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Executive Summary

This Thematic Vision outlines the strategic role of Direct Current (DC) technologies in achieving a sustainable, resilient, and cost-effective European energy system by 2050. In doing so, it positions DC technologies as enabling components of an electrified, interconnected and renewables-based European energy system. Developed by the SET Plan Implementation Working Group on Direct Current Technologies (IWG-DCT), the document consolidates a shared vision across stakeholders and provides direction for future research, innovation, and deployment efforts.

DC technologies can enhance transmission grids, distribution grids and end-user applications by providing options that a conventional AC (Alternating Current) system solution cannot similarly provide. DC technologies span all voltage levels, i.e. **high-voltage (HVDC), medium-voltage (MVDC), and low-voltage (LVDC)**[1] applications and are key enablers of Europe's energy transition. They support the integration of renewable energy sources, facilitate underground and undersea connections, enhance grid flexibility and efficiency, reduce transmission losses, and strengthen system resilience. Across all levels of the electricity system, DC solutions can enable improved control, facilitate sector coupling, optimise infrastructure expenditure (CAPEX) and reduce operational costs (OPEX).

Recent progress demonstrates strong momentum. HVDC is transitioning from niche application to mainstream transmission technology, with growing deployment in interconnections (both at cross-border and internal levels) and offshore grids. MVDC is emerging as an efficient solution for industrial loads and distributed generation, while LVDC applications are advancing in buildings, data centres, and local energy systems, delivering measurable gains in efficiency, cost reduction, and peak load management. While DC Technologies have made great technological advancements over the last decades, research and innovation (R&I) remain necessary to accelerate deployment, reduce costs and retain technological leadership in Europe.

The Thematic Vision defines a R&I pathway structured around **five key innovation themes**: industrialisation and competitiveness, technology development, system integration, sustainability and circularity, and skills and societal acceptance. These themes guide coordinated action across the value chain and address both technological and non-technological barriers.

Clear targets are established for 2030, 2040, and 2050. In the short-term, priorities include the development of full-scale pilots. In concrete, the short-term priorities relate to industrialisation through standardisation and supply chain development and to innovations in DC system integration through interoperability and the development of an enabling regulatory framework. By 2040, DC technologies are expected to reach large-scale deployment with mature markets, integrated hybrid AC/DC grids, and strong European manufacturing capabilities. By 2050, DC systems are envisioned as a core component of a fully integrated, circular, and resilient energy system, with Europe maintaining global leadership.

Overall, this Thematic Vision positions DC technologies as essential to achieving Europe's decarbonisation goals while strengthening industrial competitiveness and energy security.

[1] HVDC typically above 110 000 V, MVDC above 1500 V, LVDC 120 V up to 1500 V

1. Introduction

1.1. General introduction to the IWG DC Technologies

This document presents the Thematic Vision as collected within the EU SET Plan Implementation Working Group on Direct Current Technologies (IWG-DCT). The IWG-DCT was established in 2021 to bring together the experience and knowledge of policymakers, industry and academia in the field of research and innovation for DC technology. As part of the SET Plan, its objective is to identify and prioritise **research and innovation (R&I) needs in the domain of Direct Current Technologies** that support European energy objectives and to provide input for future **policy, funding and investment decisions**.

Initially focusing on **High Voltage Direct Current (HVDC)** [1]**,** the scope of the group was expanded in 2024 to include **Low Voltage Direct Current (LVDC)** [2] and later also **Medium Voltage Direct Current (MVDC)**, thereby covering **all voltage levels** of DC power applications. Through this work, the IWG-DCT contributes to the development of a coordinated European approach and supports the preparation of the **Strategic Research and Innovation Agenda (SRIA)** and of the **Implementation and Investment Commitments** (IIC), which all together with the Thematic Vision will constitute the **Common Implementation and Investment Plan (CIIP)**.

The IWG-DCT consists of a core group of Country Representatives from 18 countries and a technical sub-group of 156 industry, research and academia stakeholders in DC Technologies. It is supported by the secretariat, based on the DCforEU CSA.

1.2. Objective of the Thematic Vision

The objective of this document is to present a **clear, credible and forward-looking vision** of the role of DC technologies in the future European energy system, and to identify the **research and innovation efforts** required to realise this vision.

Direct Current technologies are key enabling components of a future **sustainable, resilient and cost-effective** energy system. By enhancing controllability, reducing losses and supporting system integration, they can help ensure that electricity grids evolve from **a potential bottleneck into a facilitator** of the energy transition. This Thematic Vision sets out a clear pathway for their development and identifies the actions needed to unlock their full potential while maintaining **European industrial leadership**.

The document presents the targets that will enable the energy transition, with DC technologies as **relevant, necessary, and achievable** technology. They are *relevant* because they support the integration of renewable energy and electrified loads, *necessary* because the future energy system requires **more grids due to electrification** and this with higher levels of **flexibility, controllability and efficiency**, and *achievable* because significant progress has already been made in both technology and industrial capacity.

At the same time, several barriers remain. With this Thematic Vision, IWG-DCT proposes to focus on 5 Innovation Themes**:**

- Theme 1: Industrialisation, Scale-up and Competitiveness
- Theme 2: DC technology Development
- Theme 3: DC system integration
- Theme 4: Sustainability and circularity
- Theme 5: Skills and acceptability

The thematic vision is developed considering 3 application domains[2,3]:

- **Direct Current transmission systems**, which refer to the part of the power system that connects the largest generators and loads with each other and with internal (national) as well as neighbouring systems (international) and the distributions grids. Direct current applications are the connection of synchronised and non-synchronised systems, the connection of large offshore wind farms, bulk power transmission over longer distances and controllable or flexible transmission grids that facilitate underground connections. The DC technology used is referred to as High Voltage Direct Current (**HVDC**).
- **Direct current distribution systems**, which refer to direct current applications targeted at integrating customers in a regulated distribution system. The distribution of electric power can happen at Medium and Low voltage levels (MVDC and LVDC) but generally referred to as **MVDC** in the description of visions and targets.
- **Direct Current end-user applications** (**LVDC**), including communities, which refer to equipment installed at the user side, operated and managed by that user. Such system is typically non-regulated and contains both residential, commercial and industrial applications. These systems are typically referred to as LVDC, or low voltage DC applications, without limiting to LV definition of 1.5 kV, excluding pure distribution and transmission activities.

1.3. Key developments, drivers and barriers

In recent years, there has been a strong acceleration in the deployment of DC technologies. At transmission level, **HVDC** is rapidly evolving from a niche solution to a **standard option** for large scale power transfer and offshore integration. At the same time, **distribution and end user DC applications** are emerging, supported by advances in power electronics and new types of loads. This evolution is driven by the rapid expansion of **renewable energy**, the increasing **electrification of industry and transport**, and the growing need for **flexible and controllable power systems**.

Despite this progress, several challenges remain. The lack **of interoperability between different systems and vendors**, the need for **harmonised standards and verified reliability tests**, and

[2] HVDC typically above 110 000 V, MVDC above 1500 V, LVDC 120 V up to 1500 V

[3] Note that DC technology is also used in other specific applications, in particular rail transport. This Thematic Vision does not cover that domain, although several of the R&I activities identified might benefit that sector as well.

the adaptation of **regulatory and market frameworks** are key barriers. In addition, scaling up manufacturing capacity and securing supply chains with affordable costs for critical components remain important challenges. Addressing these barriers is essential to enable **large-scale deployment** and to ensure that DC technologies can fulfil their role in the energy transition.

1.4. Current status of R&I activities in Europe

The database of past and active projects in HVDC may be found in the DCforEU Project Overview Listing [3].

As at end of April 2026[4], and focusing on research performed in the last decade:

- The listing consists of just under 75 initiatives, several of which address multiple challenges.
- The total value of the EC contribution to date on these projects exceeds EUR 300 million.
- The total value of these projects exceeds EUR 455 million in private & public investment and EC support funding of these projects.

This represents a significant sum but when comparing the annual investment needs in transmission technology, this RD&I corresponds to about 0.15 % of the annual investment needs in transmission grid in the EU[5].

1.5. Focus areas for research and innovation

To accelerate progress in the period 2028–2034, particular attention should be given to a limited number of priority areas. A first priority is the development of **interoperable and standardised DC systems**, enabling multi-vendor solutions and reducing costs. A second priority is the **integration of DC technologies within hybrid AC/DC grids**, ensuring that DC systems can effectively support and reinforce existing AC infrastructure. A third priority is the **industrialisation and scaling** of key components such as converters, cables and protection technologies, which is necessary to move from pilot projects to widespread deployment. These focus areas are essential to translate technological potential into practical implementation.

1.6. Task Force recommendation reflections

The Thematic Vision reflects the recommendations of the SET Plan **cross-cutting task forces**, which are highly relevant for DC technologies. The development of **skills** is essential to ensure that a qualified workforce is available to design, install and operate increasingly complex, power electronics-based systems. **Sustainability and circularity** considerations must be fully integrated in technology design to reduce environmental impact and dependence on critical materials. **Digitalisation** plays a key role in enabling advanced system operation, planning and asset

[4] DCforEU has mapped projects through a scan of the Horizon database and through contributions of IWG members. The data provided is an estimate and may not be exact.

[5] According to the Grid Package of the EC, 477 BEUR in transmission investments are required until 2040, which corresponds to about 32 BEUR per year, vs 45.5 MEUR of identified R&I investments in HVDC technology.

management and its relevance on (cyber-)resilience. At the same time, **societal needs** require energy systems to be affordable, reliable and publicly acceptable. Finally, improving **access to market** remains crucial, requiring the removal of regulatory barriers and support for industrial scale up. These cross-cutting aspects are integrated throughout the innovation themes and are essential for successful deployment. A more elaborate discussion of the relevance of the task force recommendations can be found in the 0.

1.7. Contribution to EU energy policies

Direct Current technologies play a key enabling role in achieving European energy policy objectives, including the **European Green Deal, REPowerEU, the Energy System Integration Strategy and the EU Grid Action Plan**. They support a more **secure, flexible, efficient and integrated electricity system** by enabling large-scale renewable integration, strengthening cross border connections, and facilitating the efficient use of energy at all voltage levels. DC technology development and deployment should therefore be embedded in forward-looking European grid planning, including central scenario-based planning and a long-term Target 2050 European Grid perspective, so that investment signals are aligned with renewable deployment, electrification, offshore wind build-out and cross-border system needs. The challenge is massive, as the EC estimates that the grid infrastructure modernisation will require about 1200 billion euro by 2040 [4].

2. Vision and targets

2.1. Vision for Direct Current Technologies

The future energy system will be predominantly electric. Recent advances have made direct current (DC) technologies ideally suited to complement alternating current infrastructure and realise such a system supporting sustainable economic growth and infrastructure scalability. This will result in future electrical infrastructures that are more resilient, efficient, cost-effective, sustainable and scalable, thereby promoting sustainable economic growth, better integration of renewable energy sources and the electrification of demand.

For each time frame (2030, 2040, 2050), generic system-level targets for DC technologies are provided, after which specific targets are given for the transmission system, distribution system and end-user applications.

2.2. Short-term (2030) Targets

2.2.1. System-level targets for DC technologies

DC technologies are recognised at European level as a key contributor to a resilient, efficient and flexible power system.

By 2030, direct current technologies will be recognized and demonstrated as an essential element of a modern electricity system, enabling their integration into EU energy strategies and planning. Their contribution goes beyond simple transmission of power and includes their ability to enhance system controllability, improve stability, and support resilience under a wide range of operating conditions. In particular, DC systems provide fast and precise control of power flows, enabling operators to anticipate and respond effectively to disturbances, including those related to extreme weather events, hybrid physical and cyber incidents [5], or system imbalances. As the energy system becomes increasingly complex and dependent on renewable generation, this controllability is a critical enabler of secure system operation.

Building blocks for modular DC systems are defined

By 2030, significant progress has been made in defining common technical requirements and functional specifications for key DC components, such as converters, DC circuit breakers, cables, and control systems. These standardised building blocks enable the development of **modular DC systems** that can be deployed more efficiently and scaled more easily. The move towards modularity reduces the need for bespoke engineering solutions, lowers costs, and accelerates project development timelines. Furthermore, it allows different equipment from multiple vendors to be combined in a coherent system, thereby supporting interoperability and fostering competition within the European market.

Circular design principles and harmonised life-cycle assessment methodologies are fully established for DC technologies.

Sustainability considerations are fully integrated early in the design of DC components and systems. By 2030, design approaches prioritise material efficiency, recyclability, and lifetime extension, ensuring that DC technologies contribute to broader EU objectives on circular economy and resource

efficiency. At the same time, harmonised life-cycle assessment methodologies are available and widely applied, enabling consistent evaluation of environmental performance across projects and technologies. This provides decision-makers with robust information on environmental impact and supports more informed investment and policy choices.

A coordinated, secure-by-design and competitive European industrial ecosystem for DC technologies is strengthened and scaled.

The deployment of DC technologies is supported by a stronger and more integrated European industrial base. By 2030, collaboration between manufacturers, system operators, engineering companies and research institutions has intensified, leading to improved coordination across the value chain. Production capacity for critical components, such as converters and protection devices, is expanding, supported by industrial policies and targeted investments. This reduces dependence on external suppliers, mitigates supply chain risks, and ensures that Europe maintains a leading role in the global development of DC technologies. At the same time, increased industrial competition contributes to cost reductions and innovation.

2.2.2. Transmission system targets (HVDC)

Multi-terminal, multi-vendor HVDC systems are successfully demonstrated in a realistic simulation environments.

By 2030, the first practical demonstration of a multi-terminal HVDC system involving equipment from multiple vendors and, where relevant, multiple system operators, has been defined and is planned. This represents a critical step beyond point-to-point HVDC links. Demonstrating interoperability between different converter technologies is essential to enable future large-scale grid developments, particularly in offshore and cross-border applications. These pilot projects provide valuable operational experience and reduce investment uncertainty for subsequent deployments.

A coordinated approach to (HVDC) grid planning is established.

Transmission planning evolves from a project-by-project approach towards a more structured and coordinated master plan. By 2030, system operators and planners increasingly adopt long-term, cross-border perspectives that consider the gradual development of interconnected HVDC infrastructures. This includes improved coordination between countries and stakeholders, as well as the emergence of planning methodologies that integrate DC technologies alongside traditional AC grids. Such approaches enable the efficient and stepwise expansion of transmission capacity, avoiding suboptimal investments and facilitating the integration of large-scale renewable energy sources, especially offshore wind. They should also support offshore wind connection corridors, hybrid offshore assets, cross-border offshore infrastructure and the stepwise development of meshed offshore HVDC grids.

Advanced tools for the analysis, design and operation of hybrid AC/DC systems are available.

The integration of DC technologies into the transmission grid requires new computational tools to analyse the system behaviour. By 2030, the first prototypes of advanced tools that allow accurate modelling of hybrid AC/DC systems, including their dynamic behaviour and interactions, are available to system operators. These tools support planning, design and real-time operation, ensuring that system stability, protection coordination and operational security are maintained. Standardised

models and data formats are increasingly used, allowing consistent analysis across different projects and facilitating collaboration between stakeholders.

2.2.3. Distribution system targets (MVDC)

MVDC systems contribute to increasing system hosting capacity and reducing grid congestion.

As demand for electrification and renewable integration grows, MVDC solutions are increasingly recognised as an effective way to enhance the capacity of existing networks. By enabling more efficient power transfer and improved control of power flows, MVDC systems help to alleviate congestion and delay the need for grid reinforcements, e.g. for the integration of renewables or to support the electrification of industry. This is particularly relevant in areas with high concentrations of renewable generation or large industrial loads, where conventional AC solutions may reach their limits. As a result, the system-level value of MVDC technologies is increasingly recognised in planning and economic assessments, broadening the application of DC technology in distribution systems.

MVDC solutions should be considered alongside anticipatory distribution grid investments, transparent hosting-capacity information and flexibility measures, ensuring that optimization complements, rather than replaces, the grid reinforcements needed for electrification and renewable integration.

Reliable, accessible and industry-accepted design tools for MVDC systems are developed.

The adoption of MVDC systems is supported by the development of design tools that simplify engineering processes and reduce project risk. By 2030, these tools are capable of supporting complete system design, including component selection, protection strategies and performance analysis. They are increasingly integrated into existing planning workflows, enabling engineers and planners to evaluate MVDC solutions alongside traditional AC options. This reduces barriers to adoption and supports more consistent and efficient project development.

2.2.4. End-user application targets (LVDC)

Pilot DC systems are demonstrated in a growing range of end-user applications.

By 2030, Low Voltage Direct Current systems are deployed in commercial buildings, industrial facilities, data centres and residential pilot developments. These deployments provide robust evidence of the benefits of DC systems in real operating conditions, including improved energy efficiency, better integration of distributed energy resources and enhanced operational flexibility. The increasing number of applications also demonstrates the versatility of DC solutions across different user contexts.

Easy-to-use design tools and integrated solutions for DC systems are widely accessible.

By 2030, design and engineering tools for end-user DC applications are widely available and aligned with existing building and electrical design practices. These tools support system configuration, safety design and performance assessment, enabling engineers, installers and integrators to implement DC systems with confidence. The availability of standardised solutions reduces complexity and accelerates market adoption.

Standardised, safe and interoperable DC solutions are established for end-user applications.

Clear and harmonised standards for DC systems at building and community level are established, ensuring safe and reliable operation. These standards cover components, interfaces and system integration, and are aligned with international frameworks. They reduce fragmentation in the market and enable interoperability between products from different manufacturers, supporting the creation of a competitive and scalable European market.

The interaction between DC systems and the distribution grid is better understood and increasingly optimised.

By 2030, the impact of DC systems on grid operation is more clearly understood, particularly in terms of load profiles, peak demand and power quality. This improved understanding allows for better integration of DC systems into grid planning and operation, taking advantage of their potential to reduce grid stress and support overall system efficiency.

2.3. Medium-term (2040) Targets

2.3.1. System-level targets for DC technologies

DC technologies are established as standard solutions to enhance resilience and flexibility across the European energy system.

By 2040, DC technologies are no longer considered emerging solutions but are widely adopted as standard tools for system operators and end-users. Their capability to provide controllability, fast response, and flexible power flow management is fully integrated into power system operation.

DC systems actively contribute to system resilience by supporting fault management, limiting cascading failures, and enabling stable operation under increasingly dynamic and decentralised conditions. Their role in strengthening system robustness against climate-related events, hybrid threats and cyber risks, and operational disturbances is clearly demonstrated and embedded in system planning practices.

Through DC system modularity and digitalisation, DC technologies will be fully integrated in energy systems, and are easy to upgrade, repair and have long system lifetimes.

Advanced tools for the planning, design and operation of power-electronics-dominated systems are fully developed and commercially deployed.

By 2040, the energy system is characterised by a high penetration of power electronic devices, requiring advanced analysis and operational capabilities. Comprehensive toolsets are available and widely used for steady-state, dynamic and stability analysis of hybrid AC/DC systems. These tools allow system operators to accurately model system behaviour, assess interactions between components, and optimise system performance. Standardised modelling approaches and data formats are widely adopted, enabling consistent analysis across Europe and facilitating coordination between stakeholders. The tools also allow to integrate sustainability, resource use and lifecycle considerations.

DC/DC converters are developed to enable direct interconnection between transmission, distribution and end-user systems.

Technologies such as DC/DC converters are demonstrated and deployed, enabling direct interconnection between different voltage levels. By 2040, transmission, distribution and end-user systems can be interconnected through DC technologies, creating new levels of flexibility and enabling optimised energy flows across the system. This contributes to a more integrated and efficient electricity system, reducing conversion losses and enabling novel system architectures.

A strong and competitive and circular European DC supply chain is established at scale.

By 2040, Europe has developed a robust industrial base covering the full DC value chain, from materials and components to system integration and services. Large-scale manufacturing of key components such as converters, DC circuit breakers and power electronic devices is fully established. This industrial scaling leads to significant cost reductions, improved reliability and wider market uptake. European industry maintains a leading position globally, supported by innovation, standardisation and coordinated industrial strategies.

A skilled workforce for DC technologies is fully established across Europe.

DC technologies are fully integrated into academic and vocational education systems. By 2040, engineers, technicians and installers are trained to design, deploy and operate DC systems as part of standard practice. Dedicated training programmes and continuous professional development ensure that the workforce keeps pace with technological advancements. This addresses one of the key bottlenecks identified in earlier stages of deployment.

2.3.2. Transmission system targets (HVDC)

Multi-terminal, multi-vendor HVDC systems are deployed as cost-effective and scalable solutions for large-scale offshore and onshore transmission applications.

By 2040, HVDC systems with multiple terminals and multiple vendors are no longer pilot projects but are deployed at scale, particularly in offshore, onshore, internal (embedded) and cross-border applications. These systems are economically competitive and technically mature, enabling efficient integration of large renewable generation sources and facilitating cross-border electricity exchange and offer higher public acceptance through easier undergrounding. New applications such as deep-sea applications and complex offshore installations are enabled.

2.3.3. Distribution system targets (MVDC)

MVDC systems are deployed at scale and integrated into existing distribution networks.

MVDC transitions from pilot projects to mainstream deployment across European distribution systems. Multi-terminal MVDC networks operate reliably in combination with existing AC infrastructure, enabling improved power flow control, increased hosting capacity and enhanced system flexibility.

Technology agnostic regulatory frameworks fully reflect the value of MVDC systems.

By 2040, market structures and tariff mechanisms recognise the benefits of MVDC systems, including loss reduction, flexibility and deferred infrastructure investment. As a result, planning and economic assessments of investment options, yield into widespread adoption of MVDC without the need for additional incentives.

Harmonised European and international standards for MVDC systems are fully established.

A complete standardisation framework exists for MVDC technologies, covering components, system architecture and grid integration. These standards ensure interoperability, safety and compatibility across different applications and vendors. European leadership in standardisation supports global market development and competitiveness.

2.3.4. End-user application targets (LVDC)

DC systems reach market maturity and are widely deployed across end-user applications.

By 2040, DC systems are no longer niche solutions but are widely used in commercial buildings, data centres, industrial facilities, renewable sources, batteries and energy communities. A significant share of new developments adopts DC technologies as standard practice, often in combination with AC systems. The use of DC technologies will reduce conversion losses and enable efficient integration of local energy resources and reducing overall system complexity.

DC systems support large-scale electrification while reducing pressure on distribution grids.

By enabling efficient integration of generation and loads at local level, DC systems reduce peak demand and limit stress on the distribution network. This contributes to lowering the need for grid reinforcement and supports the development of a hybrid energy system where DC and AC infrastructures coexist and complement each other.

2.4. Long-term (2050) Targets

2.4.1. System-level targets for DC technologies

DC technologies are fully embedded across all levels of the electricity system.

By 2050, Direct Current technologies are fully embedded across all levels of the energy system and are considered a standard solution alongside AC technologies. Their deployment spans transmission, distribution and end-user applications, and they are systematically applied where they provide technical, economic or environmental advantages. As a result, the European energy system operates as an integrated hybrid AC/DC system, combining the strengths of both approaches to deliver optimal performance. As a result, DC technologies will play a central role in ensuring system resilience and operational security by 2050. Their ability to precisely control power flows, isolate disturbances and support system stability is fully utilised. DC systems actively contribute to AC grid-forming capabilities, system restoration and the management of complex power flows in a highly electrified and decentralised energy system. This makes them a critical enabler of a secure and adaptable infrastructure.

Design, planning and operation of DC systems are supported by advanced, highly automated engineering and optimisation tools.

By 2050, the design and operation of DC systems are supported by advanced digital platforms that integrate real-time data, predictive analytics and automated optimisation. These tools enable highly efficient system design and operation, reduce engineering complexity and support rapid deployment at scale.

The European DC value chain is fully integrated and globally leading, ensuring strategic autonomy and industrial competitiveness.

Europe maintains and strengthens its global leadership in DC technologies. A fully developed supply chain covers all stages, from raw materials and component manufacturing to system integration, operation and recycling. European companies lead global markets in key technologies such as converters, cables and power electronic systems. This leadership supports strategic autonomy in critical energy infrastructure and contributes to long-term economic competitiveness.

A highly skilled workforce and advanced digital ecosystem fully support DC system deployment and operation.

DC technologies are fully incorporated into education, training and professional development across Europe. At the same time, advanced digital solutions, including automation and intelligent system management, support the design, operation and optimisation of complex energy systems. Human expertise and digital tools work in synergy, ensuring safe, efficient and reliable operation at scale.

2.4.2. Transmission system targets (HVDC)

A meshed HVDC backbone grid is established across Europe, integrating offshore and onshore systems.

By 2050, a large-scale HVDC backbone or overlay grid spans both offshore and onshore networks, connecting renewable generation sources and load centres and realising a seamless interconnected European electricity grid. This grid operates in coordination with existing AC infrastructure, enabling efficient long-distance power transfer and supporting a highly integrated European energy system.

HVDC systems enhance system integration, flexibility and public acceptance of transmission infrastructure.

The widespread use of HVDC enables increased underground and subsea transmission, reducing visual impact and land use. Combined with improved system performance and flexibility, this contributes to higher public acceptance and facilitates the large-scale development of transmission infrastructure required for the energy transition.

2.4.3. Distribution system targets (MVDC)

MVDC networks are fully integrated as a core component of distribution and hybrid grid architectures.

By 2050, MVDC systems are widely deployed and form an integral part of distribution networks. They operate seamlessly alongside AC infrastructure in hybrid configurations, enabling efficient power

exchange, enhanced controllability and improved integration of distributed energy resources and high-power loads.

2.4.4. End-user application targets (LVDC)

End-user DC systems are fully integrated into the wider energy system and actively support grid stability and resilience.

DC systems at the user level are no longer passive consumers but active participants in the energy system. They interact dynamically with the grid, support demand flexibility and contribute to system stability. Local DC systems can operate autonomously when needed, providing resilience during disturbances and supporting faster system restoration.

Local DC networks and microgrids enable highly efficient and flexible energy use at community level.

DC-based local grids and energy communities enable efficient integration of renewable generation, storage and flexible demand. These systems optimise local energy use, increase self-consumption and reduce reliance on centralised infrastructure. At the same time, they remain fully interoperable with the wider grid, contributing to overall system efficiency.

DC systems support large-scale electrification while optimising the use of existing infrastructure.

By enabling efficient local energy management and reducing peak demand, DC systems limit the need for extensive grid reinforcements. This allows large-scale electrification to be achieved while making optimal use of existing infrastructure, contributing to a cost-effective energy transition.

2.5. Pathway to reach goals

IWG-DCT has identified a wide range of research activities to realize the targets identified in this document. In Appendix 0the general approach which organizes the pathway to implementation in four hierarchical levels is explained. In Appendix 0the status (mid 2026) of the R&I roadmap structure is provided.

Next to the R&I challenges, there are also several policy and organisational issues which would facilitate or even remove unnecessary barriers to the use of DC technologies.

Recent policy work by the European Commission has focused on the development of a more streamlined international power system development through initiatives concerning permitting, cross-border collaboration, cost-sharing mechanisms and this through various legislative works such as the electricity market design [6], the grids package [4] and Net-Zero Industry Act [7]. Given the importance of grids in the future energy system, such efforts should be continued such that the most efficient, sustainable and reliable energy system can be built on time and operated at the lowest costs.

For cross-border and hybrid offshore projects, technology development should be accompanied by bankable regulatory and investment frameworks, including clear approaches to cost sharing, benefit allocation, congestion income treatment, risk allocation and revenue certainty, so that projects delivering system-wide benefits can reach investment decisions in time.

To reduce supply chain issues, long term signals should be given to support initiatives for DC production capacity increase in Europe.

To achieve these goals, EU policy should be leveraged to strengthen the role of key industry initiatives within European institutions and standardisation bodies. By consolidating their position, these organisations can more effectively shape and drive DC-related standardisation efforts at European level.

3. Conclusions and next steps

Direct Current (DC) technologies constitute **key enabling components** of a climate-neutral, resilient and integrated European energy system, supporting energy transition and industrial competitiveness objectives of the European Union. Complementing Alternating Current (AC) grids, DC systems can improve energy efficiency, facilitate renewable energy integration, reduce grid congestion and enhance stability, power flow controllability, and response to disturbances, across all voltage levels of the transmission and distribution networks, as well as end-user applications.

To unlock this potential, a **coherent and coordinated European energy policy and infrastructure planning framework is required**, integrating DC technologies in a technology-neutral approach that enables their deployment where they deliver system-wide benefits.

- By 2030, direct current (DC) technologies will be demonstrated in R&I activities and commercial installations, and will be widely recognized as a key component of a resilient and flexible European power system. Standardized, modular DC systems will be defined to enable scalable, interoperable, and cost-effective deployment. At the same time, circular design principles and harmonised life-cycle assessment methodologies will be available for DC systems. Supported by coordination at the European level, the industrial ecosystem of direct current technologies is developing into an innovative and resilient supply chain, strengthening Europe's position in the global market and reducing external dependencies.
- By 2040, direct current (DC) technologies are fully established as a standard solution at all voltage levels. Modular and digitalized DC systems allow easy upgrades and long lifetimes, while advanced tools support the operation of power-electronics-based networks. DC/DC converters enable seamless integration across transmission, distribution, and end-user levels, improving efficiency. Supported by a strong European supply chain and skilled workforce, these technologies benefit from large-scale deployment, reduced costs, and sustained innovation.
- By 2050, direct current (DC) technologies are seamlessly integrated across transmission, distribution, and end-user applications, forming a fully hybrid AC/DC power system where each technology is applied for maximum technical and economic benefit. Their large-scale deployment is enabled by advanced digital platforms with automated design and optimisation capabilities, thus reducing development effort and cost. At the same time, Europe sustains global leadership through a fully integrated and competitive DC value chain, supported by a highly skilled workforce.

Further efforts are needed to **remove regulatory and market barriers**. This includes advancing **harmonised standards, grid codes and interoperability frameworks**, alongside streamlined permitting procedures for innovative infrastructure. At the same time, **market design and tariff structures should better reflect the value of flexibility, loss reduction and congestion management**, thereby incentivising the uptake of DC solutions across transmission, distribution and end-user applications. Where DC and power-electronics-based technologies provide measurable system value, including stability, AC-grid-forming capability, damping, restoration support, flexibility or congestion management, regulatory frameworks should ensure technology-neutral requirements and appropriate procurement or remuneration mechanisms.

Strengthening **European industrial leadership and strategic autonomy** remains essential. **Innovation in DC technologies is needed**, to further enhance the technology and its integration in the existing power system. On top of that, initiatives are needed to support the industrialisation of

the technology: **scale-up of manufacturing, secure supply chains, and deployment of key technologies**, in line with broader EU initiatives on clean technology and critical materials. In parallel, IWG-DCT recommends to develop the appropriate **skills development and workforce upskilling**, as well as the integration of **circularity and sustainability principles**, will be critical enablers for large-scale deployment.

As a next step, the IWG-DCT will develop a **Strategic Research and Innovation Agenda (SRIA)** by October 2026, translating this vision into concrete priorities and coordinated actions at EU and national levels.

In conclusion, **decisive and coordinated research and innovation activities,** across policy, regulatory and industrial domains, is essential to enable the large-scale deployment of DC technologies. This will support the development of a **future-proof hybrid AC/DC energy system**, delivering on Europe's objectives of decarbonisation, competitiveness, resilience and security of supply.

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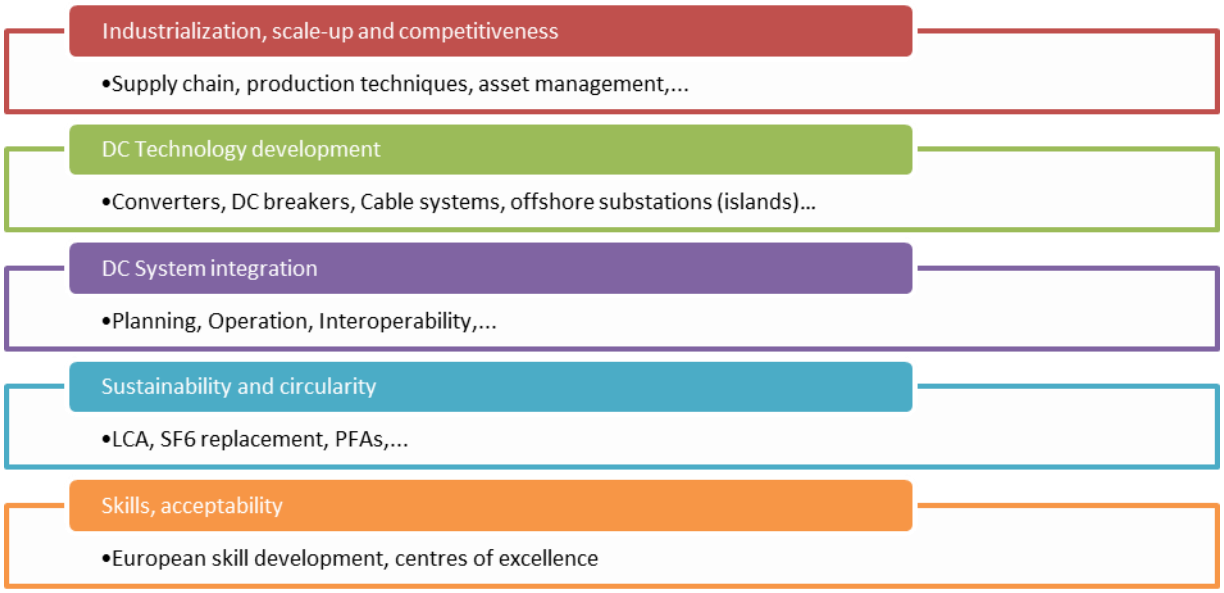
Appendices

Appendix A – Pathway forward to implementation

A.1 General approach

The IWG-DCT will work towards a Strategic Research and Innovation Agenda (SRIA) by end of October 2026, focussing on the 5 Innovation Themes identified in this domain as presented in this document. Each of these Innovation Themes has multiple key challenges in which milestones and R&I targets are being identified.



In this the innovation theme is a high-level field in which research and innovation is needed.

- Theme 1: Industrialization, scale-up and competitiveness
  - To address the need to move from bespoke products to industrialized solutions
  - To address the supply chain issues expected as deployment accelerates
  - To ensure faster, less human resource constrained approaches, e.g. for offshore installations
  - Large-scale production of power electronics in Europe
- Theme 2: DC Technology (components)
  - To ensure continued improvements in technology and in cost reduction
  - To ensure increasing scale and efficiency
  - To ensure DC grid technology development
- Theme 3: DC system integration
  - To ensure the necessary components, tools and methodologies to facilitate the seamless integration of DC technology into an anticipated future hybrid AC and DC grid
  - And this for all relevant time domains and applications
- Theme 4: Sustainability and circularity
  - To ensure that DC technology will be based on circular design principles, and correctly accounted for from a circularity and sustainability perspective, and the technological constraints associated with that
- Theme 5: Skills, acceptability
  - Ensure continued education in the field of direct current and power electronics (academic, and vocational career paths)
  - Enhanced international coordination through centres of excellence in DC technology

The IWG-DCT has developed a R&I innovation needs structure with 4 levels to provide a more granular roadmap:

1. **Innovation theme:** high level area of innovation area
    a. **Key challenge (KC)**: specific area of innovation need within a theme
        i. **Milestones (M)**: intermediate, significant achievement towards addressing the key challenge (time-bound)
            1. **Activities (A)** / steps to reach the milestones

Figure 4 shows the process of identifying targets to meet specific milestones that are identified within IWG-DCT. A milestone to realise a particular key challenge is achieved by realising a number of innovation activities of different TRL levels.

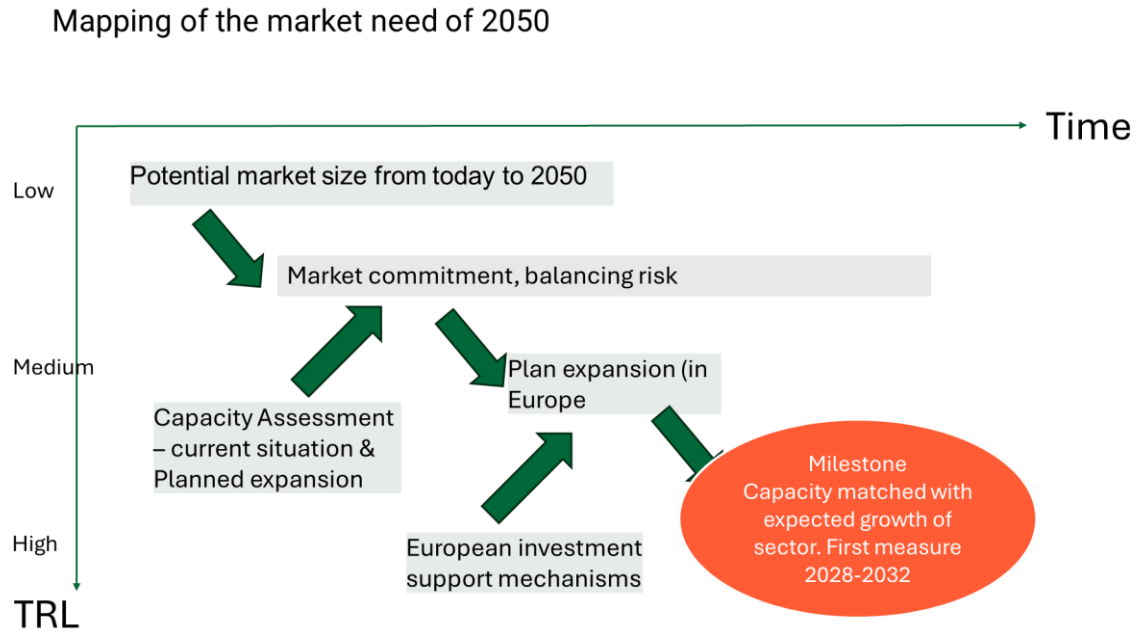


Figure 1: Example of process mapping activities to a single milestone: Capacity matched with expected growth of sector by 2028-2032. The time is placed on the x-axis, while the TRL level is on the y-axis.

A.2 Pathway to implementation: R&I needs status mid 2026

This has led to the following list of activities that we see as necessary to be performed to achieve the overall targets. This work is ongoing and will be completed in preparation of the SRIA. For now, the focus has been on transmission level applications, but shall contain distribution applications and end-user applications as well.

Theme 1. Industrialization, scale-up and competitiveness
- KC 1. Scaling up production
- KC 2. Standardization
    - M1. HVDC standards
        - A1. Pre-standardisation
        - A2. Creation and maintenance of standardization roadmap
        - A3. Development of an IEC standard
    - M2. LVDC standards
        - A1. Pre-standardisation
        - A2. Creation and maintenance of standardization roadmap

A3. Development of an IEC standard

KC 3. Asset Management

M1. Use of digitalization and AI to reduce engineering time for asset management by 2030

A1. Automated testing utilizing digital substation infrastructure

M2. Use of digitalization and AI to optimize asset management by 2035

A1. Health monitoring of complex hybrid energy systems utilizing automated tests and digital substation infrastructure

KC 4. Methods to quantify and manage risk

Theme 2. DC Technology (components)

KC 1. DC switching stations (including DC circuit breakers and DC switchgear)

M1. Expandable multi-vendor DC switching station for selective protection schemes by 2040

A1. Multi-vendor fault interruption capability as a modular and scalable solution

A2. Specification of standardized interfaces (Cable – GIS – junctions -…)

A3. Standardized DC insulation coordination

A4. Non-selective multi-vendor MTDC with single vendor DC switching station

A5. Multi-vendor DC switching station for non-selective protection schemes

A6. Demonstrate DCCB in single vendor MTDC

A7. Demonstrate DCCB in multi-vendor MTDC

KC 2. Cable systems

M1. Modelling, monitoring and testing done by 2030

A1. Advanced thermal, electric and life/reliability modelling of cables

A2. Design- and lifetime-relevant waveforms identified

A3. Standardized test methods and equipment

M2. Futureproof Cable design 2035

A1. Effective and high-quality jointing (manufacturing, jointing different materials, joint health monitoring, joint replacement)

A2. New materials for cables (thermoplastics, lead-free radial water barriers, semiconductive materials, non-metallic armouring

A3. Deep-sea extruded cable

A4. Subsea intervention for cable repair

M3. Extra high power DC cables > 2 GW

A1. High power super conducting cable pilot

A2. UHV cables 640 kV and 800 kV

A3. Subsea super conducting cable pilot without intermediate cooling

KC 3. Converter technology

M1. Grid friendly converters by 2035

A1. Grid forming converters

A2. Grid code compliance testing

A3. More flexible converters: converter topology with DC side storage and/or overload capability

A4. Demonstrating DC side storage participation in ancillary services

- M2. Flexible DC transmission systems
  - A1. DCDC converters for transmission level application
  - A2. Demonstrating DCDC converters at HV level
  - A3. New DC power flow controlling devices and DC power quality technology
  - A4. Demonstrating new DC power flow controlling devices and DC power quality technology
- M3. Modular HVDC converters: Modularity by design by 2035
  - A1. Open HVDC control
  - A2. Demonstrating open HVDC controls
  - A3. Open submodule and converter arm specifications
  - A4. Demonstrating open submodule and converter arm specifications

KC 4. Offshore substations and energy hubs

- M1. Offshore energy hub concept ready by 2035
  - A1. Energy Hub architectures
  - A2. Condition and lifetime baseline models for offshore equipment
  - A3. C&P interoperability and offshore grid codes
  - A4. Planning Tools, CBA analysis, market and regulation barriers (see also theme 3)
  - A5. Remote monitoring solutions for offshore equipment
- M2. Offshore energy hub ready by 2045
  - A1. Submarine equipment
  - A2. Lightweight, low maintenance, compact DC equipment (DCCB, DCCB with SFCL, GIS) for offshore platforms
  - A3. Specific testing procedure and equipment / FAT + SAT testing

KC 5. Power electronic components

Theme 3. DC system/grid integration

KC 1. Analysis of hybrid AC/DC grids

- M1. Steady state analysis tools for large scale AC/DC grid analysis by 2035
  - A1. PF and OPF implementations
  - A2. Development of open pan-European grid model for steady state analysis
  - A3. Security constrained / risk-based analysis tools
  - A4. Security constrained / risk-based analysis tools in commercial software

KC 2. Planning of future AC/DC grids

- M1. Extended CBA tools for grid extensions by 2030
  - A1. Inclusion of full technical capabilities of DC technologies in CBA methodologies and tools
  - A2. Inclusion of social and environmental impact in CBA methodologies and tools
- M2. Master plan for Europe by 2035
  - A1. Policy level agreement on Europe's electric energy and grid needs
  - A2. Enhanced tools available to compute pan-European grid development

KC 3. Operation of future AC/DC grids

- M1. Continuous operation in a MTDC-multi-TSO environment by 2030

A1. Functional requirements for handling physical and operational constraints in MTDC-multi-TSO environment
A2. Functional requirements for handing contingencies (N-k and power curtailment) in MTDC-multi-TSO environment
A3. Requirements for implementation of a DC Grid Control in a MTDC-multi-TSO environment
A4. Hybrid AC/DC system operation guidelines

M2. Coordinated protection plan by 2030
A1. Methodology to define fault separation and fault isolation zones
A2. Protection algorithms
A3. DC-FRT for converter stations
A4. Switching devices
A5. Methodologies to test the MTDC protection plan

KC 4. Control of HVDC control and protection systems for seamless integration

M1. Development of network codes for HVDC
A1. Definition of DC stability classes
A2. Development of Analytical methods for the creation of DC network equivalents
A3. New requirements regarding GFM abilities of converters
A4. DC grid controller

M2. Simulation tools, compliance tests and test facilities for HVDC converters by 2035
A1. Standardisation of (offline) interfaces
A2. Accurate HIL representation of power system components
A3. Training of technicians for operation and maintenance of MV/MT

KC 5. Resilience of hybrid AC/DC grids

M1. Methodologies to integrate resilience concepts in hybrid AC/DC, multi-TSO system

M2. Tools to integrate resilience in operation of future hybrid AC/DC, multi-TSO system

M3. Tools to integrate resilience in planning of future hybrid AC/DC, multi-TSO system

Theme 4. Sustainability and circularity

KC 1. Life Cycle Analysis

M1. Full life Cycle analysis capabilities by 2035
A1. Methods and tools to account for the life cycle costs (including manufacturing and decommissioning) of DC systems are available for use by system planners
A2. Methods and tools to account for the system level life cycle costs (including manufacturing and decommissioning) of DC systems are available for use by system planners

KC 2. Reduced / low environmental impact / green certification of DC grids (no PFAs, SF6, lead in cables).

M1. Materials and components by 2040 (A Circularity by Design (product design) approach).

A1. Minimal use of critical raw materials, more efficient production: recyclable cable (materials), XLPE, Copper.
A2. Minimize dependence on semiconductor resources of power converters
A3. Reducing footprint of land use of DC solutions.
A4. SF6 replacement in substations and switchgear
A5. Increased lifetime of components

M2. Standardisation and Digitalisation of DC technology to support by 2032
A1. Standards and Certifications for Digital Product Passport
A2. Digital Product Passport creation (2030 to 2032)

Theme 5. Skills, acceptability

KC 1. Centres of excellence for DC technology

M1. Establishing Centres of excellence for DC technologies at EU level by 2030

KC 2. European wide EU education and training academy for DC technology (including vocational training)

M1. Development of training material for various DC specific needs by 2030
A1. Development of training portfolio for various profiles
A2. Design of laboratory/digital twin/HIL setup for training purposes
A3. Coordination of training courses at EU level

M2. Certified DC training offering at EU level by 2030

M3. Establishing EU master education on DC grid-based power electronics

Appendix B – SET Plan Cross-cutting task force recommendations

The Thematic Vision reflects the recommendations of the SET Plan **cross-cutting task forces**, which are highly relevant for DC technologies. The development of **skills** is essential to ensure that a qualified workforce is available to design, install and operate increasingly complex, power electronics-based systems. **Sustainability and circularity** considerations must be fully integrated in technology design in order to reduce environmental impact and dependence on critical materials. **Digitalisation** plays a key role in enabling advanced system operation, planning and asset management. At the same time, **societal needs** require energy systems to be affordable, reliable and publicly acceptable. Finally, improving **access to market** remains crucial, requiring the removal of regulatory barriers and support for industrial scale up. These cross-cutting aspects are integrated throughout the innovation themes and are essential for successful deployment.
The cross-cutting task forces that were organized in 2025 by the SET Plan, are particularly relevant for DC technology given it is a technology aimed at integrating systems. In fact, several of these task forces align with the key development needs for DC technology. The following concrete elements are considered from the different task force recommendations:

- Skills:
  - The deployment of the future energy system using DCT faces a significant challenge with respect to skills, as the transition to a fully electric energy system will require more and better skilled workforce,
  - Skills for DC technology are the integral topic of Theme 5
- Circularity and material substitution:
  - The recommendations fully align with Theme 4.
  - In particular:

        - Recommendation 2: guidelines for LCA analysis
        - Recommendation 4: Accelerate material substitution (Lead for cables, SF6, PFAS, recyclable/recycled materials for cables)

- Digitalisation:
    - Digitalisation is a general trend that is changing the industry in a rapid manner. We expect that digitalisation will lead to enhanced processes, faster development and implementation and better asset management.
    - In particular recommendation 8: a cyber resilience plan is of direct relevance to DC technologies
    - Digitalisation elements are mainly contained in Theme 1 and Theme 3.
- Societal needs:
    - As an enabling technology for energy systems, societal needs are directly linked to DC technologies, Societal needs are mainly covered in Theme 3.
    - In particular:
        - Recommendation 1: embedding societal needs into strategic planning of SET Plan actors: including societal aspects in tools for system development and operation
        - Recommendation 3: improve the accessibility and affordability of energy systems, through the cost-effective interconnection of all loads and generation, using least impact technology (e.g. underground)
        - Recommendation 5: maximise synergies between energy systems and other land uses and sectors: common infrastructure corridors and combined planning of energy systems
- Access to market:
    - DC technologies are “in the market”, but still require attention to ensure cost-effectiveness over a wider range of applications, removal of regulatory barriers, remove supply chain bottle necks, develop the necessary infrastructure to deploy the technology,
    - For DC technologies, most of the topics related to access to market, are directly or indirectly linked to Theme 1