via DC
EV Charging	16 × 11 kW AC chargers	16 × 11 kW chargers supplied from DC bus
Power Conversion	Multiple AC–DC/DC–AC conversion stages	Reduced and efficient conversion stages for DC-native sources and loads
AC–DC Interconnection	Not applicable	Bidirectional Interlink Converter (ILC)

Table 3 Key Architectural Differences Between Conventional AC and Hybrid AC–DC Distribution Systems

The electrical distribution system for the office building as represented in Figure 5 is an AC architecture, which is designed to integrate the conventional grid supply with on-site renewable energy generation, energy storage, and electric vehicle solutions. The system operates at low-voltage levels of 400 V three phase, 230V single phase, and is structured around the following key components as shown in table 3.

In the hybrid AC-DC architecture as shown in Figure 6, the office building employs a hybrid AC-DC supply and distribution system architecture designed to better utilize the DC power produced within the office facility to power the loads such as IT infrastructure that operates on DC power. There will be two sections of power supply and distribution in this case, viz., AC source and its corresponding AC loads and DC source and its corresponding DC loads.

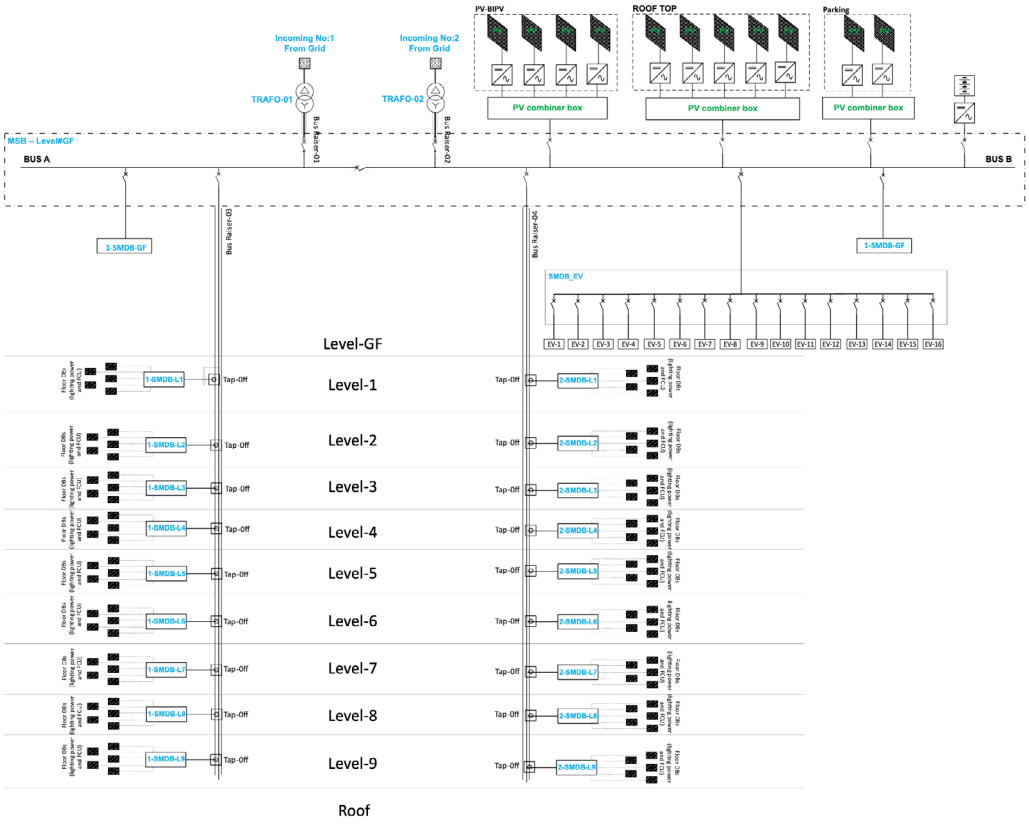


Figure 5 Conventional AC Architecture of Office building

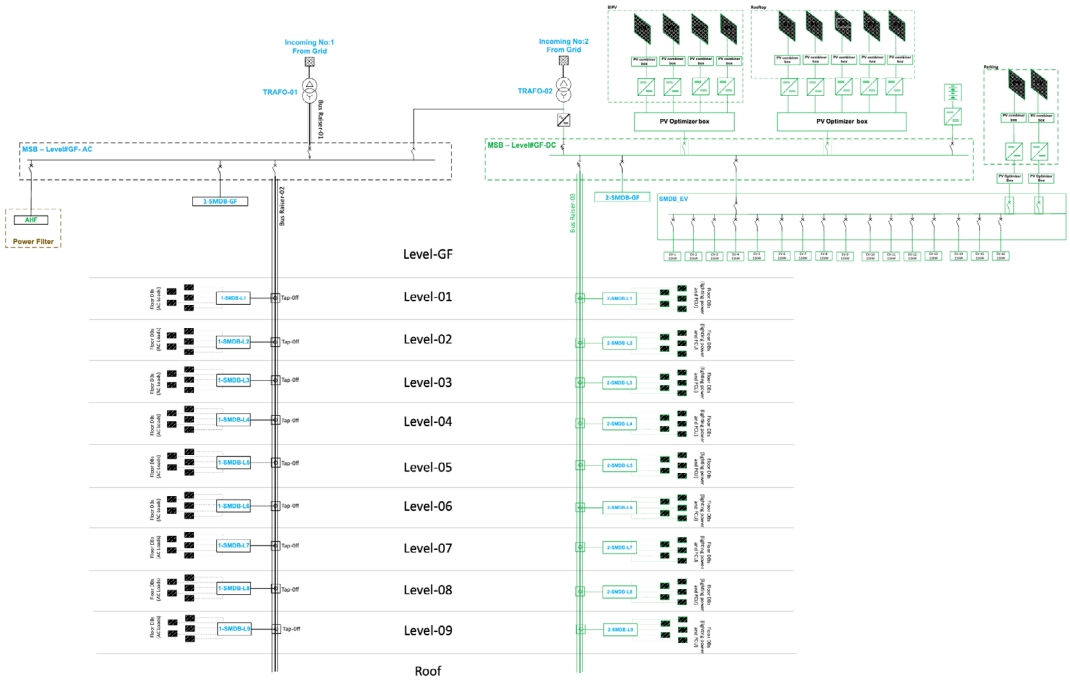


Figure 6 Hybrid AC-DC Architecture of Office Building

Equipment Sizing

Power Analysis for Component Sizing and Control Strategy Definition

The sizing of system components requires a comprehensive analysis of both DC and AC power demands. A key parameter in this process is the maximum DC load power, which directly influences the dimensioning of the Interlink Converter (ILC). For this analysis, only essential DC loads are considered excluding EV charging, which is treated as a non-priority load. This ensures that the ILC is sized to support critical DC loads under peak operating conditions.

Winter Demand Assessment and Initial ILC Sizing

The winter energy demand analysis indicates several days with elevated heating requirements. Based on these observations, an initial ILC capacity of 1 MW is proposed. Under this assumption, we evaluate the energy associated with unmet DC loads to determine whether the proposed capacity is sufficient or requires adjustment. This assessment is crucial for validating the ILC's ability to support essential DC loads during peak demand periods (as shown in Figure 7).

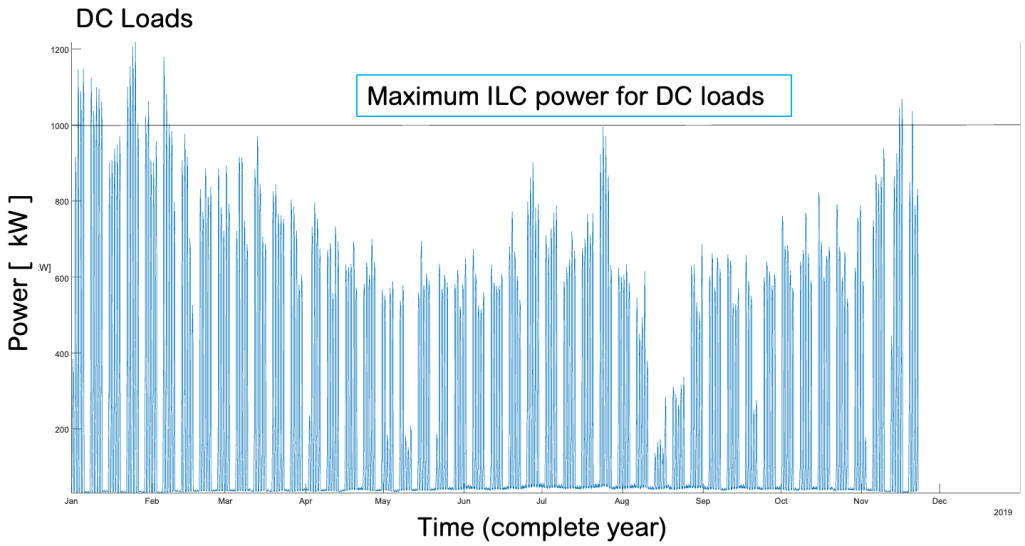


Figure 7 DC Loads power profile during the year

PV Curtailment and Minimum AC Load Considerations

The Interlink Converter (ILC) also plays a critical role in managing photovoltaic (PV) power. When PV generation exceeds local demand, the surplus energy is redirected to the building's AC loads via the ILC. In France and certain other countries, feeding excess PV power into the public grid may not be permitted due to regulatory constraints. Therefore, it is essential to determine the maximum amount of power that the ILC can safely and effectively redirect to the AC loads without exceeding system or legal limits to evaluate this function, it is necessary to identify the minimum AC power demand of the building, particularly during low-consumption periods such as summer weekends. This minimum load defines the baseline capacity required to absorb PV generation locally and avoid grid injection. Accurate estimation of this value is essential for assessing the ILC's effectiveness in PV curtailment and grid compliance. As shown in Figure 8, we can see on the AC building power profile the minimum power needs.

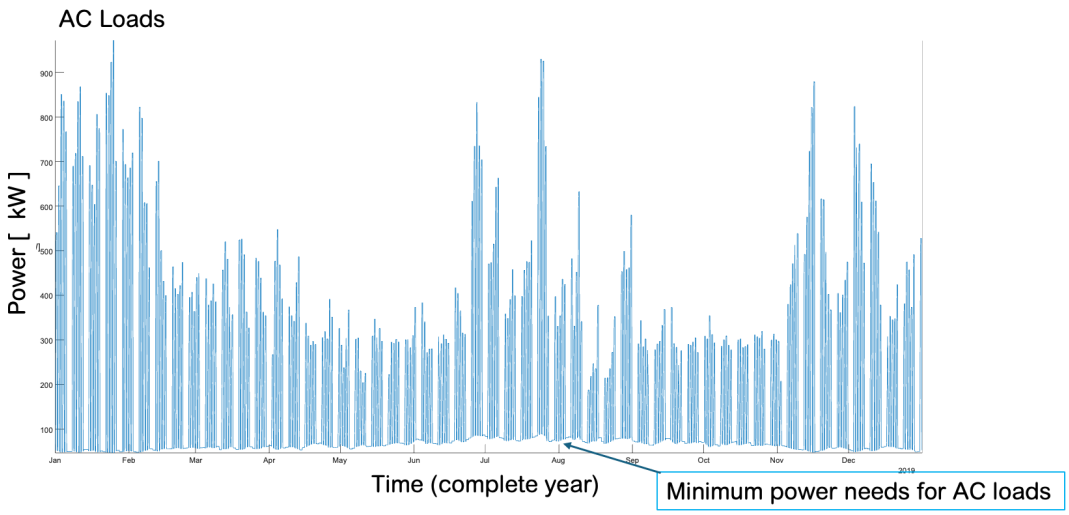


Figure 8 AC Loads power profile during the year

For example, during summer weekends when DC power demand is low, it may be necessary to curtail PV generation to maintain system stability. This is especially important when using droop control strategies and in regions where feeding excess energy into the grid is restricted or prohibited. In such cases, limiting PV output helps prevent overgeneration and ensures compliance with grid regulations. Figure 9 represents the PV curtailment when DC power demand is low.

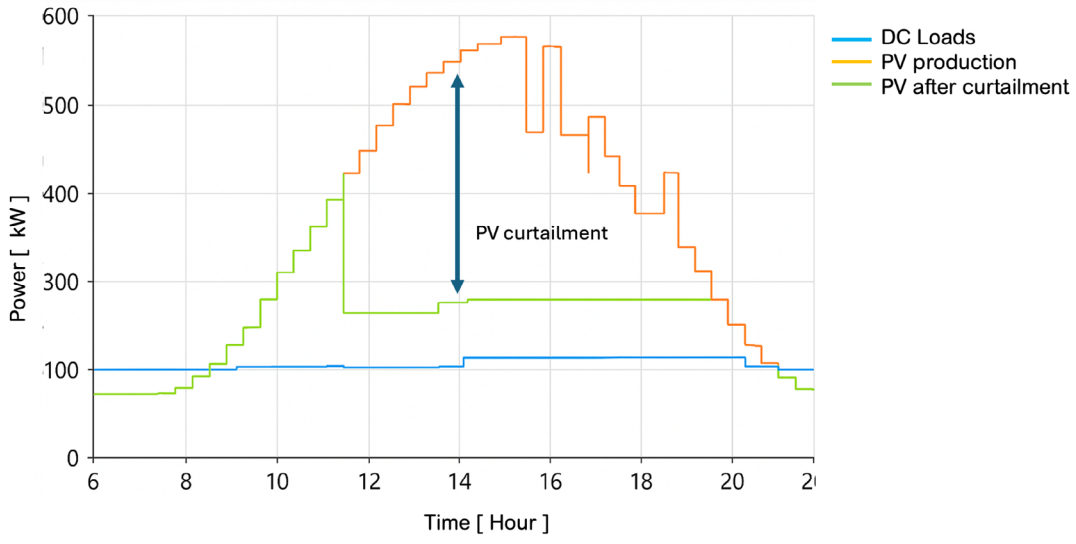


Figure 9 PV curtailment

Conversely, during summer weekdays when DC power demand is sufficiently high, the entire PV output can be utilized without curtailment, as shown in Figure 10. In such scenarios, the system operates efficiently by directly supplying DC loads from PV sources, minimizing conversion losses and maximizing renewable energy usage. This optimal alignment between generation and consumption supports both energy efficiency and grid compliance.

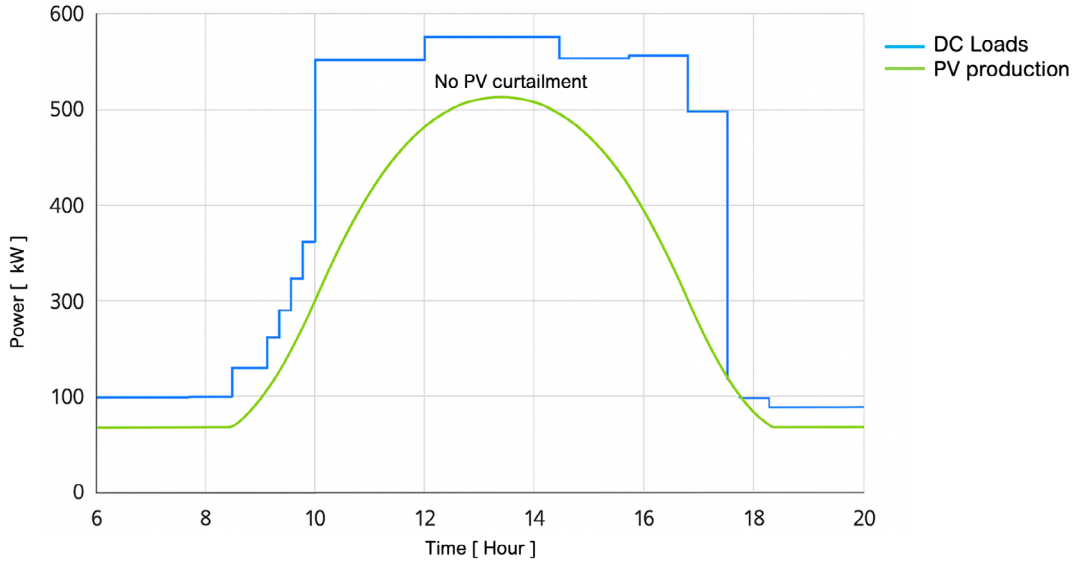


Figure 10 No PV curtailment

ILC Power Feed-In Management Strategies

To manage the maximum power feed-in from the interlink converter (ILC), several control strategies can be considered:

- Fixed Limit Strategy: A static droop curve is defined with a fixed maximum power threshold. This approach simplifies control but may not adapt well to varying AC building conditions.
- Dynamic Limit Strategy: The droop curve is adjusted in real time based on grid power measurements. This allows the ILC to respond dynamically to grid conditions, optimizing feed-in while maintaining system stability and compliance.

As a first approach, a static droop curve is implemented with a predefined maximum power threshold of 90 kW for the fixed limit strategy. This approach simplifies control but may lack adaptability to fluctuating AC building loads. These two strategies will be evaluated to determine their effectiveness in limiting PV feed-in and supporting grid-friendly operation.

BESS Sizing for AC distribution

For the AC distribution configuration, a BESS is integrated to improve grid flexibility and resilience within the low-voltage (LV) network of the office building. The BESS connects to the grid via its own inverter (AC-coupled) and operates under an intelligent EMS that balances supply and demand, optimizes stored energy use, and supports peak shaving. Time-of-use tariffs, demand response, and predictive control further enhance operational efficiency. For this case, the BESS is sized at 300 kW with a usable storage capacity of 450 kWh, supporting daily load shifting and backup capability.

BESS Sizing for hybrid AC-DC distribution

In the hybrid AC–DC configuration, the same BESS is DC-coupled, directly connected to DC-generating sources such as rooftop PV through DC/DC converters. This reduces conversion losses, improves system efficiency, and enables optimized control of the DC bus.

Voltage droop control ensures power balance within the DC microgrid, while the EMS coordinates interaction with the AC side for grid services and tariff optimization.

During periods of low DC power demand, such as nights and weekends, it is important to consider the efficiency losses of the Interlink Converter (ILC) when operating at low load. In this office building scenario, the minimum demand is below 10% of the ILC's rated capacity, a range where most converters perform inefficiently. To address this, internal designs that use parallel power modules can enhance efficiency across varying load conditions. Modular converters can deactivate some modules to match the load, maintaining a high load factor for optimal energy efficiency. Therefore, assessing the full efficiency curve is essential, rather than focusing only on peak efficiency.

To minimize power losses during low-demand periods, we recommend selecting an ILC with high efficiency across a broad operating range. Additionally, we propose a strategy to shut down the ILC during nights and weekends, when DC demand is minimal. To maintain power supply to the DC building loads during these times, the BESS is charged in advance and used to deliver the required energy.

This approach can increase overall system efficiency by 10% to 20% for office building application. In the proposed configuration, the BESS is charged twice daily during weekends or when the building is unoccupied, and once daily during regular weekdays. Based on this operational strategy, the selected capacity remains 300kW (DC/DC converter) with 450 kWh of storage, providing flexibility for DER integration, load management, and resilience improvement.

Solar PV Sizing

Due to the high-rise configuration of the building, the available rooftop area alone is insufficient to accommodate the target photovoltaic (PV) capacity. To overcome this limitation, additional building surfaces have been utilized, including Building-Integrated Photovoltaics (BIPV) on the façade and PV installations on the car park canopy. This integrated approach maximizes the use of available surfaces and enables the deployment of an overall PV capacity of approximately 600 kWp.

PV generation exhibits significant seasonal variation, with considerably lower output during the winter months. Furthermore, PV production is occasionally constrained to maintain system stability and prevent power export to the utility grid. Despite these operational limitations, the PV system plays a substantial role in meeting the building's energy requirements.

During the summer season, PV generation supplies nearly 50% of the building's DC energy demand, highlighting its importance in achieving seasonal energy balance and reducing dependence on external energy sources. However, only a small fraction of the generated PV energy is delivered to the building's AC network, with AC-side reinjection remaining minimal.

Lighting System

Lighting is a key subsystem in office buildings and, in hybrid AC/DC architectures, can be powered entirely by DC, making it a critical component for overall system evaluation. In hybrid AC/DC configurations, multiple supply topologies are possible. For outdoor lighting applications, a 700 V DC distribution system offers performance characteristics comparable to conventional 400 V AC systems while providing efficient power delivery and supporting long cable runs with reduced current levels. For indoor lighting applications, a 350 V DC distribution system provides similar functionality to traditional 230 V AC installations while maintaining compatibility with commercially available lighting technologies and building electrical infrastructure

The next distribution voltage level is the 48 V DC topology, which helps connect last-mile loads that operate at 48 V or lower. While the lower distribution voltage requires higher current for the same power transfer, potentially resulting in a marginal increase in cable voltage drop, this can generally be managed through appropriate conductor sizing and distribution design. In addition, 48 V systems offer important advantages in terms of safety, as they enable touch-safe operation and simplify installation requirements, a consideration that aligns well for high-density office fit-out practices where flexible, low-voltage desk and task lighting is common.

For reliable operation in DC, fast pre-charge during black start and defined behavior during hot-plug events shall be considered. Digital control of the lighting system is preferred as it enables both simple manual operation and automated lighting management, allowing light levels to be adjusted based on occupancy, ambient daylight conditions, and user preferences. This approach enables maximum energy savings, simplified installation, and flexible configuration of the lighting system.

In this study, the lighting system is designed for 350 V DC luminaires. The output characteristics of the LED drivers resembles that of their AC counterparts, ensuring seamless interoperability with existing LED boards. These drivers support standard lighting control interfaces (e.g., DALI) and auxiliary-powered sensors, enabling flexible installation, simplified system configuration, and optimized energy performance in hybrid AC/DC environments. The architecture also supports desk lighting and free-standing luminaires supplied via USB-C interfaces at 48 V providing additional flexibility for low-power and user-accessible applications.

DC Cables

Cables are critical in DC infrastructures, connecting DC loads to multiple sources such as PV panels and batteries. In this study, LVDC cables are designed for hybrid AC-DC office buildings, meeting efficiency, reliability, safety, and durability requirements. Key features include:

- DC-Specific Design: Optimized for building applications, addressing insulation performance, voltage levels, unipolar/bipolar configurations, safety requirements, and bus design.
- Performance & Lifetime: Engineered to maintain reliable operation under continuous DC stress, comparable to AC cables.
- Compatibility & Efficiency: Tested for interoperability with standard DC equipment. DC systems reduce losses, improve voltage utilization, and transmit more power using the same conductor material.
- Ergonomic Installation: Flexible, easy-to-handle cables simplify installation, maintenance, and dismantling.
- Enhanced Safety: Inter-tripping mechanisms and low fire hazard materials ensure safe operation across multiple sources, with features such as ripcords for knife-free dismantling.
- Sustainability: Environmentally responsible materials and transparent reporting support sustainable building design.
- Research & Innovation: Understanding LVDC behavior is key, as it differs from traditional AC systems, providing opportunities for optimized hybrid AC-DC infrastructures.

As part of this study, a thorough cable sizing calculations including the voltage drop and energy losses analysis were done for both, AC and Hybrid AC-DC configurations. Please refer below figures for the output results with respect to copper mass comparison and energy losses for AC and Hybrid AC-DC configurations.

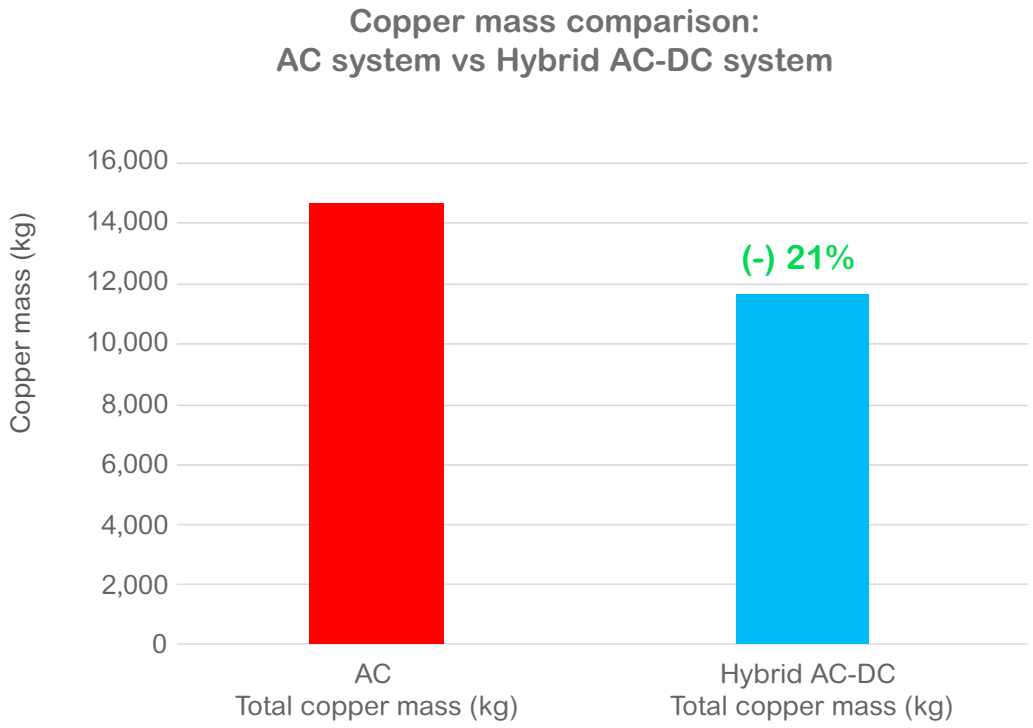


Figure 11 Copper mass comparison: AC vs Hybrid AC-DC

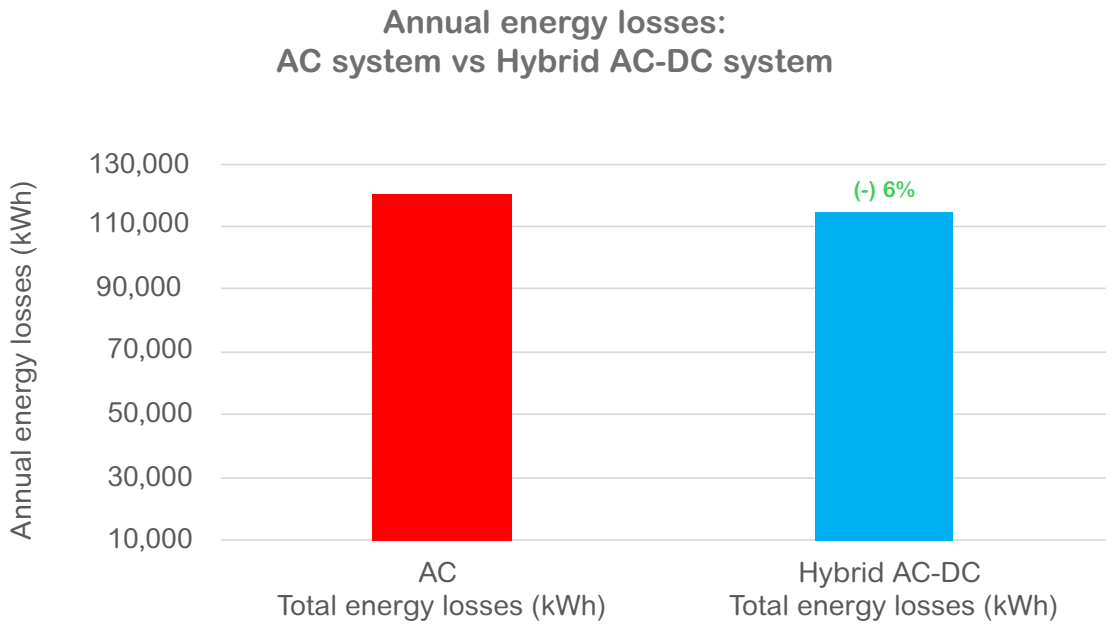


Figure 12 Annual energy losses in the cables: AC vs Hybrid AC-DC

Installation Requirements

Implementing a hybrid AC-DC system requires careful planning to ensure safe, reliable operation. Key considerations include:

- System Design & Segregation: DC cables must be sized to handle appropriate currents and voltage drops, with right cable selection. Clear physical and functional separation from AC pathways minimizes interference and simplifies maintenance.
- Protection & Switching: DC-rated protection devices and disconnectors are essential. Electronic (solid-state) circuit breakers, arc fault protection, and proper selectivity ensure safe operation for DC loads.
- DC Distribution Infrastructure: DC distribution extends to end-use applications such as lighting and device charging, while intermediate distribution supports higher-power subsystems. Dedicated distribution boards and combiner boxes interface with sources such as solar PV system and batteries.
- Monitoring & Management: Building and energy management systems should be flexible to monitor both AC and DC networks. Zone-level DC metering enables precise consumption analysis and optimized load management.
- Compliance & Certification: Systems must meet low-voltage and DC-specific guidelines, such as for arc protection and load breaking, with third-party certification recommended for regulatory compliance.

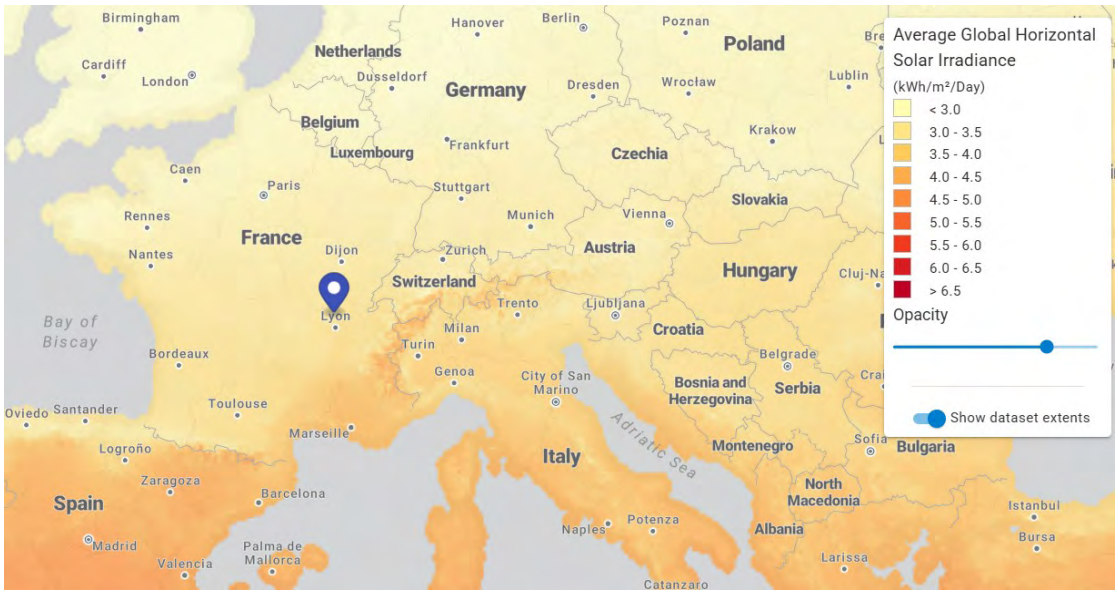
7. Benefits of Hybrid AC-DC

Energy Savings

A detailed study has been conducted to analyze the potential energy savings of a hybrid AC-DC system compared to a conventional AC system. For this analysis, energy data provided by Vinci for the office building has been used. Assuming an average energy consumption of 150 kWh/m²/year, the total annual energy use is estimated at approximately 6,900 MWh/year.

In this study, heating is excluded from the electrical load analysis, as it is assumed to be supplied by alternative energy sources such as natural gas. This allows the focus to remain on electrical consumption related to other building systems, including cooling, ventilation, lighting, plug loads, and EV charging infrastructure.

The selected location for the analysis is Lyon, France, which offers a representative solar irradiance profile that serves as a balanced compromise between northern and southern European conditions. This makes it a suitable reference point for evaluating the performance of PV-integrated energy systems in a temperate European climate.



Copyright: NSRDB: National Solar Radiation Database
The figure shows solar irradiance and temperature data are retrieved for Lyon.

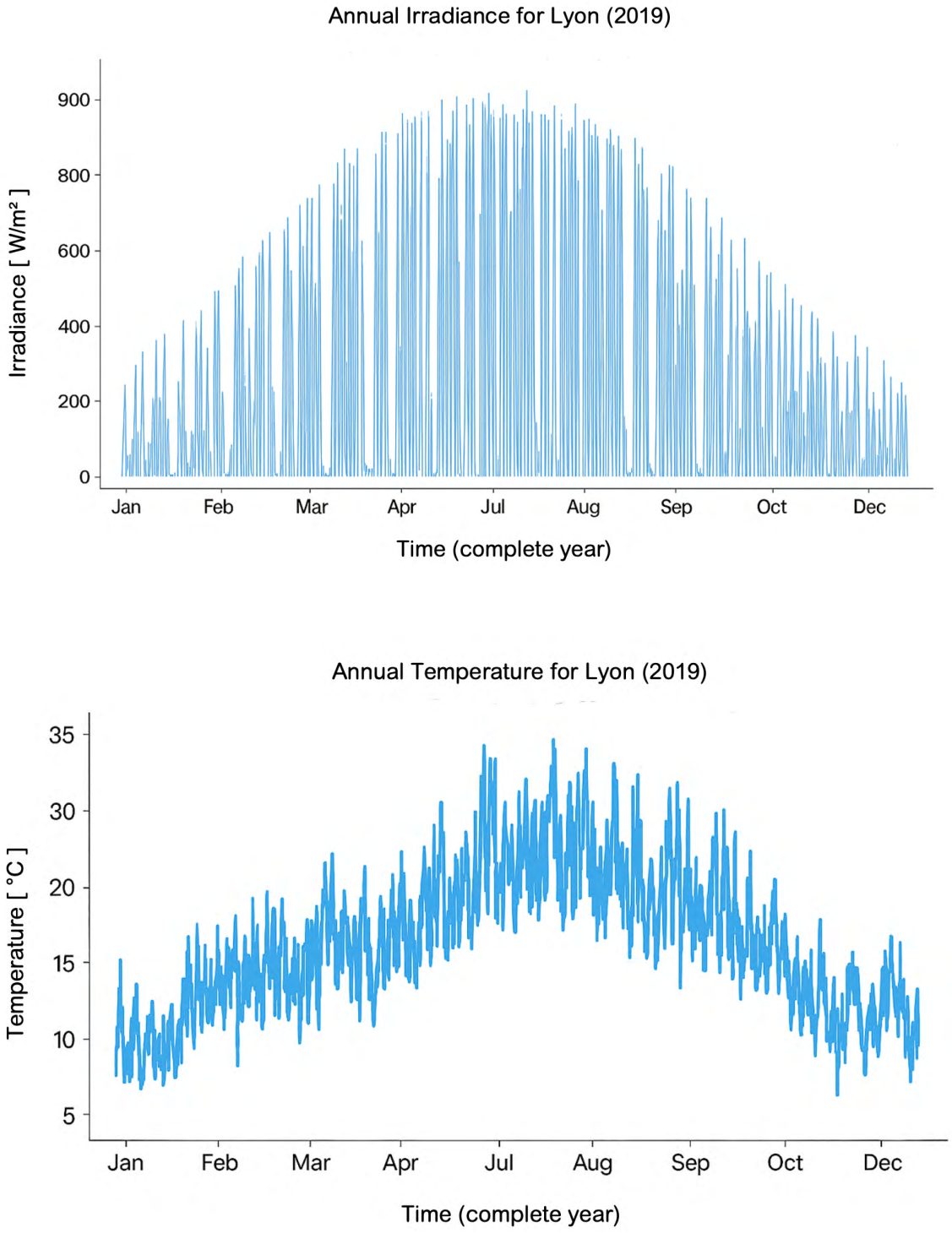


Figure 13: Annual Irradiance and Temperature for Lyon

The table shows the resultant power and efficiency of the converter in the AC and hybrid AC-DC configurations.

		AC	Hybrid	
ILC	Power		1000	kW
	Max Efficiency		98	%
PV inverter	Power	600	600	kWp
	Max Efficiency	98,5	99,5	%
BESS charger	Power	300	300	kW
	Capacity	450	450	kWh
	Max Efficiency	97	98,6	%
EV charger	Power	16 x 11	16 x 11	kW
	Max Efficiency	88	98	%
700/350V DC-DC converter	Power		1000	W
	Max Efficiency		98	%
350/48V DC-DC converter	Power		1000	W
	Max Efficiency		98	%
230/48V AC-DC converter	Power	1300		W
	Max Efficiency	88		%

Table 5 Power and Maximum efficiency of Converters

This comparison is based on simulations of building behaviour under realistic use cases and climate conditions. The goal is to evaluate energy flows and power losses while considering all relevant constraints. The developed models will incorporate converter efficiency, power limitations, and control strategies to enable a comprehensive comparison of energy exchanges between sources (grid, PV, and BESS) and all building loads.

The figure represents the Annual power flows simulation results for AC distribution.

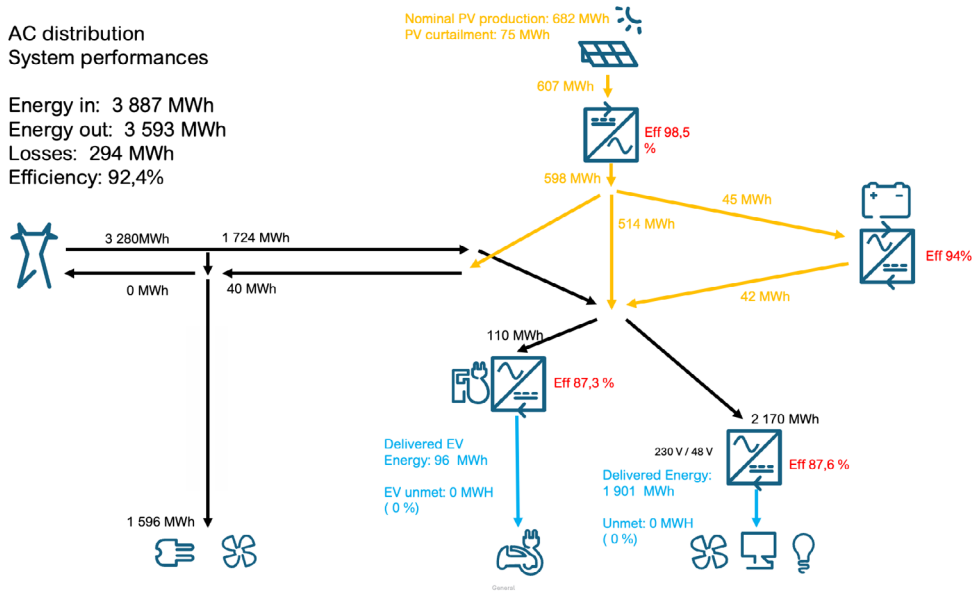


Figure 14: AC distribution power flow and energy losses

The figure below shows annual power flows simulation results for AC-DC Hybrid distribution.

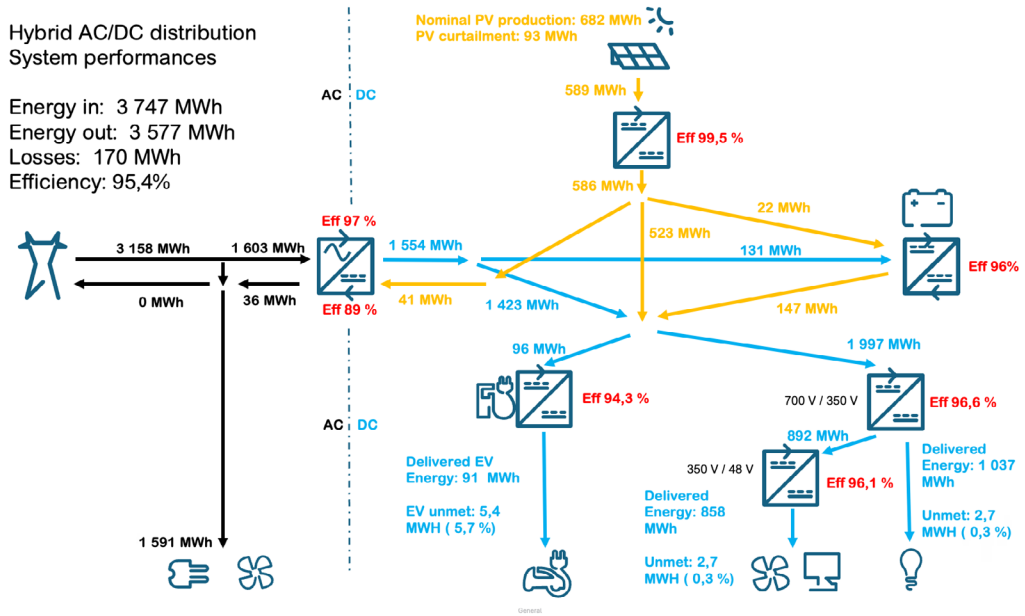


Figure 15: Hybrid AC-DC distribution power flow and energy losses

Energy flow savings

	AC	Hybrid	
Grid import	3 279 900	3 158 100	kWh
Grid feeding	0	0	kWh
PV	607 571	589 254	kWh
HVAC, Plug, DHW	1 596 041	1 591 031	kWh
Plug, CTA, light	1 900 600	1 894 490	kWh
EV (battery)	96 240	90 539	kWh
BESS	41 871	147 111	kWh

Table 5 Energy Flow savings

The hybrid architecture configuration demonstrates a 3.7% reduction in grid energy import compared to the reference scenario. This improvement reflects the enhanced energy autonomy enabled by the integration of local generation and storage.

Despite the imposed power limitations, the unmet energy for EV charging is 5.9% and DC loads remains minimal, only 0.3%, which is considered negligible in the context of overall system performance. This confirms that the proposed sizing and control strategies are effective in maintaining service continuity for critical loads while optimizing grid interaction.

Energy losses comparison

	AC	Hybrid	
ILC		57 704	kWh
PV	9 114	2 946	kWh
BESS	2 523	5 806	kWh
EV charger	14 001	5 515	kWh
700/350V DC-DC converter		68 500	kWh
350/48V DC-DC converter		34 510	kWh
230/48V AC-DC converter	269 000		kWh
Total	**294 638**	**174 981**	**kWh**

Table 6 Energy losses comparison

The adoption of a hybrid system architecture enables a significant reduction in energy losses, 42% less, compared to conventional configurations. The improvement is mainly due to the assumed reduction of losses in the converters (700V dc to 48V dc compared to 230V ac to 48 V dc). In hybrid AC-DC systems, the main energy losses often originate from the ILC, particularly during periods of low power usage. To mitigate these losses, a control strategy that temporarily disables the ILC and instead utilizes the BESS proves highly effective. This approach maximizes the use of DC sources for powering DC loads, enhancing overall system efficiency and reducing unnecessary AC-DC conversion losses. The hybrid approach not only enhances overall system efficiency but also contributes to improved sustainability and reduced operational costs.

System efficiency

Focusing on the specific perimeter of the installation where the AC and hybrid architectures differ, we can assess the respective system efficiencies. The AC architecture achieves an efficiency of 87%, while the hybrid architecture reaches 92%. This notable improvement highlights the benefits of hybrid integration in terms of energy conversion, distribution, and overall system performance.

Benefits for Cables

The shift to hybrid AC-DC power distribution improves overall system efficiency and delivers clear benefits for cabling infrastructure. These advantages become increasingly important as buildings add more renewable generation, energy storage, EV charging, and electronic loads.

Cable transmission efficiency

The transmission efficiency of AC and DC cables can be compared on two levels: intrinsic cable properties and system architecture.

Intrinsic properties: Skin and proximity effects occur only with alternating currents (frequency domain) that create changing magnetic fields. These losses depend on frequency, conductor material, cross-section, and conductor arrangement.

System architecture: AC and DC power transfer capabilities differ at the grid design level, notably in configuration, voltage selection, and cable cross-section choices.

a) Cable transmission efficiency based on electromagnetic effects

The changing magnetic field modifies the cable impedance, leading to surface current crowding (skin effect) and current crowding from nearby conductors (proximity effect). In steady-state operation, these intrinsic effects are characteristic of AC systems; in DC systems, they appear only during transient events such as short circuits. However, these effects are more pronounced for cables with large cross sections. The IEC 60364-5-52 (selection and installation of wiring systems), together with IEC 60502-1 (construction, dimensions, and tests for extruded-insulation power cables), allow cable cross-sections up to 630 mm². Therefore, for low-voltage cables with cross-sections above 300 mm², skin and proximity effects cause a difference between AC and DC current-carrying capacity. Figure 16 shows the difference in AC and DC current carrying capacity simulated for maximum conductor temperature of 90°C and ambient temperature of 30°C assuming identical configurations for AC (single-phase) and DC (unipolar) cables: three cores with XLPE insulation rated at 90°C.

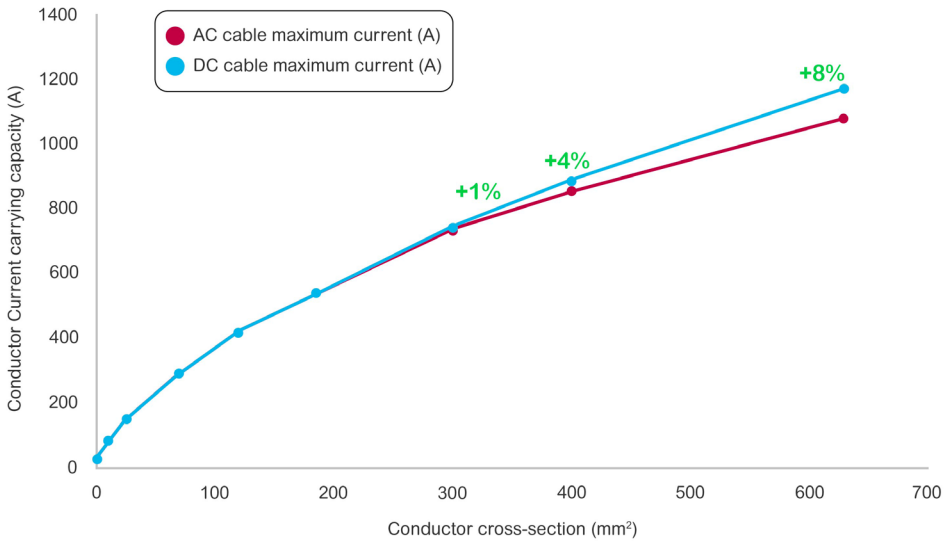


Figure 16 Maximal admissible AC and DC current for a trefoil XLPE insulated copper conductor (for comparison purpose)

There is a pronounced difference between AC and DC current-carrying capacity for cross-section above 300 mm², and this gap widens as conductor size increases.

b) Cable transmission efficiency based on system architecture

In DC building power architectures, Current/OS supports multiple voltage levels. From a distribution and end-user perspective, a unipolar 350 VDC level is comparable to single-phase 230 VAC, while a unipolar 700 VDC level corresponds to three-phase 400 VAC. Under identical installation conditions (installation method, cable grouping, ambient temperature), higher DC voltage enables lower current for the same transmitted power than AC.

Assuming skin and proximity effects are negligible for cross-sections below 300 mm² under normal operating conditions, and given that building cables are generally unshielded, the maximum admissible current specified by IEC for each low-voltage standardized cross-section can be considered equivalent for AC and DC.

This allows to quantify the power capacity increase achievable with DC by using higher voltage levels. For installations on cable trays or ladders (IEC 60364-5-52 reference method E), assuming a maximum conductor temperature of 90°C, an ambient temperature of

30°C and a power factor of 0.95 for the 230/400 VAC system, Figure 17 shows a marked difference between DC and AC in the maximum transferable power for identical cross-sections, without exceeding the thermal limits of the insulation.

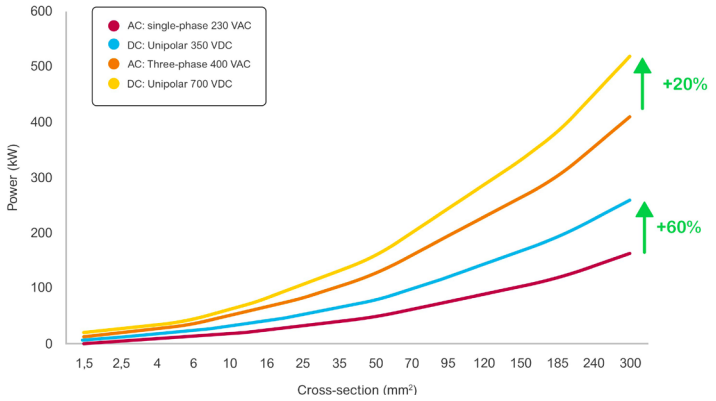


Figure 17. Comparison of maximum reachable power for each cross-section, between single phase 230 VAC and unipolar 350VDC and between three-phase 400 VAC and unipolar 700VDC power distribution systems

Simply increasing the voltage level allows a unipolar 350 VDC system to transmit about 60% more power than a single-phase 230 VAC system across all cross-sections considered. At 700 VDC, the power gain exceeds 20% compared with the maximum transmissible power of a three-phase 400 VAC distribution system

c) Cable transmission efficiency by combining electromagnetic effects with the high-level power system design

By combining the aspects that can affect cable transmission efficiency as outlined above, we can draw up a total comparison of cable transmission efficiency. A single-phase AC system with rms voltage 230 V is compared with the equivalent 350 VDC unipolar system (as per Current/OS installation rules and IEC 60502 standards). The cable cross section varies from 1.5 mm² to 630 mm². Under single phase AC, cores are usually noted as L (Live), N (Neutral) and PE (Protective Earth). For unipolar DC, the cores are designated as L+ (Live), M (Mid-point), and PE (Protective Earth).

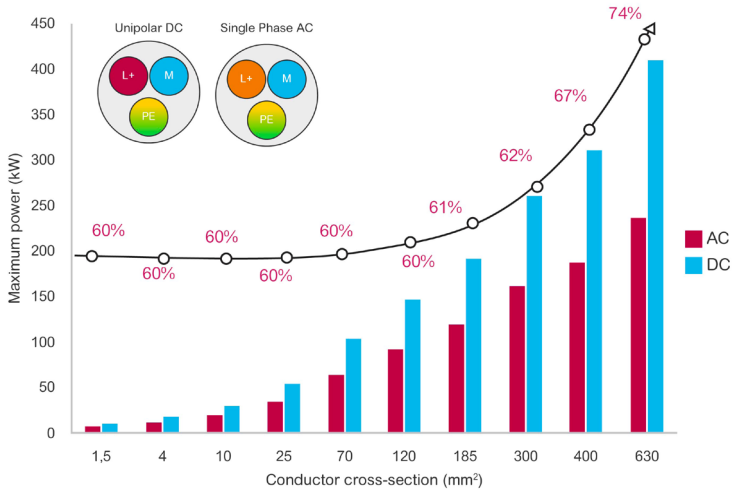


Figure 18. Comparison of maximum reachable power for each cross-section, between single phase 230 VAC and unipolar 350VDC by combining intrinsic effects with the impact of the power system voltage

Figure 18 shows the increase in DC power compared to AC power as a combined effect of the power system voltage level and the electromagnetic effects. The 60% increase in DC power transfer at 1.5 mm² until 300 mm² is mainly due to increase in system voltage, absence of reactive power and no induced currents in screen/PE. Skin and proximity effects for these cross sections are negligible. As the cross-section increases (> 300mm^2), DC becomes even more efficient since AC power transfer is limited by the skin/proximity effects.

Architecture Benefits

Efficiency & Performance

- Reduced conversion losses: Direct DC supply to DC-native loads (LEDs, EV chargers) minimizes energy waste.
- Smaller conductors: Lower current demand allows reduced cable cross-sections, saving copper/aluminum without compromising safety.
- Higher voltage efficiency: DC systems use higher voltages than AC RMS, reducing current, Joule losses, and heat—enabling tighter cable grouping and better conductor utilization.
- Improved transmission: DC eliminates reactive power, maximizing voltage usage and enabling more power through the same copper footprint.

Cable Optimization via Topology

- AC star topology: Each load has a dedicated branch, increasing cable length and material use.
- DC bus topology: Shared supply cables reduce parallel runs, simplify routing, and lower cable quantity.
- Material savings: Bus architecture allows reduced conductor sizes and less copper/aluminum usage.

Infrastructure Flexibility

- Future-ready: A common DC backbone supports easy integration of PV, batteries, EV chargers, and zone upgrades without major rewiring.

Sustainability & Material Gains

- Resource efficiency: Less raw material use lowers costs and environmental impact.
- Lower emissions: Higher system efficiency and reduced heating contribute to carbon reduction goals.
- Hybrid AC-DC benefits: Direct DC delivery at higher voltages reduces current and CO_2 emissions.

Safety & Reliability

- Stable renewable integration: Hybrid systems balance energy flows, preventing cable overloads.
- Fault isolation: Galvanic separation between AC and DC enhances protection and prevents fault propagation.
- Enhanced safety: DC systems with multi-source setups and inter-tripping wires improve fault handling and maintenance safety.

End User Experience
While the technical benefits of hybrid AC–DC systems are significant, their value is ultimately measured by how they improve the experience of the end user. Cabling solutions, together with DC-powered lighting systems and end-point socket outlets, play a critical role in ensuring that the benefits of DC distribution are translated into tangible outcomes in day-to-day operation.

Availability and Continuity of Service
- Stable supply: Hybrid AC–DC distribution reduces conversion steps and power losses, resulting in fewer disturbances and more resilient power delivery.
- Resilience with renewables: Users benefit from smoother integration of local energy sources (e.g., rooftop PV, on-site batteries), which increases availability during grid fluctuations or outages.

Improved Safety
- Reduced thermal stress: Reduced heat build-up in cables lowers the risk of overheating and fire, giving occupants greater confidence in system safety.

Efficiency and Cost Transparency
- Lower energy losses: Less wasted energy means lower utility bills, which is particularly noticeable in energy-intensive facilities such as offices.
- Optimized use of space: DC cabling reduces the physical footprint of cable trays and conduits, freeing up usable space in buildings and simplifying future upgrades.

Flexibility and Future-Readiness
- Seamless technology adoption: End users can integrate EV charging, energy storage, or smart building systems without major rewiring, reducing disruption and retrofit costs.
- Scalability: DC Cabling backbones are designed to support additional loads as demand evolves, ensuring that infrastructure remains relevant and adaptable.

Simplified Device Charging with DC
- Direct DC supply: Modern devices such as smartphones, laptops, and tablets increasingly use USB-C charging, which natively operates on DC. Hybrid AC–DC infrastructures allow USB-C sockets to be powered directly by DC, eliminating the need for multiple AC–DC converters.
- One cable, multiple devices: Users can charge several devices with a single cable, reducing clutter and improving convenience.
- Higher efficiency and speed: Fewer conversion steps mean lower energy losses and potentially faster charging times.
- Enhanced sustainability: Reduced reliance on individual chargers and adapters decreases energy waste and energy consumption.

Streamlined Design of Mobile Luminaires
- Desk lamps or free-standing luminaires may be powered directly via USB connections, thereby eliminating the necessity for electrical insulation. This increases user convenience and reduces overall costs.

Reducing Grid Congestion
A hybrid AC-DC architecture supports the reduction of grid congestion by facilitating localized power generation and direct use of DC power within the building. By integrating on-site renewable sources such as solar photovoltaic systems and supplying energy directly to DC loads like lighting, IT equipment, and electric vehicle chargers, the system reduces reliance on grid-supplied AC power.

This approach lowers peak demand; eases stress on transmission infrastructure and contributes to a more balanced and resilient electrical network within the building and its connection to the broader grid.

Effective Utilization of Power
A hybrid AC-DC architecture enables more effective utilization of power by aligning supply with the nature of the connected loads and minimizing unnecessary conversion steps. DC power generated from on-site sources such as solar PV systems can be directly consumed by compatible DC loads including lighting, IT equipment, and variable speed drives, reducing conversion losses typically associated with alternating between AC and DC. This targeted distribution approach ensures that energy is delivered effectively, improving system performance and allowing the building to make better use of available power resources.

Modularity and Expansion
A hybrid AC-DC architecture in office buildings enhances modularity and expansion by enabling seamless integration of DC powered systems such as LED lighting, IT equipment, EV chargers, and renewable energy sources like solar PV and battery storage. As office needs evolve, such as expanding workstations, data centers, or charging infrastructure, new DC loads can be directly connected to the existing DC bus without major rewiring or additional conversion equipment. This plug and play flexibility reduce infrastructure complexity, lowers energy losses, and simplifies the integration of DERs. In addition, the DC mesh architecture enables distributed energy resources and storage systems to be connected closer to load centers throughout the building, allowing power to be supplied locally where it is needed. This decentralized approach reduces dependence on the main electrical distribution network, minimizes power flow through central infrastructure, and can defer or even eliminate costly upgrades to primary electrical distribution equipment as load demand grows. If there is a need to increase the building's PV capacity, the expansion is straightforward and efficient on the DC side, as the solar generation can be directly fed into the DC bus without unnecessary AC to DC to AC conversions, making the system more scalable, resilient, and future ready.

8. Innovation Opportunities in Next Generation Buildings

Building Integrated Photovoltaic (BIPV)
Building-Integrated Photovoltaics (BIPV) provides a multifunctional solution for sustainable buildings by combining renewable energy generation with structural and aesthetic elements such as façades, skylights, and curtain walls. In the context of DC distribution, BIPV offers distinct technical advantages, as photovoltaic modules inherently generate direct current through the photoelectric effect. The generated DC power can be directly connected to the building's main DC bus, enabling local power injection at the point of consumption. This architecture minimizes the need for intermediate DC/AC conversion stages, thereby reducing conversion losses and improving overall system efficiency. Furthermore, by locating generation close to DC-native loads and energy storage systems, BIPV can reduce power transmission distances within the building, resulting in lower cable losses and reduced distribution infrastructure requirements

Hydrogen Fuel Cells
Hydrogen-fueled Proton Exchange Membrane (PEM) fuel cell systems represent a promising pathway for clean and decentralized energy generation in buildings. Hydrogen can be extracted from sources such as town gas through Pressure Swing Adsorption (PSA) purification, which delivers high-purity hydrogen suitable for fuel cell operation. The compact, containerized PEM fuel cell system generates direct current electricity that can be directly integrated into the DC distribution network, coupled with battery energy storage systems (BESS), and is compatible with building loads as well as electric vehicle charging. For building integration, PEM fuel cells provide a sustainable alternative to diesel generators

for backup power, offering lower emissions, enhanced energy resilience, and alignment with decarbonization goals. The modular design allows installation in basements, rooftops, or utility spaces, providing flexibility for both new construction and retrofits. The rapid response characteristics of PEM fuel cells make them well-suited for managing dynamic building loads. Furthermore, the system supports combined heat and power (CHP) applications, as waste heat can be recovered for space heating or domestic hot water, thereby improving overall building energy performance.

V2G and V2X

Vehicle-to-Grid (V2G) and Vehicle-to-Everything (V2X) technologies enable electric vehicles (EVs) to interact bidirectionally with the electrical system, allowing stored energy in EV batteries to be discharged back to the grid or to other connected loads. In V2G applications, EVs act as distributed energy resources, supporting grid stability, peak load management, and integration of intermittent renewable energy sources. V2X extends this concept, enabling EVs to supply power to buildings, microgrids, or other energy systems, as well as participate in ancillary services such as demand response and frequency regulation. By leveraging the flexibility of EV batteries, V2G and V2X can enhance energy efficiency, reduce reliance on stationary storage, and provide additional revenue streams for EV owners while contributing to resilient and decarbonized energy infrastructure.

Solid State Transformers

Solid-state transformers (SSTs) represent a transformative advancement in power distribution technology, offering high-efficiency, compact, and highly controllable alternatives to conventional electromagnetic transformers. Unlike traditional transformers, SSTs leverage power electronics to provide bidirectional power flow, voltage regulation, and real-time monitoring, enabling integration of distributed energy resources, renewable generation, and advanced loads such as electric vehicles. Their fast response and controllability open opportunities for dynamic load management, grid support, and enhanced power quality in commercial and industrial buildings. In the context of hybrid AC–DC architectures, SSTs can reduce energy losses associated with multiple conversion stages, optimize system footprint, and enable innovative applications such as localized microgrids, DC distribution, and vehicle-to-grid integration. The adoption of SSTs represents a strategic innovation pathway for improving energy efficiency, resilience, and flexibility in modern electrical infrastructure.

9. Business Success Stories

Schneider Electric – Empowering Smart EV Infrastructure at a.s.r.

The a.s.r. Smart Car Park in Utrecht, Netherlands, is a landmark in sustainable urban mobility and a showcase of how Schneider Electric, along with its endorsed company DC Systems, is redefining energy infrastructure. As the world's largest bi-directional EV car park, this facility integrates over 2,000 solar panels and 250 smart DC chargers, forming a dynamic energy hub that supports a.s.r.'s carbon-neutral office initiative.

At the heart of this innovation is a DC microgrid architecture, powered by Schneider Electric's advanced energy management and DC distribution solutions. This system connects solar panels directly to bi-directional DC chargers, allowing electric vehicles not only to charge efficiently but also to return energy to the grid—enhancing grid stability and reducing congestion.

Key Outcomes:

- 15% reduction in energy consumption, thanks to minimized conversion losses and optimized DC distribution.
- Autonomous operation in island mode, ensuring uninterrupted service during grid outages.
- Resource efficiency, with reduced copper usage due to high-voltage DC power distribution.
- Scalable and replicable model for future-ready commercial infrastructure.

This project, developed in collaboration with the Amsterdam University of Applied Sciences and other partners, demonstrates Schneider Electric's commitment to decarbonization, digitalization, and distributed energy integration. It serves as a blueprint for smart buildings and mobility hubs that are resilient, efficient, and aligned with net-zero goals.

VINCI Energies building solutions

Building Solutions is VINCI Energies business line dedicated to buildings. Buildings are at the heart of the major transformations underway: environmental transition, economic challenges, and sovereignty, particularly digital, demographic and societal changes. VINCI Energies Building Solutions contributes to their adaptation by making them more sustainable, liveable and performant through customized multi-technical solutions and services throughout their life cycle.

As part of this commitment to innovation and sustainable building performance, VINCI Energies Building Solutions developed a pilot site to demonstrate that direct current (DC) distribution is a viable and scalable solution for future buildings. This full-scale laboratory was designed to quantify the real benefits of DC power architectures in terms of energy efficiency, system simplification and operational flexibility. We tested and validated the direct DC power supply for several load families:

- LED lighting,
- Sockets and USB-C plugs,
- Computer equipment

Beyond efficiency gains - elimination of unnecessary conversions, reduction of losses, better PV/BESS integration – this approach paves the way for a new modularity in electrical design. DC allows a more direct connection of DC sources: photovoltaic panels, batteries, and native DC loads: Computer & LED luminaire.

The experiment conducted on Wave and our ongoing projects highlight several levers for the future:

1. Maximize renewable self-consumption:
   The direct PV interconnection BESS DC-loaded allows to consume locally the energy produced, reducing losses and minimizing the use of the network during price peak.
2. Develop DC zones in buildings:
   The hybrid AC/DC model with zoning by use (e.g. lighting, IT, EV) optimizes investments and facilitates a gradual migration to more DCs without disrupting operations.
3. Reducing the carbon footprint:
   Fewer conversions mean less energy-consuming equipment and therefore lower associated emissions, while improving overall energy efficiency.
4. Facilitate the integration of new technologies:
   The ramp-up of USB-C loads, universal power supplies and distributed storage solutions reinforces the relevance of a DC backbone in buildings.
5. Train and support the actors:
   The success of these projects depends on the development of the skills of the design, installation and maintenance teams, as well as the increasing availability of DC-certified equipment.

In summary, our feedback proves that the DC distribution is no longer a futuristic idea: it is a solution ready to be deployed, as soon as it is designed in a hybrid and scalable architecture. With our partners, we intend to continue this trajectory, deploy new use cases and contribute to making the buildings of future energy platforms that are sober, flexible and resilient.

10. Conclusion

Category	AC Architecture	Hybrid AC-DC Architecture
Integration of DERs and Loads	The solar PV system and BESS connect to the AC backbone via converters, resulting in multiple energy conversions before reaching the loads. Although many devices like LEDs, IT equipment, and EVs operate on DC, they are typically powered through AC and require additional conversion.	The solar PV system and BESS are DC-coupled using DC/DC converters with better efficiency to supply native DC loads like LEDs, IT devices, EV chargers, and USB-C ports, reducing conversion losses, improving efficiency and optimizing power utilization.
EV Charging Infrastructure	**The onboard charger converts the AC input to DC for battery charging, while the external AC charger primarily serves as a power conduit. This setup introduces additional conversion stages and equipment, reducing overall system efficiency to 88%.**	The DC bus bypasses the onboard charger, improving efficiency to around 98% and simplifying infrastructure. The direct DC-to-DC pathway minimizes energy losses from repeated power conversions and delivers DC power straight to the electric vehicle battery.
Energy Losses	The annual energy losses are approximately 294,638 kWh/year due to multiple AC-DC and DC to AC conversion stages.	The annual energy losses are approximately 170,981 kWh/year achieving a 42% reduction due to direct DC distribution and optimized converter usage.
System Efficiency	The overall system efficiency is around 87%, limited by conversion inefficiencies and reactive power losses.	**The overall system efficiency is 92% overall, gaining approximately 5% from direct DC supply, reduced conversion stages, and optimized control strategies.**
Grid Energy Import	The grid energy import is approximately 3.28 GWh/year with higher reliance on grid during peak loads.	The grid energy import is approximately 3.16 GWh/year achieving 3.7% reduction due to better local generation and storage utilization.
Grid Congestion	Relies heavily on the grid during peak loads and limited ability to use local renewables efficiently, leading to higher congestion and energy losses.	By directly supplying native DC loads from onsite PV generation and storage, the system can dynamically balance demand using ILC, reduce reliance on grid power, and lower peak load periods.
Copper Usage & Cable Sizing	**Approximately 14.6 tons of copper with larger cross-sections needed for the total cables associated for AC configuration due to higher current and associated losses.**	**Approximately 11.5 tons of copper, achieving 21% savings due to lower current, higher voltage, and efficient DC transmission.**
Cable Transmission Efficiency	The AC cables are affected by skin and proximity effects; especially above 300 mm^2.	The DC cables avoid skin effect allowing higher current capacity and reduced losses, especially in large cross-sections.
Modularity & Scalability	Expansion is relatively challenging because adding new loads or renewables requires rewiring, extra AC/DC converters, and complex protection adjustments, making upgrades costly and time-consuming.	Expansion is modular, allowing direct connection of DC loads and renewables to the DC bus without major rewiring or additional conversion equipment, simplifying scalability.
Cost Effectiveness	The system has lower initial cost, but higher energy losses and reliance on multiple converters increases operational costs over time.	The system may have higher upfront cost due to interlink converter and advanced protection system, but improved efficiency and reduced energy losses make it more cost effective in the long run.

11. Key findings

- Hybrid AC-DC architecture reduces energy losses by 42% through optimized energy flows, load management, and strategic use of storage and conversion systems. Disabling the ILC during low power periods and leveraging BESS maximizes DC source utilization, improving efficiency and cutting conversion losses.
- The 3.7% reduction in grid energy import in the case of hybrid architectures compared to the AC scenario is primarily driven by the integration and management of local generation and storage together at the DC backbone, which enhances energy autonomy and minimizes dependency on grid.
- 21% reduction in copper reduction, cutting material costs owing to lower current, higher voltage, and efficient DC transmission.
- In the case of EV charging, a substantial efficiency improvement can be achieved when the charger is supplied directly from the local solar PV DC network, with efficiency increasing from approximately 88% in conventional AC systems to 98% in DC systems. In contrast, when power is supplied from the AC grid, the overall efficiency is lower due to the additional losses associated with the AC/DC interface converter and the EV charger itself.
- Interlink Converter (ILC) regulates the bidirectional power flow between AC and DC networks, supporting dynamic load balancing and compliance with grid requirements.
- DC-coupled BESS reduces conversion losses, improves efficiency, and ensures reliable power during low-demand period, enhancing system performance by up to 20%
- Integration of distributed energy resources (DERs) is more effective in hybrid systems, aiding decarbonization efforts and mitigating grid congestion.

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