EUROPEAN COMMISSION
DG RTD, Directorate C - Clean Planet
DG ENER, Directorate B - Just transition, Consumers, Energy Efficiency and Innovation
JRC, Directorate C - Energy, Transport and Climate
SET Plan Secretariat

IMPLEMENTATION PLAN ON

"HIGH VOLTAGE DIRECT CURRENT (HVDC) & DC TECHNOLOGIES"

October 2021

CONTENTS

1. Executive Summary

The SET Plan R&I activities aim at developing, maturing and demonstrating technologies, systems and services sustainably up to a Technology Readiness Level 7-9, i.e. up to demonstration-pre-commercial or pilot or real industrial project. These will enable developing, upgrading and operating the power system with the appropriate level of sustainability, reliability and economic efficiency, while integrating variable renewables, such as wind and solar generation. The goal of this Working Group is to support the development of DC Technologies and Systems, with the initial focus on HVDC, within the existing power system which utilises Alternating Current (AC).

The electricity production landscape is evolving from centralised generation in conventional power plants to decentralised and local generation by renewables. The rollout of renewables results in an increasing number of Power-Electronic Interfaced Devices (PEIDs) in electricity supply. In this context, the new energy system has to fulfil new tasks such as bidirectional power transfer, active management of power quality, ensuring system security, controllability and dynamic stability, integrity and interoperability, while in addition, covering long distances. Furthermore, the offshore generation development prospected from the Offshore Renewable Energy Strategy (ORES) entails a transformation of the grid infrastructure to enable the transport of large amounts of energy generated offshore over very long distances to the consumption centres. With its high-power transmission capabilities, different technological options, applicable topologies and precise power flow controllability, HVDC systems are key for designing reliable power grids. DC Technologies can be applied in any area of the electric energy sector and can play a key role to seamlessly integrate RES in the European energy system. To fully exploit the potentialities of HVDC and DC Technologies and Systems, more Research, Innovation and Demonstration actions (R&I&D) are needed.

The implementation of HVDC systems and grids require developments in different fields and over a longer period of time. The key areas in which innovation is needed are: (i) Technology; (ii) Control and Protection; (iii) Operation and (iv) Planning.

The overall targets considered in the Implementation Plan are:

- *Short-term targets (now – 2027)*:
    - An operable multi-terminal, multi-vendor HVDC system in Europe (e.g. hybrid interconnector)
- *Medium-term targets (2027-2035)*:
    - Multi-terminal, multi-vendor HVDC system becomes a cost-effective and scalable solution for large offshore projects
    - Multi-terminal multi-vendor HVDC system for onshore ready for deployment or expansion and integration into a stable and resilient AC grid.
- *Long-term targets (2035-2050)*:
    - Backbone HVDC grid covering offshore and onshore networks (while integrating smaller systems)
    - HVDC available for deep sea applications

Thirteen short term implementation actions were identified and grouped according to the key areas mentioned above.

2. INTRODUCTION

2.1. Integrated SET Plan and the ten key priority actions

Since 2008, the SET Plan has been the core instrument to help aligning European and national clean energy R&I priorities across Europe by fostering cooperation between governments, the research community and industry.

This cooperation mechanism helps to leverage the use of funding instruments and to attract private investments in key clean energy technologies needed to reach the European Green Deal objectives, including renewables, batteries and smart grids.

The integrated SET Plan identifies 10 actions for research and innovation:

- integrating renewable technologies in the energy systems
- reducing costs of technologies
- new technologies and services for consumers
- resilience and security of energy systems
- new materials and technologies for buildings
- energy efficiency for industry
- competitiveness in global battery sector and e-mobility
- renewable fuels and bioenergy
- carbon capture and storage
- nuclear safety

The actions address the whole innovation chain, from research to market uptake, and tackles both financing and regulatory framework.

To ensure an effective interaction with all partners, the plan has an overall governance structure for measuring key performance indicators (KPIs), including level of investment or cost reduction. The Infographic of the SET Plan in Fig. 1 shows the above actions, divided into 6 domains for clarity. It also lists the 13 SET Plan implementation working groups (IWGs).

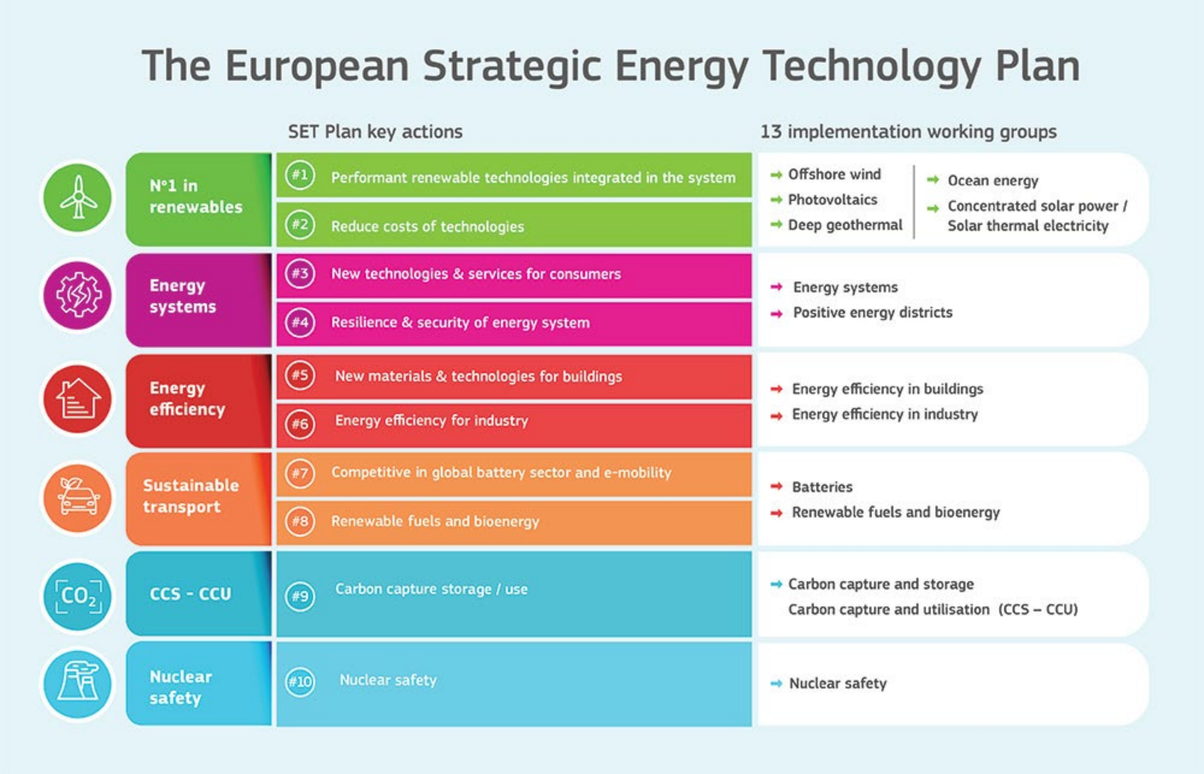

Figure 1: SET-Plan Infographic

Implementation Plans (IP) aiming at reaching the targets have been prepared by Temporary Working Groups (TWG), each led (or co-led) by one (or two) SET Plan country(ies)[1]. The IPs describe what needs to be done, how, by whom and when, and how to monitor progress.

With this in mind, the new Temporary Working Group will develop the Implementation Plan on HVDC & DC Technologies.

2.2. Policy framework

In 2018 the European Commission (EC) published its long-term strategy "A Clean planet for all", which identifies offshore renewable energy, amongst others, as a key source to realise our clean energy transition. In November 2020, the Offshore Renewable Energy Strategy has set objectives of at least 60 GW of offshore wind energy and 1 GW of ocean energy by 2030, and 300 GW of offshore wind and 40 GW of ocean energy by 2050 to harness the vast potential for offshore renewable energy generation in various European water basins.

The Offshore Renewable Energy Strategy addresses many aspects related to the deployment of offshore energy infrastructures, including the technologies needed to transmit the generated energy to land, among which a key option is based on High Voltage Direct Current (HVDC) transmission. For each aspect identified, the strategy proposes a series of key actions, including the launch of an additional SET Plan Working Group on HVDC to support development of technology and the associated

[1] The TWGs are formed by countries interested in a particular action, stakeholders and the European Commission.

value chain, namely through the installation of the first Multi-vendor Multi Terminal HVDC in EU by 2027.

The steadily increasing rollout of renewable energy both offshore and onshore, as promoted by the European Green Deal (EGD), represents a paradigm shift and requires appropriate means for integration in the energy system such as storage, demand response and electricity transmission technologies.

2.3. Overarching Goal

The SET Plan R&I activities aim at developing, maturing and demonstrating technologies, systems and services sustainably up to a Technology Readiness Level 7-9, i.e. up to demonstration-pre-commercial or pilot or real industrial project. These will enable developing, upgrading and operating the power system with the appropriate level of sustainability, reliability and economic efficiency, while integrating variable renewables, such as wind and solar generation. The goal of this Working Group is to support the development of DC Technologies and Systems, with the initial focus on HVDC, within the existing power system which utilises Alternating Current (AC). This will include the assessment and management of a wide-spread AC/DC hybrid system, allowing a high onshore and offshore RES penetration, as well as fostering the resilience of the grid, making both the offshore and onshore grid fit-for-purpose by 2050. The activities of the Working Group will entail the following wider impacts:

- Increase interest and acceptance of HVDC systems among professional engineers, industries and decision-makers, favouring value chain development and availability of skilled labour.
- Stimulate R&D to increase the interoperability, controllability, security, dynamic stability and efficiency of the electricity grid equipped with many HVDC systems.
- Introduce and evaluate the benefits of new technologies that can support the roll out of HVDC grid and AC/DC hybrid grids.
- Provide the grounds to decision-makers and investors to make better-informed decisions regarding the HVDC systems as an important grid development option. These decisions usually concern major investments, multiple stakeholders and multiple countries and require multiple analyses of the benefits that can be provided.
- Support the Offshore Renewable Energy Strategy, the Green Deal, the Energy Union and the Long-Term Strategy

3. Problem Definition and state of the art

The electricity production landscape is evolving from centralised generation in conventional power plants to decentralised and local generation by renewables. The rollout of renewables results in an increasing number of Power-Electronic Interfaced Devices (PEIDs) in electricity supply, which adds up to those in load, storage, sector coupling and interconnections. In this context, the new energy system has to fulfil new tasks such as bidirectional power transfer, active management of power quality, ensuring system security, controllability and dynamic stability, integrity and interoperability, while in addition, covering long distances. Furthermore, the offshore generation development prospected from the Offshore Renewable Energy Strategy (ORES) entails a transformation of the grid infrastructure to enable the transport of large amounts of energy generated offshore over very long distances to the consumption centres. In course of using more and more remote generation, power transmission becomes more and more important maintaining the security of supply. This requires appropriate design of the transmission system. With its high-power transmission capabilities, different technological options, applicable topologies and precise power flow controllability, HVDC systems are key for designing reliable power grids. At the same time, HVDC technology must be reliable. The technology is based on converters utilizing thousands of power electronic components, will be largely based on underground power transmission, transferring bulk amounts of power. On the other hand, they provide new flexibility means. This change compared to traditional energy transmission requires special attention to ensure system reliability, both from component and system level.

DC Technologies can be applied in any area of the electric energy sector and can play a key role to seamlessly integrate RES in the European energy system. To fully exploit the potentialities of HVDC and DC Technologies and Systems, more Research, Innovation and Demonstration actions (R&I&D) are needed.

3.1. HVDC technology

HVDC is a Power Electronics (PE) based technology that enables the transmission of electricity over long distances and allows integrating high shares of RES in the actual Alternating Current (AC) energy system. It is an efficient and economical option for long distance bulk transmission of electrical power compared to the High Voltage Alternating Current (HVAC) systems. An HVDC transmission system consists primarily of:

1. an AC/DC converter station at one end of the HVDC transmission system (on the left in Figure 1), where the power from the HVAC grid is converted from Alternating Current (AC) to Direct Current (DC);
2. transmission lines (namely overhead lines or cables) that connect the AC/DC converter station to the DC/AC converter station and transmit the HVDC power;
3. and a DC/AC converter station at the other end of the HVDC transmission system (on the right in Figure 1), where the power is converted from (DC) to (AC) for delivery back into the HVAC grid.

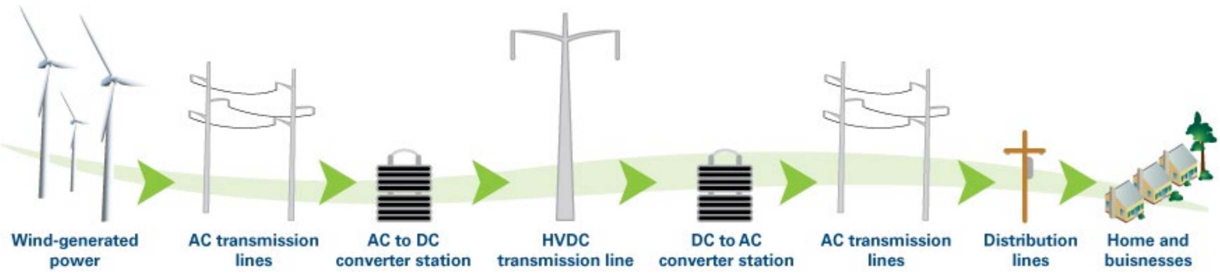

Figure 1 HVDC system integrated in the AC grid. Source: Duke-American Transmission Co.

Considering the DC transmission technologies available today, the characteristics of the latest generation of High Voltage Direct Current (HVDC), namely the Voltage Source Converter (VSC) prospects solutions addressing the highlighted challenges.

HVDC systems can be integrated in the AC electric grid and allow the control of direction and amount of power to be transferred. HVDC can offer several distinct advantages over a typical Alternating Current (AC) Transmission system. The key characteristic is that the power can be transmitted over very long distances without compensation for the reactive power[2]. Furthermore, HVDC stations can be connected to networks that are not synchronised or do not even operate at the same frequency. HVDC systems help to prevent the transmission of faults between connected AC grids and can serve as a system "firewall" against cascading faults.

The first generation of HVDC technology, the Line Commutated Converter – "LCC-HVDC", also referred as Current Source Converter (CSC) or HVDC Classic, is available since the 50's and enables mostly point to point connection of regions or countries for the market exchange of electricity or more recently for the connection of windfarms.

Voltage Source Converter HVDC, also known as self-commutated converter HVDC offers many advantages over LCC HVDC due to its difference in construction. VSC HVDC has a high degree of flexibility with in-built capability to control both its active and reactive power, which makes it attractive for urban power network areas and offshore applications. In addition, the control strategies of the converter can be engineered to make it a "Grid Follower Converter or Grid Forming Converter", addressing the issue of loss of system's inertia and guaranteeing the manageability of the grid under a high penetration of RES.

Different types of VSC are available, which provide additional flexibility in system planning. Such different types of converters can be seen in so-called Half Bridge Type MMC, Full Bridge Type MMCs or converters representing a combination thereof.

The interconnection of more than two VSC HVDC converter stations leads to Multi-Terminal VSC-HVDC (MT VSC HVDC) in different topologies, e.g., radial, ring and meshed or through a DC power hub. MT HVDC provides the ability to connect multiple AC grids, remote power plants and remote loads together. MT HVDC networks can be applied offshore as well as onshore to increase system reliability, contribute to smoothen wind power variability and trade electric energy safely across national borders.

In short, MT VSC HVDC transmission is considered a promising technology for the integration of massive generation from renewable sources into the power system.

---

[2] Reactive power does not contribute to the effective real power transmitted (active power) flowing from generator to load but it involves an exchange between them. Moreover, it refers the extra power that needs to be spent to transfer active power over the network due to the physical and electrical characteristics of AC transmission. Since in HVDC the voltage is constant in time domain, reactive power is not generated. Only two conductors are needed (or even one conductor if the ground or the sea is used as return) for HVDC compared to the three conductors traditionally used for HVAC.

4. CHALLENGES TO ADDRESS

4.1. Core topics of the WG

The implementation of HVDC[3] systems and grids require developments in different fields and over a longer period of time.

The key areas in which innovation is needed are:

- **Technology:** The development of components that constitute the HVDC system is key to its deployment: these components allow new features and can drive the economics. The components consist of ***primary equipment*** such as HVDC converters (half-bridge, full-bridge, but also DC-DC converters), HVDC cables, HVDC overhead lines and conductors, switchgear (e.g. DC breakers, but also DC GIS cable termination including standardization) and the power electronic components[4] themselves, and ***secondary equipment*** such as measurement equipment and protection relays. The developments can lead to more sustainable, efficient, reliable or cheaper solutions, but could also lead to higher power ratings or operating voltages. Additionally, technology developments with respect to supporting equipment can accelerate the deployment of HVDC systems, e.g., through the development of cheaper / smaller (offshore but also onshore) substations.
    - **Examples of innovation needs:** developments and improvement of all HVDC system components: converters and their auxiliaries, submarine/underground cables, overhead lines, junctions and conductors, GIS without SF6, new converter topologies, DC Switchgear, DC/DC converters, DC flow control, DC fault current limiting devices, storage integration into HVDC systems or converters, etc. with the objective of realizing larger power ratings (e.g. 4-5 GW), higher efficiencies, cost-reduction measures, improved life-cycle analysis, etc.
- **Control and protection:** With control and protection of HVDC (grids), and coordinated with the ones in the AC grids, the set of equipment and the associated software/settings which regulates the behavior of the system and the interactions with the remainder of the system is meant. In particular, it is responsible for the correct behavior of the power electronic converters, the speed and accuracy of services provision, the detection and selective clearing of faults, etc.
    - **Examples of innovation needs:** Multi-vendor interoperability, grid forming mode, ancillary services capabilities for the DC grids, enhancing the capabilities of ancillary services towards the AC grids, AC and DC side protection, integration of HVDC in

---

[3] In the initial phase, the priority lies with the development of an implementation plan and roadmap for HVDC systems. In a second phase, this will be extended with MVDC research. Some of the key elements related to MVDC development needs are included in the Annex

[4] e.g.: WBG materials, such as Silicon Carbide (SiC), represent the key enabling technology for an innovative and very efficient class of power devices suitable for a wide range of power conversion applications, in particular within the HVDC systems. SiC MOSFETs and diodes, in addition to wider energy gap with respect to Silicon, exhibit very high critical electric field and electron saturation velocity, making them the most advanced power semiconductor switches to fit into converters for HVDC systems.

emergency and restoration of the AC grids, firewalling, communication protocols adapted to hybrid AC-DC systems

- **Operation:** With operation, the system level management of the power system is meant. Power system operation ensures a reliable, economic operation of the power system. With increased use of HVDC systems, operators will have additional degrees of freedom to increase the AC system controllability, but the influence of HVDC control actions will affect local stability issues. HVDC transmission systems could interconnect multiple synchronous areas and provide connection to RES. Indeed, the future system will work as a system-of-systems, with an agile (situation dependent) interaction resulting in a more resilient system. In order to achieve that, management approaches that will incorporate the controllability of HVDC systems are needed. This will need to be translated into operational rules (grid codes) and implemented in the tools (e.g. SCADA/EMS).
    - **Examples of innovation needs:** Incorporation of HVDC control principles into control room software, HVDC Grid supervisors and coordinated controls that are able of controlling the DC grid and contribute to the proper functioning of the hybrid AC/DC systems (e.g. monitoring higher dynamics of [hybrid] grids, dynamic load flow and stability calculations), AC/DC power flow and OPF tools, Congestion management, sharing reserves over HVDC, integration of preventive and corrective actions, risk based reliability management,…
- **Planning:** HVDC systems need to be integrated in the future power system in such a way that they can form multi-terminal HVDC grids. This includes integrated and onshore grids, (inter-) connection of different control zones and synchronous areas, power wheeling over larger distances and reliability management[5]. System expansion towards HVDC links or meshed HVDC grids should result in a cost-effective and well accepted solution for society (social welfare) and the individual investor to be supported by commonly accepted methodologies and decision supporting tools. System planning should provide some form of top-down orchestration, to guide and enable step-wise organic development of HVDC grid system pieces.
    - **Examples of innovation needs:** Technical economic analysis tools, System expansion planning tools with HVDC, hybrid interconnection planning with Cross-border investment planning for backbone application, combined AC/DC expansion planning at offshore and onshore level, HVDC grid planning standards in the EU context (architecture principles, technologies, control and protection), Consolidated vision of HVDC transmission long-term needs.

4.2. Linked topics to the WG

Next to the four key areas mentioned above, there are four linked areas which are expected to have a significant influence on HVDC system requirements, operations and development. While not a particular topic of the WG activities, the developments in these areas must be monitored as their

[5] "Power system reliability management allows the electricity grid to maintain performance at a desired level, while minimizing the socio-economic costs of maintaining that performance level", reproduced from https://cordis.europa.eu/article/id/221334-new-reliability-criteria-for-power-system-management

evolution may govern the innovation needs in the core topics. While these topics themselves are not part of the innovation roadmap, innovation actions at the interface of core topics with these linked topics are anticipated.

The linked topics are:

- **RES integration:** Arguably, the development of future HVDC grids is driven by the transition to more renewables, which are located further from the load centers and have lower capacity factors.
- **Economic framework and developments**: While no direct concern of the HVDC system, its economic viability and its use are determined by the energy flows and the services. Some of the elements which are of particular interest to the HVDC community are the manner in which HVDC technology/grids will be incorporated into congestion management, provision ancillary services and their harmonization across borders.
- **Regulation and governance:** the framework under which the system is developing is crucial as it determines the technical requirements and the responsibilities e.g., different ownership models are possible, and that will have an impact on the HVDC grids development.
- **Social and environmental:** The future (HVDC based) power system should not only be technically sound, but also be a sustainable and socially acceptable solution. As such, solutions need to adhere to circular economy principles and be well accepted in communities.

4.3. Time horizon of HVDC development needs

In this section, first the overall targets are identified on a short-, medium- and long-term. They are guiding the development needs.

4.3.1. *Short-term targets (now – 2027)*

- An **operable** multi-terminal, multi-vendor HVDC system in Europe (e.g. hybrid interconnector). The number of interconnections with integrated DC systems will increase, thereby raising the need of standard and extendable technological solutions covering multi-terminal, multi-vendor and multi-purpose capability including interoperability among different vendors' HVDC converter stations. This will be very important also towards the future realisation of multiple, coordinated VSC HVDC links (and maybe some LCC equipped with reactive compensation devices), embedded within the European continental HVAC system (onshore).
- Top-down orchestration of HVDC grid planning, enabling an efficient step-wise organic development of future HVDC grid system pieces: consolidated vision of HVDC transmission development long-term needs, HVDC grid planning standards which are emerging, in order to enable multiple projects.

4.3.2. *Medium-term targets (2027-2035)*

- Multi-terminal, multi-vendor HVDC system becomes a cost-effective and scalable solution for large offshore projects
- Multi-terminal multi-vendor HVDC system for onshore ready for deployment or expansion and integration into a stable and resilient AC grid.

4.3.3. *Long-term targets (2035-2050)*

- **Backbone** HVDC grid covering offshore and onshore networks (while integrating smaller systems)
- HVDC **available for deep sea applications**

4.4. Non-technical

The level of penetration and integration of HVDC systems prospects a series of non-technical issues such as legal framework, network code, market conditions, environmental, governance, roles and responsibilities, circular economy, social acceptance, which can constitute a barrier for the deployment of HVDC systems and needs to be addressed. Below are reported only some examples of areas of non-technical matters to be further developed[6].

The legal framework

Offshore wind and offshore grid connections have developed strongly in the past few years while the legal framework lags behind. While solutions have been sought to facilitate offshore wind, hybrid solutions that combine interconnection with offshore wind connection are often not yet supported by legal frameworks. Therefore, the legal framework needs to be adapted to facilitate the development of a meshed offshore electricity grid. For example, regarding the applicability of EU law at sea, according to the EU founding treaties, EU law is applicable to the Member States of the European Union[7]. Therefore, except for a few specific cases, EU law is applicable to the territory of the Member States. However, it is not evident to what extent EU law is applicable to the Northern Seas.

Network Codes

The Regulation (EC) No 714/2009 provides for the cooperation of the European electricity TSOs through the establishment of the European Network for European Electricity TSOs (ENTSO-E). The Regulation's assignments to ENTSO-E are the promotion of cross-border electricity trade, the coordinated operation and optimal management of the transmission network and the completion of the internal market in electricity. One of the tasks of ENTSO-E is the development of European network codes (at the initiative of the Commission, and via ACER). These network codes serve specifically to facilitate cross-border trade and transmission of electricity. The COMMISSION REGULATION (EU) 2016/1447 of 26 August 2016 establishes a network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules. The network code

---

[6] Extracted from the deliverable "Legal framework and legal barriers to an offshore HVDC electricity grid in the North Sea" of the project PROMOTIoN by Ceciel Nieuwenhout

[7] TEU, art. 52; Treaty on the Functioning of the European Union (TFEU) art. 355

regulates requirements for HVDC connections, such as for example active power control and frequency support, reactive power control and voltage support, fault ride through capability, control and protection devices. Future HVDC system developments might result into a need for changes into existing network codes, or into the development of new network codes that govern the DC side behaviour. HVDC innovation actions might provide insights and recommendations for such network code developments.

Market rules

The rules on priority access and dispatch reduce the risk on investments for RES, as the certainty that the generated electricity can be sold on the market is increased when the access to the grid is prioritised. However, in a meshed offshore grid where connection of OWFs[8] is mixed with interconnection between countries, clear agreements have to be made. For example, it should be decided whether the full capacity of the cable is available for transportation of the offshore generated electricity (which means that this electricity always has priority access), or whether part of the cable is separated in some way and reserved for interconnection, as is suggested in some studies[9].This should be examined in more detail.

Environmental Impact

The Environmental Impact Assessment Directive obliges Environmental Impact Assessments (EIAs) to be carried out before projects that are likely to have an impact on the environment are approved[10]. The EIA Directive is applicable to windfarms as far as national authorities determine so. There is no specific mention of OWFs, so it seems that these fall under the same rules as onshore windfarms, namely, at the discretion of the national authorities. Concerning electric cables, there is a mention of overhead electrical lines and cables, but there is no similar mention of specifically underground (or even sub-sea) cables. Nevertheless, there has not been any concrete change in the revision of the EIA Directive of 2014[11]. Therefore, the EIA Directive does not impose EIAs on (offshore) underground electricity cables at this moment.

However it is a purpose of the IWG to stimulate the development of technology which respects the circular economy principles and so there will be the need investigate and account life cycle environmental impact of these kind of structures, such as: raw materials mining and treatment (before installation), energy consumption from components and equipment manufacturing, soil occupation (during installation and use); equipment disassembly, components end-of-life recovery (e.g. reuse or recycling).

Social impact

Onshore HVDC deployment may require identifying NIMBY phenomena and analysing how to deal with it through technology design and network planning.

---

[8] or hybrid farms, comprising of wind, ocean and/or other technologies

[9] See, for example, NSCOGI Market Arrangements Paper, 31-7-2014, p. 5/6 (virtual case 1).

[10] Council Directive 85/337/EEC of 27 June 1985 on the assessment of the effects of certain public and private projects on the environment (EIA Directive), as amended by directives 97/11/EC and 2003/35/EC

[11] Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014, amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment, OJ L 124.

5. State of affairs on HVDC & DC Technologies

Significant progress in the development of the HVDC technology has been done in the past decade or so. HVDC converters based on VSC technology have been used for connecting offshore wind power plants or for interconnecting countries and/or power systems. Many of the developments have been facilitated by multiple initiative and R&D projects at national and EU level. This section aims at briefly introducing the main developments and initiatives at national and EU level. It will also highlight the main initiatives from the main stakeholders (ENTSO-E, T&D Europe and WindEurope) towards the development of multi-vendor HVDC systems.

5.1. Main stakeholders' joint activities on HVDC

The European Network of Transmission System Operators (ENTSO-E) , who represents 42 electricity transmission system operators from 35 countries across Europe, together with the European association of the electricity transmission and distribution equipment and services industry (T&D Europe) and WindEurope , an association promoting the use of wind power in Europe outlined their joint perspective on research directions to solve the technical challenges caused by the integration of a large number of converter stations delivered by various technology providers. The focus is placed on the development, delivery and deployment of multi-terminal, multi-vendor high-voltage direct current (HVDC) systems providing the connection to offshore wind. Five interlinked workstreams are proposed and their performance detailed in a coordinated approach between different development stages (research and development [R&D] and industrial implementation) to achieve multi-terminal, multi-vendor HVDC systems: (i) Development of Standardised Interaction Study Processes and Interfaces; (ii) Assessment of Interoperability for Multi-Terminal, Multi-Vendor HVDC Systems; (iii) Multi-Terminal, Multi-Vendor Real Industrial-Scale Project; (iv) Cooperation Framework and Governance; (v) Network Planning, Project Financing and Procurement.

5.2. Members States and Associated Countries activities on HVDC

Multiple R&D projects – of various sizes and ambitions – have been funded at national levels. A more detailed list is given in the appendix. In this section, some of the larger ones are briefly described.

MultiDC[12] (Denmark), 2017-2022, funded by Innovation Fund Denmark has addressed challenges related to dynamic stability and security of inverter-based power systems, AC/DC coordinated control in the Nordic Power System and inclusion of HVDC links into market operation. The research included validation on RTDS and PHILS of the developed concepts, elevating he TRL level at 4-5.

NEPTUNE[13] (Belgium). 2018-2023, funded by the Energy Transition Fund focuses on three axes: (i) Planning and rollout of the grid in a cost-efficient and reliable way; (ii) Reliable protection to prevent grid outage or component damage due to faults; (iii) Control of the converters to achieve stable grid operation.

RSE - RdS C.4 T&D-CC (Italy), 2015-2018, was funded by the Italian Ministry of Economic Development - Fund for National Energy System Research, performed research on: (i) Analyses of HVDC systems integration in traditional AC transmission networks; (ii) Study of HVDC technology evolution; (iii)

[12] http://www.multi-dc.eu/
[13] https://www.energyville.be/en/research/neptune-north-sea-energy-plan-transition-sustainable-wind-energy

Assessment of control logics of HVDC system components, also for multiterminal application; (iv) Analyses of MVDC and LVDC systems integration in AC distribution networks, also for multiterminal application; (v) Investigation on conductors for HVDC transmission; (vi) Techno-economic assessment of new SACOI interconnection; (vii) Evaluation of AC-to-DC transmission OHL conversion and (viii) Analyses and development of LV DC breaker prototype. The target TRL level was 4-6.

OffshoreDC[14] (Nordic), 2011-2015, funded by the Nordic Energy Research, had as overall objective to identify and pursue solutions to offshore HVDC grids and their functionality as means of integrating large amounts of offshore wind power. With voltage-source converter-based HVDC possibilities for integrating multiple wind plants with multi-terminal DC transmission promises benefits in power flow control and asset utilisation. DC network operation, multi-plant control and connection to land AC grids are among the challenges to be solved. The results were at TRL level 3-4.

Ensure[15] **& Ensure 2** (Germany), 2016-2022, funded by Federal Ministry of Education and Research, are part of Kopernikus, a large research initiative in Germany in the field of the energy transition. The aim is to make it possible for Germany to be climate-neutral by 2050. Ensure is a two phases project; the integration of HVDC into the existing grid is only one part of the project, as it considers all aspects of the power grid of the future. The goal of the second phase of ENSURE is to draft an overall systemic concept for the energy supply that is embedded in the existing socio-economic framework, and to ensure transferability of the results within Germany and Europe, with a time horizon of 2050. It also includes research on (i) Hybrid AC/DC transmission grid; (ii) Intelligent components: DC breakers and sensors; (ii) Capacity of HVDC converters and the associated grid-serving capabilities and (iii) Piloting of an MVDC direct coupling, aiming at reaching TRL 7-9 (components)

Multi Terminal Test Environment for HVDC Systems[16] (UK), funded by OFGEM, has materialized in the National HVDC center in UK, and provides live project support for HVDC in GB, R&D support in key HVDC innovations, replica hosting, update tracking, enhanced FST design & implementation.

5.3. Overview on International activities on HVDC

Several European projects have addressed the development of VSC-HVDC technology and provided steps towards the development of offshore HVDC grids and the associated technical challenges and regulatory and financial barriers. This section – not exhaustive – aims at presenting the main R&D projects identified. They have provided important steps, paving the way towards the demonstration of multi-terminal, multi-vendor HVDC systems.

TWENTIES[17], 2010 – 2013, was funded under the Seventh Framework Programme and was one of the first large European projects that addressed HVDC converters, HVDC breakers and planning of offshore HVDC grids. It provided initial results in all of the topics, combining simulations studies with laboratory setups for a TRL level of 3-5.

---

[14] http://www.offshoredc.dtu.dk/
[15] https://www.kopernikus-projekte.de/en/projects/ensure
[16] https://www.hvdccentre.com/
[17] http://www.ewea.org/fileadmin/files/library/publications/reports/Twenties.pdf

E-Highway 2050[18]**,** 2012 – 2015, funded by the Seventh Framework Programme, and following the Study "Roadmap towards a Modular Development Plan on the Pan-European Electricity Highways System 2050" performed by ENTSO-E members in response to the Energy Infrastructure Package blueprint published by the European Commission (EC), a consortium of 28 partners, involving a wide spectrum of stakeholders, proposes the development and implementation of a top-down long-term planning approach, coordinated by RTE France. One overall result is the Modular Development Plan which will present the architectural possibilities of the electricity transmission network in 2050, including, among other information, the assumptions and calculations for electricity generation, demand and transmission technologies until 2050. Moreover, a network planning method is developed to serve as the basis for all future long-term network planning.

The approach begins with the Pan-European Transmission Network as proposed by the Ten-Year Network development Plan (TYNDP) 2012, which is assumed to be in line with the 2020 EU energy targets.

MEDOW[19], 2013-2017, funded the Seventh Framework Programme's Marie Curie-Sklodowska Initial Training Networks, was one of the first large scale educational programme in offshore wind and HVDC grids. It had a broad spectrum, covering topics from connection of offshore wind to HVDC grids, to HVDC protection and components and interactive AC/DC grids. Most of the results were of lower TRL level, creating fundamental knowledge in the area of offshore wind and HVDC. The TRL levels were 3-4.

BestPaths[20], 2014-2018, was funded under the Seventh Framework Programme, addressed challenges related to HVDC links in offshore wind and offshore interconnectors and HVDC-VSC multi-vendor interoperability. It provided laboratory scale experimental results, equivalent to a TRL level of 4-6.

InnoDC, 2018-2021, is funded under European Union's Horizon 2020 research & innovation programme under the Marie Sklodowska-Curie training networks. It covers a broad spectrum of topics in HVDC technology and grids and offshore wind, developing tools and methods for design and operation of offshore wind and HVDC grids. The TRL level is 4-5

PROMOTioN[21], 2016-2020, was funded under European Union's Horizon 2020 research & innovation programme, being the largest to date energy project in the program. The research in PROMOTioN focused on three areas: (i) Linking technology research, validation (testing), and the development of proposals and recommendations for meshed offshore grids; (ii) Identifying technical requirements and investigating possible topologies for meshed HVAC/DC offshore grids; (iii) Developing recommendations for a coherent EU and national regulatory framework regarding DC offshore grids. It provided the first full scale test of DC breakers components, elevating the technology to a TRL level 7, HVDC grids control technology to TRL 6, HVDC grids protections to TRL level 6 and HVDC gas insulated systems to TRL level 9.

[18] https://docs.entsoe.eu/baltic-conf/bites/www.e-highway2050.eu/e-highway2050/
[19] http://sites.cardiff.ac.uk/medow/
[20] http://www.bestpaths-project.eu/
[21] https://www.promotion-offshore.net/

5.4. IEEE and Cigre

IEEE (the institute for electric and electronics engineers) (http://www.ieee.org) and Cigre (conseil international des grands réseaux électriques) (http://www.cigre.org) are member based engineering associations that on the one hand organize events, conferences and symposia on scientific and technical matters, and on the other hand organize expert working groups and committees to develop technical training, guidelines and standards. Both organizations have dedicated activities with respect to HVDC.

The HVDC related activities of IEEE are organized under the HVDC & FACTS (https://site.ieee.org/pes-hvdcfacts/).

The HVDC related activities of Cigre are organized under the study committee B4 (https://b4.cigre.org). The scope of SC B4 covers High Voltage Direct Current systems and power electronic equipment for AC systems. The study committee also covers DC systems and equipment and Power Electronics for other applications such as distribution, and Power Quality improvement. Overhead lines or cables, which may be used in DC systems are not included in the scope of SC B4. DC converters for energy storage are part of the activities of SC B4. The members of SC B4 come from manufacturers, utilities, transmission system operators (TSOs), distribution system operators (DSOs), consultants and research institutes.

The extensive list of current working groups can be found on their website: https://b4.cigre.org/GB/technical-activities/working-groups.

5.5. Cen - Cenelec and IEC

The IEC are responsible for the creation and maintenance of the applicable standards, which are adopted by CEN or CENELEC as European EN standards.

For IEC, most HVDC related standards are organized under the technical committee 115 (TC115[22]). The scope of this committee is standardization in the field of HVDC Transmission technology above 100kV. The task includes HVDC system oriented standards as design aspects, technical requirements, construction and commissioning, reliability and availability, and operation and maintenance. Standards of HVDC equipment so far related to the system aspects are prepared in close collaboration with the relevant Technical Committees and Subcommittees.

There are also notable developments under IEC technical committee 22 (TC22[23]) which covers the field of Power electronic systems and equipment. The task of this technical committee is to prepare international standards regarding systems, equipment and their components for electronic power conversion and electronic power switching, including the means for their control, protection, monitoring and measurement. Of particular relevance here is that of sub committee SC22F who focus on the aspects of power electronics and/or semiconductor switching equipment related to electrical transmission and distribution systems.

[22] https://www.iec.ch/dyn/www/f?p=103:7:606079806990061::::FSP_ORG_ID,FSP_LANG_ID:3988,25
[23] https://www.iec.ch/dyn/www/f?p=103:7:::::FSP_ORG_ID:1293

Most recent activities of Cenelec related to this working group are covered in CENELEC - CLC/TS 50654 HVDC Grid Systems and connected Converter Stations - Guideline and Parameter Lists for Functional Specifications - Part 1&2. There is also working group 06 (WG06) which considers System aspects for HVDC grids as part of the CENELEC technical committee CNC/TC 8x.

6. SET Plan Strategic Targets on HVDC & DC Technologies

The overarching target – in the short term – is to enable the radical transformation of the European power system towards climate-neutrality and to facilitate a very high offshore and onshore RES share. On the medium & long term, the strategic target is to develop hybrid AC/DC grids, foster the resilience of the grid and make both the offshore and onshore grid fit-for-purpose by 2050.

Reaching the short-term target will not be possible without developing the framework – technical, legal and regulatory – for demonstrating interoperability of HVDC systems (control and protection) in a multi-vendor environment.

6.1. List of actions on HVDC identified

To timely unleash the offshore and onshore RES potential in support to the Offshore Renewable Energy Strategy and the European Green Deal, efforts from all stakeholders should ensure achievement of the targets listed below – while respecting the intrinsic process - in a timeframe as short as possible:

6.1.1. *Short term implementation needs*

Technology:

Code	Description
ST-T-1	Converters (and other components such as DC breakers, GIS, etc) – higher voltage & current ratings, integration of storage (within converters or HVDC systems), capability to withstand high fault currents
ST-T-2	Cable systems – higher voltage & current ratings, monitoring systems; cable system ageing; reliable and easy-to-install cable joints and terminations, eco-designed and manufactured cable systems; predictive models for cable system ageing (fraction-of-life lost, remaining life), life and reliability; monitoring and fault location systems
ST-T-3	Further development of Wide Band Gap (WBG) materials.
ST-T-4	Conversion technics and standards of HVAC overhead lines to HVDC

Control and protection

Code	Description
ST-CP-1	Multi-vendor interoperability - first European full-scale implementation of Multi-Vendor Multi Terminal VSC
ST-CP-2	Grid forming capabilities offered by HVDC systems and DC connected power park modules – demonstration of grid forming control
ST-CP-3	Components and interfacing for AC & DC side protection system design ensuring that all possible faults are detected and cleared sufficiently fast, in a selective manner

ST-CP-4	Techno-economic benefits of the capability of HVDC converters in acting as a firewall, i.e. blocking the spread of disturbances while permitting the interchange of power

Operation

Code	Description
ST-O-1	Software tools for AC/DC hybrid systems (online power flow calculation, stability assessment)
ST-O-2	Methods for balancing & reserves sharing over MT HVDC
ST-O-3	Operational models and tools to accommodate different governance options (including Ownership and responsibilities) over large HVDC grid system assets (off-shore, on-shore, off-on-shore)
ST-O-4	Operation principles for large HVDC grid system assets (off-shore, on-shore, off-on-shore)

Planning

Code	Description
ST-P-1	Methods and tools for combined system (HVAC and HVDC) expansion

6.1.1. *Medium term implementation needs*

Technology

Code	Description
MT-T-1	Converters – cost efficient & standardized HVDC converters blocks
MT-T-2	O&M technology to reduce operational costs of HVDC systems
MT-T-3	DC-DC converters and DC power flow control technologies
MT-T-4	Development of subsea components for deep sea HVDC links
MT-T-5	Development high voltage, industry grade WBG

Control and protection

Code	Description
MT-CP-1	Demonstration of grid forming control at system level & assessment of its impact on the stability of the connecting AC system.

Operation

Code	Description
MT-O-1	Implementation of methods and tools for stability management in hybrid AC-DC power system
MT-O-2	Recommendations to network codes for HVDC grids

Planning

Code	Description
MT-P-1	Back-to-back HVDC applications for internal continental AC grid segmentation and controllability as well as for asynchronous systems interconnection and integration
MT-P-2	Definition and agreement on HVDC-based high power corridors which will form the backbone systems
MT-P-3	Life cycle environmental impact assessment of HVDC

6.1.2. *Long term implementation needs*

Code	Description
LT-TCOP-1	Backbone HVDC grid covering offshore and onshore (integrating smaller systems)

7. Glossary

N.	Acronym	Description
1	AC	Alternating Current
2	AC / DC hybrid grid/system	A grid composed of a mix of AC and DC based grid technologies
3	ACER	European Union Agency for the Cooperation of Energy Regulators
4	CBA	CBA Cost–Benefit Analysis
5	CCP	Common Connection Point
6	CSC	Current Source Converter
7	DC	Direct Current
8	DG	Distributed Generation
9	DSO	Distribution System Operator
10	E.DSO	European Distribution System Operators
11	EC	European Commission
12	EGD	European Green Deal
13	ENTSO-E	European Network of Transmission System Operators
14	EU	European Union
15	EVs	Electric Vehicles
16	FACTS	Flexible Alternating Current Transmission System
17	GaN	Gallium Nitride
18	GW	Giga Watt
19	HVAC	High voltage Alternating Current
20	HVDC	High voltage Direct Current
21	IEA	International Energy agency
22	IP	Intellectual Property
23	ISGAN	International Smart Grid Action Network
24	KPIs	Key Performance Indicators
25	LCC-HVDC	Line Commutated Converter HVDC

26	MLC	Multi-Level Converter
27	MMC	Modula Multi-level Converter
28	MVAC	Medium voltage Alternating Current
29	MVDC	Medium voltage Direct Current
30	NIMBY	Not In My Back Yard
31	NRAs	National Regulatory Authorities
32	ORES	Offshore Renewable Energy Strategy
33	PCI	Project of Common Interest
34	PE	Power Electronics
35	PEIDs	Power Electronics Interfaced Devices
36	POD	Power Oscillation Damping
37	PV	Photovoltaics
38	R&I&D	Research, Innovation and Demonstration
39	RES	Renewable Energy Sources
40	ROI	Return On Investment
41	SET-Plan	Strategic Energy Technology-Plan
42	Si	Silicon
43	SiC	Silicon Carbide
44	STATCOM	Static Synchronous Compensator
45	STATCON	Static Synchronous Condenser
46	SWG	Sub-Working Group
47	TCP	Technology Collaboration Programme
48	TSO	Transmission System Operator
49	UHVDC	Ultra High Voltage Direct Current
50	VSC - HVDC	Voltage Source Converter HVDC
51	WG	Working Group

8. Annexes

8.1. Activity fiches

HVDC R&I Activity ST-CP-1		
Title: Multi-vendor interoperability - first European full-scale implementation of Multi-Vendor Multi Terminal VSC		
TRL: 6-7		

Description:

In line with the EU's ambition to attain climate neutrality by 2050, HVDC is the key enabling technology necessary to integrate renewable energy into the European Grid.

Interoperability of Multi-terminal Multi-vendor HVDC Systems is a fundamental topic that shall be addressed in order to ensure security of supply and scalability of the power system integrating renewable energy sources.

To this end, a real-time demonstrator is the preliminary step to de-risking the multi-terminal multi-vendor technology and enabling a real-life demonstrator application, which will pave the way to the exploitation of the offshore RES and the development of the offshore grid.

Note: this proposal is in line with the scope of the HORIZON-CL5-2022-D3-01-09 funding call.

Targets/Milestones

- Development of Standardised Interaction Study Processes and Interfaces for Multi-Terminal, Multi-Vendor (MTMV) HVDC Systems
- Definition of functional requirements at the AC and DC connection points, including grid-forming controls (GFCs) for MTMV HVDC Systems
- Definition of the Governance, as well as Cooperation and Legal Framework for MTMV HVDC systems
- Common approach to modelling and simulation framework, and data sharing principles for multi-vendor HVDC interaction studies and large-scale EMT simulations
- Assessment of Interoperability for MTMV HVDC Systems
- Network Planning, Project Financing and Procurement
- Definition of roles, responsibilities and methods needed within the interoperability process
- Importance of financing MTMV real industrial-scale demonstrators, and associated funding schemes
- Potential functional specification options
- Potential for future extendibility of MTMV HVDC systems
- Grid concept development (topology and potential operational configurations, control and protection strategies)
- Focus on control and protection solution ensuring interoperability of MTMV HVDC systems
- Realisation of the first European MTMV HVDC Real Industrial-Scale Project

Deliverables:	**Total Budget:**
- Requirements and definitions for MTMV HVDC interaction studies - Standardised interface definition report	TBD

- Definition of standardised interaction study process including inputs and outputs required from each stakeholder - Standard process for defining functional specifications for MTMV HVDC systems - Functional requirements of GFCs for MTMV HVDC systems - Recommendations of GFCs for DC grid codes, in the context of MTMV HVDC systems - Topology diagram of HVDC Grid System for the MTMV HVDC project - Demonstration of interoperability of MTMV HVDC systems in a HIL environment - Recommendations on the construction phase of the first MTMV HVDC system from a technical and interoperability perspective - First Multi-terminal, multi-vendor HVDC installation in operation	

<table>
<tr><td colspan="3">HVDC R&I Activity ST-CP-2</td></tr>
<tr><td colspan="3">Title: Grid forming capabilities offered by HVDC systems</td></tr>
<tr><td>TRL: 4-6</td><td></td><td></td></tr>
<tr><td colspan="3">Description:

The Offshore Renewable Energy strategy of the European Commission sets up the target of integrating 30GW offshore wind power by 2030 and 300GW by 2050 into the European Synchronous area. The grid integration of this huge amount of wind power generation cannot be achieved without the deployment of HVDC systems including multi-terminal HVDC grids. Besides the key task of transmitting bulk amount of wind power generation from the offshore sides to the onshore AC transmission grids, HVDC converters stations shall provide a system supportive behaviour at the onshore grid connection point. Grid forming capabilities[24] offered by HVDC converter stations is an important pillar of the stability management in the future converter-based AC-DC transmission grid. On that basis, this activity provides key research milestones needed to be addressed in future research.

Targets/Milestones:
- Functional requirements and demonstration of grid forming capability at the onshore high voltage transmission system interface (grid connection point of the onshore HVDC converter station) of an HVDC system connecting offshore wind power parks.
- Functional requirements and demonstration of grid forming capability at both the sending and the receiving converter station of an embedded HVDC transmission system.
- Functional requirements and demonstration of grid forming capability at the onshore grid connection point of an HVDC converter station being part of a multi-terminal HVDC grid.
- Validation procedure for testing grid forming capabilities offered by HVDC systems (embedded or connecting offshore wind power parks in point to point or multi-terminal connection) by means of simulation models.</td></tr>
<tr><td colspan="2">Deliverables:

- Definition of functional requirements for grid forming capabilities offered by HVDC converter station in the above-mentioned use cases.
- Implementation of control concepts and validation of grid forming capabilities
- Quantification of the impact of functional requirements on the system capabilities and control chain including DC connected power park modules where applicable.
-</td><td>Total Budget:
TBD</td></tr>
</table>

[24] A possible definition is grid forming capability can be found at the ENTSO-E technical report: "High Penetration of Power Electronic Interfaced Power Sources and the potential contribution of grid forming converters," signed by ENTSOE, WindEurope and TD Europe, published in 2019.

HVDC R&I Activity ST-CP-3		
Title: Components and interfacing for AC & DC side protection system design ensuring that all possible faults are detected and cleared sufficiently fast, in a selective manner		
TRL: 4-6		

Description:

In order to achieve high reliability, HVDC grid protection is indispensable. However, the nature of the HVDC grid and the DC-side fault behaviour makes its protection difficult. In comparison to AC protection, the main technical challenge of HVDC grid protection is interrupting a DC fault current—without naturally reoccurring zero-crossings—within a very short amount of time. The promotion project has resulted in significant progress with respect to the development of DC-side protection, however several open questions remain..

Targets/Milestones:

Maturity of AC & DC side protection strategies and readiness of their functional design, to support grid optimal architecture planning and prepare project tendering

- Methodology to assess admissible temporary loss of transmitted power in case of DC fault
  - AC-DC transient stability, when DC transmitted power is temporarily and partially interrupted, in case of a DC fault
  - Impact of reactive power supply transient interruption (converter blocking)
  - In case of HVDC-connected Off-Shore Wind farm: coordination of control actions from HVDC and wind turbines
  - Anticipation of new system dynamics due to high PEID penetration
  - Impacts of partially selective versus fully selective DC fault-clearing strategies
  - Impacts mitigation
  - Recommendation for AC-DC system design and DC protection design
- Multi-vendor interoperable HVDC grid protection
  - Improved methodologies for the determination of functional requirements of DC grid protection in a technical and vendor neutral manner
  - Standardised validation tests for de-risking interoperability issues
  - Specification of protection component and auxiliary ratings
  - DC substation Communication architecture and protocols (e.g. IEC 61850 for DC)
  - Protection system simulation models and information exchange
- HVDC grid protection strategies and design
  - Methodologies for the protection of mixed (OHL/cable, bipolar/monopolar) DC grids
  - Methodologies to optimally determine the optimal HVDC grid protection system, including combined selective, non-selective and partially protection schemes within the same DC grid
  - Development of converter assisted HVDC grid protection
  - DC station design and optimization from protection point of view
- AC & DC side protection system functional design for fully selective and partially selective fault clearing strategies, including the connection to low inertia AC systems
  - Protection functions
  - Mains, back-ups
  - KPIs

Deliverables:	**Total Budget:**
Methodology to assess admissible temporary loss of transmitted power in case of DC fault	TBD

- Methodology principles validated with system operators - Methodology implementation demonstrated on use cases HVDC grid protection strategies and design: - Consolidated strategies with associated single line diagrams - Consolidated vision of admissible strategies, according to application (off-shore grids, on-shore grids, distances, size of nodes) - Consolidated TEA, according to different level of admissible temporary loss of transmitted power in case of DC fault HVDC grid protection standards: - Communication standards - Development of generic protection system simulation models - Definition of information exchange between protection equipment and other HVDC equipment Multi-vendor interoperability of HVDC grid protection demonstration: - Development of functional specs - Standardized test procedures for HVDC grid protection equipment AC & DC side protection system functional design for fully selective and partially selective fault clearing strategies - Functional design, functional specifications - Industrial relays - Demonstration in the Lab (off-line, HIL) - Inputs for standardization - Inputs for project tendering	

HVDC R&I Activity ST-O-1		
Title: Development and integration of advanced software tools in SCADA systems for AC/DC hybrid systems		
TRL: 5-8		

Description:

The aim is to develop innovative algorithms and software tools for analysing and controlling the system of mixed, hybrid AC/DC grids and to integrate them into the control room software. The objective is to ensure a secure and stable system state of both the AC and DC systems at all times while determining optimal power flows. For the estimation of the current system state and its security assessment, online and real-time capable algorithms and tools must be developed in order to enable optimal operation of the hybrid AC/DC system (e.g. avoidance of circular flows) and to support security analyses. Furthermore, innovative ancillary services (e.g. frequency control, mitigation of periodic frequency fluctuations), which are required by a multi-terminal DC grid integrated into the AC transmission grid, will also be deployed, in addition to the crucial voltage regulation and reactive power control. The framework of the markets as well as impacts on them have to be considered appropriately. The tools shall support different levels of autonomy, starting from recommendations for operators up to fully autonomous operation as far as possible.

In addition to managing control operation through largely autonomous acting, the software tools must also deliver automated actions or assistance to personnel in critical system states, as far as possible. In the event of a fault, support is required for fault identification and return to safe, normal operation. Here, analysis is required for the behaviour in an AC and / or DC fault case in order to assess the effects of a fault clearing in the HVDC system on the AC grid with regard to stability aspects. These elements are very critical towards the reliable and stable operation of hybrid AC/DC grids, especially for multi-terminal DC grids integrated into the AC transmission grid. The possibilities offered by fast HVDC control in terms of islanding, black-start capability, firewalling shall be exploited for fault impact minimisation/avoidance in this sense.

These new tools must be successively integrated into the control room software after tests in realistic environments and continuously upgraded with additional functionalities. In this context, inter grid-operator communication and coordination must be supported by the software tools in order to optimise and ensure operation beyond control and regulation zones. Future developments of these tools can be further envisaged to provide proper observation of the whole pan-European AC/DC grid.

The tools and algorithms shall support systems and components from various manufacturers, as well as offer and support appropriate interfaces for interoperability and enable multi-vendor operation. Preferably, joint development by different manufacturers and software providers should be aimed for, and this can benefit from the use of open-source technologies in terms of transparency, reproducibility, and flexible adoption. It will enable faster development of new functions and faster bug fixing.

Targets/Milestones
Development and integration of advanced software tools in SCADA systems for AC/DC hybrid systems.

Work should focus on developing and demonstrating methodologies, algorithms and software tools to

- Scalable and flexible software framework for operation of hybrid AC/DC power systems supporting various vendor-dependent system and component models, e.g. more accurate and wider representation of connected systems, power flow calculations

- Upper level Control of voltage source converters (multi-vendor, multi-terminal), including changing active power setpoints, voltage/reactive power control setpoints and changing controller parameters. - Robust online estimation and calculation of the system state of the AC, DC and hybrid system - Control of the hybrid system taking into account system stability, optimal asset utilisation and market requirements - Manage ancillary and balancing services across hybrid AC/DC grids - Safety and reliability analysis of the system state, analysis of possible failure situations as well as curative measures for the failure event, e.g. transient and dynamic stability, coordinated risk management - Calculation and determination of solutions for AC/DC system protection - AI-based decision support systems supporting technical and market aspects - Unified Human Machine Interface (HMI) - Integration of cyber secure, resilient ICT platforms and communication for data exchange - Integration of standardised data protocols -	
Deliverables: - Definition of required basic software tools features set to support operation for multi-vendor operation - Upgrade of power flow control tools and sophisticated optimisation techniques considering AC/DC systems - AI-based decision support systems - Vendor independent hybrid HVDC/AC network SCADA/Energy Management System - Pilot for fully automated decision support systems for better supported decisions in the control centres	**Total Budget:** TBD

HVDC R&I Activity ST-P-1		
Title: Methods and tools for combined system (HVAC and HVDC) expansion		
TRL: 2-5		

Description:

The aim is to develop innovative methods and adequate tools able to properly take account of mixed, hybrid AC/DC grids towards the future pan-European system evolution and expansion. The need for integration of HVDC systems regards multi-terminal HVDC grids, both offshore and onshore, and HVDC links embedded within the HVAC network as well as HVDC ties (inter-)connecting different control zones and synchronous areas (in full or in back-to-back schemes). Methods and tools for combined HVAC and HVDC transmission expansion planning are to be crucially set for a top-down orchestration, to guide and enable stepwise organic development of future pan-European HVAC and HVDC grid system pieces.

The combined HVAC and HVDC transmission expansion planning need to account for the various uncertainties and operational changes that drive investment needs. It is crucial that the methodological framework and the related (set of) tools for the combined HVAC and HVDC transmission expansion planning can comprehensively and fully capture all costs and benefits, including flexibility and controllability, that can be provided by the different (HVAC and HVDC) system extension options. Of course, all possible configurations (monopolar, bipolar, mixed) need to be considered, and this for both onshore and onshore expansion options. For this goal, the methodological framework and the related (set of) tools must also properly represent and model further innovative and flexible technologies that, in addition to HVDC, can play a role in the future pan-European system development: FACTS, DLR/RTTR, HTSC (superconductors), storage, DR/DSM, EVs. The tools shall allow the selection of the most suitable system extension candidate(s) by static and dynamic approaches towards the calculation of the related benefits and costs.

Within this view, while taking stock of experiences with the application of DC model (linear)-based optimisation, it is essential that the combined HVAC and HVDC transmission expansion planning relies on detailed representation of the non-linear nature of the hybrid AC/DC grid. E.g. through the development of expansion models based on AC model (non-linear)-based optimisation or convex relaxations. The methodologies and tools for the combined HVAC and HVDC grid expansion can set a framework that shall also include reliability and resilience methodologies for properly addressing security and adequacy issues and criteria via not only deterministic but also probabilistic (e.g. Monte-Carlo) methods.

The inclusion of environmental assessments in the methodological framework for the combined HVAC and HVDC transmission expansion planning shall be also pursued.

Future extensions of the methodological framework and the related (set of) tools for the combined HVAC and HVDC transmission expansion planning may also include the representation and modelling of distribution grids as well as multi-energy vector integration (sector coupling) for long-term analyses.

Targets/Milestones

- Development of a solid methodological framework and an adequate set of tools for combined HVAC and HVDC transmission expansion planning

Deliverables:	**Total Budget:**

- Review of state-of-the-art of transmission expansion methodologies with the inclusion of HVDC technologies and links - Development of a solid methodological framework for combined HVAC and HVDC transmission expansion planning (techno-economic assessment) - Development of a solid methodological framework for combined HVAC and HVDC transmission expansion planning (addition of environmental assessment) - Development of an adequate set of tools for combined HVAC and HVDC transmission expansion planning -	TBD

HVDC R&I Activity ST-T-1		
Title: Converters (and other components such as DC breakers, GIS, etc) – higher voltage & current ratings, integration of storage (within converters or HVDC systems), capability to withstand high fault currents		
TRL: 6-8		

Description:

In line with the EU's ambition to attain climate neutrality by 2050, HVDC is the key enabling technology necessary to integrate renewable energy into the European Grid.

With the increasing penetration of power-electronic-interfaced devices and renewable energy sources by virtue of HVDC systems - a key enabling technology - new requirements regarding voltage level, current ratings and integration of energy storage, among others, shall be addressed by new technological developments.

Understand and manage how faults within the DC part of the grid affect AC parts and vice-versa when substituting switchgear, gas-insulated lines and gas-insulated substations with SF6-free equipment while ensuring resilience, reliability, safety, and security of the power system and reducing environmental impact.

Targets/Milestones

- Investigation and development of additional energy storage solutions, interfacing with HVDC systems, to support the AC system.
- Investigation of DC breaker integrated in Multi-terminal DC (MTDC) systems. DC breakers may be required when multiterminal dc grid is materialised, to limit the loss of infeed caused by single point of failures
- Investigation of the application of DC GIS in VSC HVDC converters, including economic benefits on overall system solution
- Development of smaller and more compact converter topologies could potentially, resulting in significant cost savings offshore
- Investigation of high-fault currents' HVDC converter topologies. Increasing the fault current capability of the HVDC converter without a corresponding proportional increase in its cost would require a drastic rethink of how the VSC topology currently looks like
- Boost SF6-free technologies in high-voltage equipment, as well as a regulatory roadmap for replacement and new assets
- Carry out a technical analysis of possible trade-offs in performance, ambient condition impact, maintenance, reliability, dimensioning, testing procedures, etc.

Deliverables:

- Demonstration of enhancement of AC system stability and AC system frequency by providing energy storage systems interfaced to HVDC systems
- Assessment of technical and economic feasibility of application of DC breakers in MTDC systems
- Demonstration of DC fault ride through capabilities in MTDC systems by using DC breakers
- Assessment of potential new converter topologies addressing future offshore developments with the aim of reducing the CAPEX and OPEX of the investments, and with increased fault current capabilities

Total Budget: TBD

- Economic and environmental assessment of replacement and new installation roll-out options (timeline, perspective of global market, full lifecycle impact) - Regulatory recommendations at EU level to cope with financial risks inherent with putting novel technologies into the system and transition time options to move from SF6 to SF6-free technology for new equipment - Actual demonstrator for an SF6-free gas-insulated substation or for air-insulated SF6-free instrument transformers or switchgear at different voltage levels	

<table>
<tr><td colspan="3">HVDC R&I Activity ST-T2-2</td></tr>
<tr><td colspan="3">Title: Cable systems – higher voltage & current ratings, monitoring systems; cable system ageing; reliable and easy-to-install cable joints and terminations, eco-designed and manufactured cable systems; predictive models for cable system ageing (fraction-of-life lost, remaining life), life and reliability; monitoring and fault location systems</td></tr>
<tr><td>TRL: 5-6</td><td></td><td></td></tr>
<tr><td colspan="3">Description:

Cables are required to timely realise the goals of the European Green Deal, integrate the renewable energy generation, improve the European electricity market, and increase power grid stability through enhanced interconnectors between countries.

Targets/Milestones:
- Improved by incorporating innovative technological solutions such as robotic technologies for data collection and maintenance in in all type of location (easy-to-access and inhospitable)
- Develop procedures for optimised maintenance and repair concepts of offshore stations using BIM and 3D-Models
- Further improving different types of extruded insulation materials (e.g., DC-XLPE, Polypropylene) cables, by refining the procedure of separation of the many components of the cable – insulation, wires, tapes, sheaths, etc. – from each other and their recycling procedure separation of the many components of the cable – insulation, wires, tapes, sheaths, etc. – from each other and their recycling procedure.
- Feasibility study for use superconducting cables for submarine connections since they do not emit any heat.
- Develop and pilot new network components with reduced environmental impact such as EHV/HV cables without lead, application of superconductors, DC cables/gas insulated lines for voltages above 550 kV
- Further development and improvement of on-and off-line diagnostics and condition monitoring techniques for HVDC cable systems such as PD and leakage current measurements for online and space charge and dielectric permittivity and loss factor measurements for offline.</td></tr>
<tr><td colspan="2">Deliverables:

- Development of not only better performing, but also more environmentally friendly materials for cable insulation
- Improved tools for remote monitoring, repair and maintenance of equipment
- Assessment of the feasibility of new cable technologies</td><td>Total Budget:
TBD</td></tr>
</table>

HVDC R&I Activity ST-T-3		
Title: Further development of Wide Bandgap (WBG) materials		
TRL: 4-6		

Description:

With regard to the semiconductor technology used, HVDC systems particularly require components with low conduction losses, high power ratings and high reliability, which is why the use of wide bandgap semiconductors has such high potential. For HVDC converters, silicon (Si) devices are state-of-the-art today.

The properties of semiconductor materials are substantially determined by the bandgap between the valence band and the conduction band. In the case of the semiconductors most commonly used to date, the bandgap is in the lower range (e.g. germanium at 0.67 eV, silicon at 1.12 eV), while in the case of wide bandgap semiconductors the bandgap is very large (e.g. > 3 eV). The use of wide bandgap materials therefore enables lower losses in switching devices, the handling of higher voltages, operation at higher (environmental) temperatures, the operation at higher frequencies or a higher reliability. Thus, the performance of the HVDC is essentially determined by the used semiconductor components. New submodule topologies for HVDC converters offer benefits in combination with these new wide bandgap semiconductors.

Targets/Milestones

Improvement of wide bandgap semiconductors for integration in HVDC components. Work should focus on improving wide bandgap semiconductor devices, packaging and their integration in converter submodules:

- Improved WBG power devices with better performance metrics, e.g. lower conduction losses, higher blocking voltage, better surge current capability, higher switching frequencies, better short-circuit capability
- Improved cost efficiency of power devices and semiconductor fabrication processes
- Advanced control circuits for WBG based bridges
- Improved packages featuring high-voltage insulation, high temperature operation, robustness, and low parasitics
- New submodule topologies for HVDC converters with WBG semiconductors and better performance metrics, e.g. reduced losses, higher reliability, lower volume / weight, less costs
- Implementing WBG semiconductor devices for DC protection devices, e.g. DC breakers

Deliverables:	**Total Budget:**
- WBG devices with better performance metrics - Improved packaging options - Lab tested new submodules based on WBG devices - Submodules based on WBG devices in field trial	TBD

8.2. MVDC Technology

Technology description

Today the transmission grid uses HVAC and HVDC whereas for the distribution grid Medium Voltage AC (MVAC) only is used. This is due to the simplicity, effectiveness and efficiency of the transformer needed to step-up or step-down the voltage. In the same way as for HVDC, the evolution of high-voltage and high-current Power Electronics (PE) devices has paved the way to design sophisticated high-power electronic converters suitable to perform AC/DC voltage conversion in the medium voltage range at considerably high efficiencies. The relevant aspect of an MVDC grid is the innovative infrastructure aiming at potential applications. Today, considering that renewables such as PV or windfarms could be connected in MVDC, instead of performing the conversion to AC, the MVDC distribution grid becomes an area of interest for grid optimisation. Moreover, the segmentation of MVAC grids through sections in DC could offer several advantages to DSOs to increase flexibility and controllability of distribution systems, that are more frequently required to act as active (and not passive like in the past) grids due to the continuously increasing penetration level of Distributed Generation and RES in medium voltage systems. Furthermore, cross-border exchange of electricity could be performed at MVDC level with the liberalisation of the electrical energy market, instead of stepping-up the Medium Voltage to High Voltage through the border and then back to Medium Voltage again. In this context, MVDC grids could reduce the number of required energy conversion stages on both the supply and load sides, thus simplifying the overall electrical architecture. As a result, the distribution of electricity would be performed at not only higher efficiency and reliability, but also with higher control flexibility.

Challenges to address

MVDC networks offer the opportunity to "mesh" the current MVAC distribution network to make it more robust and controllable, thereby ensuring the decoupling of AC sections and facilitating RES integration at distribution level. The consequent evolution of an MVDC network towards multi-terminal configurations requires the implementation of suitable fault protection strategies, including fault detection/location methods and selectivity logics for fault suppression. These logics are achievable thanks to devices such as: active current limiters, solid-state MVDC breakers and a fast communication infrastructure. In addition, a further deep penetration of RES and of EVs can be fostered only by upgrading the existing grid through MVDC technologies, creating fast recharge connections directly supplied by RES and supported by suitable solid state switching technologies. For these reasons, the deployment of efficient solid state circuit breakers, the development of breaker-less protection approaches based on fully controlled power converters having inherent fault current limiting capabilities, and a suitable standardisation are to be considered crucial challenges. In the same way, the development of new highly efficient DC/DC and DC/AC converters (e.g., based on wide band gap material-based devices) is to be considered a crucial technological challenge for the short term.

8.3. HVDC TWG Members

N.	Name	Institution / Company	EC, MS, AC / Association	Status: Full / Correspondent Member (FM / CM)
1	Andrade, Ana	Directorate-General of Energy and Geology	Portugal	FM
2	Baldursdottir, Iris	ENTSO-E	ENTSO-E	FM
3	Barker, Carl	GE	T&D Europe	FM
4	Basosi, Riccardo	MUR - Italian Ministry of University & Research	Italy	FM
5	Bikulcius, Ramunas	Head of Strategy and Research Division Litgrid AB (National TSO)	Lithuania	FM
6	BİLGİN, Hazım Faruk	Tubitak	Turkey	FM
7	Bongiorno, Massimo	Chalmers University of Technology	Sweeden	FM
8	Bray, Morris	National Grid Ventures UK	Wind Europe	FM
9	Butkus, Paulius	ENTSO-E	ENTSO-E	FM
10	Capra, Marcello	MITE – Italian Ministry for Ecological Transition	Italy	FM
11	Charalambous, Chrysanthos	University of Cyprus	Cyprus	FM
12	CLOCCHIATTI, Alessia	DG ENER	European Commission	FM
13	Collombet, Rémi	Oceanenergy	Ocean Energy Europe	FM
14	Constantinescu, Norela	ENTSO-E	ENTSO-E	FM
15	Cruz, José Ignacio	Faculty of Electrical Engineering	Spain	FM
16	Cutululis, Nicolaos Antonio	DTU	Denmark	Co-chair
17	DIONISIO, Mario	DG ENER	European Commission	FM
18	Van Hertem, Dirk	KU Leuven, Department of Electrical Engineering	Belgium	Co-chair
19	Efthymiou, Venizelos	University of Cyprus	Cyprus	FM
20	Eickhoff, Ralf	Forschungszentrum Juelich GmbH Project Management Juelich	Germany	FM
21	El-Khatib, Walid	Vattenfall	Wind Europe	FM
22	Ging, John	Sustainable Energy Authority of Ireland	Ireland	FM
23	Klonari, Vasiliki	Wind Europe	Wind Europe	FM
24	L'Abbate, Angelo	RSE	Italy	FM
25	Lampasona, Alberto	Europacable	Europacable	FM
26	Le, Khanh Tuan	The Research Council of Norway	Norway	FM
27	LIMA DA CUNHA, Carlos Eduardo	RTD	European Commission	FM
28	Lundberg, Peter	Hitachi ABB Powergrids	T&D Europe	FM
29	Luscan, Bruno	Supergrid Institute	Supergrid Institute	FM
30	Marshall, Benjamin	National HVDC Centre	Wind Europe	FM
31	Montagne, Xavier.	Ministry of higher education, research and Innovation	France	FM
32	Morollon, Gonzalo	ENTSO-E	ENTSO-E	FM

33	Müller, Zdenek	Head of the Department of Electrical Power Engineering Czech Technical University in Prague	Czech Republic	FM
34	Ndreko, Mario	ENTSO-E	ENTSO-E	FM
35	Palsson, Magni	Landsnet, Iceland	Iceland	FM
36	Peereboom, Diederik	T&D Europe	T&D Europe	FM
37	Pirttimaa, Lotta	Oceanenergy	Ocean Energy Europe	FM
38	Riva Sanseverino, Eleonora	Università di Palermo	Italy	FM
39	Rodriguez, Pedro	Universitat Politècnica de Catalunya	Spain	FM
40	Schettler, Frank	Siemens Energy	T&D Europe	FM
41	Sharifabadi, Kamran	Equinor	Wind Europe	FM
42	SHTJEFNI, Drilona	JRC	European Commission	FM
43	SOEDE, Matthijs	RTD	European Commission	FM
44	Sørensen, Troels Stybe	Ørsted	Wind Europe	FM
45	TELSNIG, Thomas	JRC	European Commission	FM
46	van der Meijden, Mart	Technical University Delft	Netherlands	FM
47	VAN STIPHOUT, Mark	DG ENER	European Commission	FM
48	Wendt, Volker	Europacable	Europacable	FM
49	Winter, Wilhelm	ENTSO-E RDIC-WG2 Convenor for Security and operations of tomorrow	ENTSO-E	FM
50	YILDIRIM, Çağrı	SET Plan country representative of Turkey	Turkey	FM
51	Zachia, Oana	CNTEE Transelectrica S.A.	Romania	FM
52	Zsolt Zoltán, LENGYEL	MAVIR Hungarian Independent Transmission Operator Company Ltd.	Hungary	CM

8.4. HVDC projects inventory

Nr	Research Project	Dates	Research Organizations	Funding Organization(s)	Funding	Important Results	TRL Level	Demonstrator(s)	Topics addressed (add rows for multiple selection)	Links
1	PROMOTION	2016-2020	DNV GL, TSOs, HVDC Manufacturers, wind turbine suppliers and offshore developers	Horizon 2020	42.8M Euro	Meshed offshore HVDC Technologies HVDC grid protection equipment and principle validations Regulatory and financing recommendations ...	7-9	DC breaker testing DC grid protection Laboratory validation	Technology RES Integration Regulation and governance Planning Control and protection	https://www.promotion-offshore.net/
2	BEST PATHS	2014-2018	Research centres, Universities, TSOs, HVDC manufacturers, wind turbine manufacturers, generation company, cable manufacturers, offshore developers	EU FP7	62.8 M Euro (total funding, of which 35.5 M Euro EU contribution)	HVDC links in offshore wind farms and offshore interconnections	7-9		Technology	
3	FASTGRID	2017-2020	Research centres, Universities, TSOs, HVDC manufacturers, wind turbine manufacturers, generation company, cable manufacturers, offshore developers	H2020	€ 8 602 250,54 (total funding, of which € 7 248 235,42 EU contribution)	improving the properties of the REBCO tapes to enhance significantly (by 2 to 3 times) the electric field limit and so the economical attractiveness of SCFCL	7-9		Control and protection	Home (fastgrid-h2020.eu)
4	HYPERRIDE	2020 - 2024	Research centres, Universities, TSOs, HVDC manufacturers, wind turbine manufacturers, generation company, cable manufacturers, offshore developers	H2020	€ 8 233 501,25 (total funding, of which 6 965 520,50 EU contribution)	on-going			grid planning, operation strategies and its implementation	Objectives - HYPERRIDE
5	TIGON	2020 - 2024	Research centres, Universities, TSOs, HVDC manufacturers, wind turbine manufacturers, generation company, cable manufacturers, offshore developers	H2020	€ 7 996 115 (total funding, of which € 6 957 197,01 EU	on-going				https://tigon-project.eu/
6	Celtic Interconnector		EirGrid							The Project (eirgridgroup.com)
7	EuroAsia Interconnector		EuroAsia Interconnector Limited	Connecting Europe Facility	estimated total cost: 29 000 000 € - maximum EU contribution 14 500 000 €					EuroAsia Interconnector (euroasia-interconnector.com)
8	CABOTioN	2021-2023	AALBORG UNIVERSITET	H2020-MSCA-IF-2020 EXCELLENT SCIENCE - Marie Skłodowska-Curie Actions	€ 219 312	cable modelling	4-6		Control and protection	
9	VILB	2018-2021	AUXEL	H2020-EU.3.4.5.6. - ITD Systems	€ 668 276,25 (total funding, of which € 497 355 EU contribution)	Advanced busbar technology for high-temperature applications				
10	9eGEN	2016-2021	ASE SPA	H2020-EU.3.4.5.3. - IADP Fast Rotorcraft	€ 1 670 550 (total funding, of which € 1 169 385 EU					
11	HYPNOTIC	2020 - 2022	Universities,	H2020-EU.3.4.5.6. - ITD Systems	€ 1 044 943,75 (total funding, of which € 822 962,50 EU	set of bidirectional converters (at least 5), acting together as only one equipment.				
12	GB HVDC de-risking via MTTE project	2013-2021	SHE Transmission, National Grid Electricity Trans	Ofgem, Network Innovatio	£11m	live project support for HVDC in GB R&D support in key HVDC innovations replica hosting, update tracking, enhanced FST de	7-9 4-6 7-9	TSO test facilities Laboratory validation TSO test facilities	Planning Technology Operation	https://www.ofgem.gov.uk/cy/publications/funding-decision-letter-2013-nic-project-direction-multi-terminal-test-environment-mtte https://www.hvdccentre.com/completed-innovation/ https://www.hvdccentre.com/our-centre/our-services/replicas/why-replicas/
13	Caithness- Moray Project	2017-2019	SHE Transmission, National HVDC Centre, Natio	Ofgem		Enhanced Functional Testing using enhanced syst validation of onshore AC system focussed controls Tracking control modifications and verifying post	7-9 7-9 7-9	TSO test facilities TSO test facilities TSO test facilities	Control and protection Control and protection Operation	https://www.hvdccentre.com/our-projects/caithness-moray/
14	COMPOSITE Project	2020-2020	National HVDC centre, RTE international, Nation	National HVDC Centre		identifying key tools and analysis/ test across proj identifying key wide area and supervisory control Identifying key risks and considerations for co-ord	7-9 4-6 4-6	TSO test facilities TSO test facilities TSO test facilities	planning Control and protection Control and protection	https://www.hvdccentre.com/composite/
15	Future protection in a low strength HVDC dominated environment	2021-2024	SHE Transmission, National HVDC centre.	Ofgem via ENA (Network Innovation Allow		identifying new tests required for new solutions o install in open loop and evaluate practical perforr Review and refine against testing expectations an	4-6 7-9 7-9	Laboratory validation installation on TSO sy TSO test facilities	Control and protection Control and protection Control and protection	https://smarter.energynetworks.org/projects/nia_shet_0033/
16	Moyle HVDC control refurbishment	2019-2021	Mutual Energy, National HVDC centre	Mutual energy	TBC	Provide replica hosting and associated de-risking	7-9	TSO test facilities	Control and protection	https://bidstats.uk/tenders/2020/W08/721223852 https://www.hvdccentre.com/wp-content/uploads/2019/07/Operators_Forum_2019_Hemphill.pdf
17	GB stability pathfinder & Grid Forming testing	2019-2021	National Grid ESO, National HVDC centre, Grid c	National Grid ESO	c.£150k equival	Defined key differences across grid following and supported key Grid code change specification and	4-6 7-9	TSO test facilities TSO test facilities	Control and protection Regulation and governance	https://www.hvdccentre.com/our-projects/eso-stability-pathfinder/ https://www.nationalgrideso.com/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required https://www.nationalgrideso.com/document/185286/download
18	Offshore Co-ordination project	2020-2021	DNVGL, National HVDC centre, National Grid ES(	National Grid ESO	c. £250k total	identified key capabilities and performance of HV introduced a proposed holistic approach to GB pl identified the key services and control and operat conducted CBA into value of new approaches, anc	4-6 4-6 4-6 4-6	TSO test facilities TSO test facilities TSO test facilities Laboratory validation	Control and protection Planning Operation Regulation and governance	https://www.nationalgrideso.com/document/182931/download https://www.nationalgrideso.com/document/183031/download https://www.nationalgrideso.com/document/176251/download https://www.nationalgrideso.com/document/182936/download
19	Caithness- Moray- Shetland Functional System Tests	2019-24	SHE Transmission, National HVDC centre	SHE Transmission	c. £500k total e	examine composite control function behaviour su HVDC intefacing a wide variety of power electroni services and performance design	7-9 7-9 7-9	TSO test facilities TSO test facilities TSO test facilities	Control and protection Planning Operation	https://www.ssen.co.uk/WorkArea/DownloadAsset.aspx?id=5334
20	Open MMC -VSC-HVDC model	2016-19	University of Strathclyde, National HVDC centre	National HVDC Centre	c.£200k total	develop an RT granular generic MMC VSC-HVDC n conduct multi-vendor interoperability investigatic	4-6 4-6	Laboratory validation TSO test facilities	Control and protection Control and protection	https://www.hvdccentre.com/open-source-converters/
21	AC protection verification to support Dersalloch Windfarm in grid forming operation	2019-2020	Siemens, Scottish Power Renewables, Scottish Pc	Scottish Power Transmissi	c. £150k total e	verify AC protection performance across blackstar	7-9	TSO test facilities & fie	Control and protection	https://www.hvdccentre.com/wp-content/uploads/2021/04/HVDC-Centre-Newsletter-April-2021.pdf https://globalpst.org/wp-content/uploads/Survey-of-Grid-Forming-Inverter-Applications-Julia-Matevosyan.pdf https://strathprints.strath.ac.uk/77609/1/Harrison_etal_IEEEA_2021_Impact_of_wind_variation_on_the_measurement_of_wind_turbine_inertia_provision.pdf
22	Distributed Re-start analysis.	2020-22	Scottish Power Transmission, TNEI, National Gric	Ofgem (Network Innovatio	c. £250k total e	analysis in detail of conventional and unconventic specify wide area control testing needs to support verify AC protections and protection strategies acr test distributed controller designed to support cur	7-9 7-9 7-9 7-9	TSO test facilitues & fi TSO test facilities TSO test facilitues & fi TSO test facilitues & fi	Planning Control and protection Control and protection Control and protection	https://www.hvdccentre.com/wp-content/uploads/2021/07/HVDC-Centre-Newsletter-July-2021FINAL2.pdf https://www.nationalgrideso.com/document/172166/download
23	North Sea Link connection analysis	2019-2021	Scottish Power Transmission, National Grid Elec	Scottish Power Transmissi	c. £250k equiv	test HVDC effect on onshore AC system including s cross platform RMS-EMT-RT-EMT with protection Protection system HiL verification across circuits a	7-9 7-9 7-9	TSO test facilities TSO test facilities TSO test facilities	Control and protection simulation Control and protection	https://www.hvdccentre.com/our-projects/north-sea-link-protection-coordination-testing/
24	HVDC SCADA for operational training	2019-2021	SHE Transmission, National HVDC centre	SHE Transmission	contract specifi	establish control room emulation for Caithness-M	7-9	TSO test facilities	Operation	https://www.hvdccentre.com/current-projects/
25	multi-vendor investigations for Shetland extension of Caithness-Moray	2017-2019	SHE Transmission, National HVDC centre	MTTE project scope	included within	linked to use of generic modelling above	7-9	TSO Test facilities	control and protection	https://www.ssen.co.uk/WorkArea/DownloadAsset.aspx?id=5334
26	HVDC blackstart and AC system protection performance	2019-2020	EPRI, SHE Transmission, Scottish Power Transmis	National HVDC centre	c. £150k equiv.	simulate credible sequential black start re-energis consideration of conventional and soft-start strate consideration of AC and HVDC protection needs t	4-6 4-6 4-6	TSO Test facilities Laboratory validation TSO Test facilities	Operation and control and Protection Planning and Operation Control and protection	https://www.hvdccentre.com/ac-protection-dc-energisation/
27	Maximising black start capability from HVDC	2019	Scottish Government, National HVDC Centre	Scottish Government	included within	black start approaches, options and key considera	4-6	Laboratory validation	Regulation and Governance	https://www.hvdccentre.com/our-projects/maximising-hvdc-for-black-start/
28	Stability of co-located convertors	2016	University of Manchester	National HVDC centre	c.£100k equiv.	provided advice on the development of a detailec	4-6	Laboratory validation	Planning	https://www.hvdccentre.com/stability-assessment-for-co-located-converters/
29	Design of DC/DC converters	2015	University of Aberdeen	National HVDC centre	c.£100k equiv.	specifying a particular example of a DC/DC conver	4-6	Laboratory validatior	Planning	https://www.hvdccentre.com/design-of-dc-dc-converter/
30	Stability assessment and mitigation of convertor interactions (stage1)	2019-2020	University of Strathclyde, National HVDC centre,	National HVDC centre	c.£100k equiv.	delivered a new method of small signal analysis tc critiqued completeness of vendor supplied model	4-6 4-6	Laboratory validation TSO Test facilities	Planning control and protection	https://www.hvdccentre.com/hvdc-stability-assessment/
31	Stability assessment (stage 2)	2020-2021	University of Strathclyde, National HVDC centre,	National HVDC centre	c.£100k equiv.	considered completeness and considerations acro	4-6	Laboratory validation	Planning	https://www.hvdccentre.com/stability-phase-2/
32	Stability assessment (stage3)	2021-2022	University of Strathclyde, National HVDC centre,	Engineering Technical Pro	c.£100k equiv.	explores how best to define network elements an develops a small signal tool to deliver scanning of	4-6 4-6	Laboratory validation Laboratory validation	Planning Planning and Operation	https://lnkd.in/deNu-dX
33	Investigation of effectiveness of HVDC Power Oscillation Damping Controls	2020-2021	EPRI, SHE Transmission, National Grid ESO, Natic	National HVDC centre	c.£100k equiv.	develop an adaptive, HVDC focussed POD solutior analyis optimality of parrallel HVDC vs radial HVD analysis of inter-area mode change on a weak syst illustrate use and effect of HVDC POD control on l implement a physical optimised controller in real-	4-6 4-6 4-6 4-6 7-9	Laboratory validation Laboratory validation Laboratory validation Laboratory validation TSO Test Facilities	Planning, Control and Protection Planning, Control and Protection Planning Planning, Control and Protection Planning, Operation	https://www.hvdccentre.com/pod_project/
34	GB Research and Development priorities for HVDC in advancing co-ordinated offshore	2021	BEIS, Ofgem, National HVDC centre	National HVDC centre	c. £70k equiv.	identify key challenges and priority analysis	7-9	TSO Test Facilities	Regulation and Governance	https://www.hvdccentre.com/wp-content/uploads/2021/07/Offshore_Co-Ordination_RD_Strategy_v2.0.pdf https://www.hvdccentre.com/wp-content/uploads/2021/07/Offshore_Co-Ordination_Supply_Report_v2.0.pdf
35	Improving Grid code for HVDC and convertor sources.	2019-2020	Cardiff University, National HVDC centre	National HVDC centre	c.£100k equiv.	reverse-engineer HVDC control strategies to delive identify Gaps & opaque requirements/ highlight li	4-6 4-6	Laboratory validation Laboratory validation	Control and Protection Regulation and Governance	https://www.hvdccentre.com/hvdc-grid-code-compliance/
36	protection challenges and testing in a converter domininated environment	2020-2021	University of Strathclyde, SHE Transmission, Nati	National HVDC centre	c.£180k equiv.	test vendor relays within a TSO network relevant designed te identify source of vulnerabilities & potl solutions		Laboratory validation Laboratory validation	Control and Protection Control and Protection	https://www.hvdccentre.com/innovation/dc_with_ac_protection/
37	protection modelling in PSCAD in a converter dominated environment	2020-2021	Manitoba Hydro International, Scottish Power Tr	National HVDC Centre	c. £60k equiv	improve PSCAD protection models, applying to de	4-6	Laboratory validation	Control and Protection	https://www.hvdccentre.com/protection-overview/

						identify key areas of vulnerability within models 8	4-6	Laboratory validation	Control and Protection	
38	Shetland island protection testing	2021-2022	SHE Transmission , National HVDC Centre	SHE Transmission	c. £250k equiv	construct detailed transmission and distribution E integrate into these replica control and protectior	7-9 7-9	TSO Test Facilities TSO Test Facilities	Control and Protection Control and Protection	https://www.hvdccentre.com/library/evolution-of-protection-testing/
39	multiDC	2017-2022	DTU Elektro, Energinet, Svenska kraftnat, ABB, K'	Innovation Fund Denmark	3.5 Meuro	Operation, control and stability of Offshore Energ Sharing reserves over HVDC lines to reduce costs and mutually assist neighboring as Market integration of HVDC lines	4-6	HIL of low-inertia and	Technology RES Integration Operation Economics/market integration Planning Control and protection	
40	Best Paths for Denmark	2014-2018	DTU	FORSKEL (Danish Research	0.5 Meuro	Impact assessment of HVDC interconnections on t	4-6	Technical Feasibility c	Operation Planning Control and protection RES Integration	
41	OffshoreDC	2011-2015	DTU, NTNU, Chalmers, VTT, ABB, Vestas, Statnet	Nordic Energy Research	1.5 Meuro	Control of MMCs HVDC trasmission for offshore wind Stability assessment of HVDC links Planning of HVDC offshore grids	4-6		Technology Control and protection Operation Planning RES Integration	
42	MEDOW	2013-2016	U Cardiff, KU Leuven, UPC, U Porto, DTU	FP7	4 Meuro		4-6		Technology Control and protection Operation RES Integration	
43	InnoDC	2017-2021	U Cardiff, KU Leuven, UPC, U Porto, DTU	H2020	3.7 Meuro				Control and protection	
44	Mutig	2017-2020	ABB Power Grids Germany AG, Fraunhofer-Institu	Federal Ministry for Econc	3.3M Euro	Analysis of multi-terminal offshore DC structures Protection schemes and failure analysis Parallel operation and interaction	4-6	Laboratory validation Test of protection sch	Technology Control and protection Operation	https://www.iwes.fraunhofer.de/en/research-projects/finished-projects-2020/mutig.html
45	DemAnDS	2021-2024	Rheinisch-Westfälische Technische Hochschule A	Federal Ministry for Econc	2.1M Euro	Analysis of converter design and operation Grid-supporting and grid-forming converter functions System stability in converter-dominated grid areas Digital-twin modelling	4-6	Hardware-in-the-loop Validation of convert	Technology Control and protection Operation	
46	NSON NSON II	2014-2017 2020-2022	Fraunhofer-Gesellschaft zur Förderung der angev	Federal Ministry for Econc	2M Euro 1.5M Euro	Analysis and evaluation of different market and gr Connection of existing storage capacities Integration of novel offshore storage concepts to provide balancing and flexibility ca Planning and operational optimization and power flow calculations	4-6 4-6	Numerical simulation	Planning Operation Economics/market integration RES Integration	https://www.iee.fraunhofer.de/de/projekte/suche/2017/nson.html
47	HGÜ Projekt H3-Netzeffizienz	2016-2019 2019-2021	Infineon Technologies AG, Universität Rostock, S	Federal Ministry for Econc	2M Euuro 2.7M Euro	Optimization of semiconductor design (IGBT) for ir Novel IGBT control concepts and circuits Mounting and contacting concepts Integration in optimized MMC modules	4-6 4-6	Numerical simulation Laboratory testing of integrated MMC modules	Technology	
48	OVANET OVANET 2.0	2014-2018 2018-2021	Technische Universität Darmstadt, Technische U	Federal Ministry for Econc	2M Euro 1.3M Euro	Operation of a meshed overlay DC grid System stability of overlay grids Solutions for DC breakers Control and operation modes of converter stations	1-3 4-6	Simulations	Control and protection Operation	https://www.sense.tu-berlin.de/menue/forschung/nationale_projekte/ovanet/ https://www.tu-ilmenau.de/universitaet/fakultaeten/fakultaet-elektrotechnik-und-informationstechnik/profil/institute-und-fachgebiete/fachgebiet-elektrische-energieversorgung/forschung/projekte/ovanet-2
49	DynaGridCenter HyLite	2015-2018 2018-2021	Siemens AG, Fraunhofer-Gesellschaft zur Förderu	Federal Ministry for Econc	4.5M Euro 2.8M Euro	Concept and implementation of dynamic control (Predictive assessment of system behavior and syst Dynamic network security studies, adaptive protection parar Dynamic Digital Mirror using a digital twin centric system	7-9 7-9	Hardware-in-the-loop Real-time simulation (Dynamic grid control center	Control and protection Operation	https://new.siemens.com/global/en/products/energy/topics/dyna-grid-center.html https://www.iff.fraunhofer.de/de/geschaeftsbereiche/energiesysteme-infrastrukturen/hylite.html
50	ENSURE ENSURE2	2016-2019 2020-2023	Öko-Institut. Institut für angewandte Ökologie e.V	Federal Ministry of Educa	32M Euro 45.8M Euro	Hybrid AC/DC transmission grid Intelligent components: DC breakers and sensors Capacity of HVDC converters and the associated grid-serving Piloting of an MVDC direct coupling	4-6 7-9	Laboratory validation Component and devic Field installations anc	Technology Control and protection Operation	https://www.kopernikus-projekte.de/en/projects/ensure
51	ENSIEL ST 191	2020-2021	University of Padova (Dept. Industrial Eng.)	TERNA S.p.A.	0.15 M Euro	HVDC-VSC modelling and availability analysis	7-9	Simulation validation	Control and protection	
52	ENSIEL ST 200	2020-2022	University of Bologna	TERNA S.p.A.		HVDC cable system reliability in the presence of time-varying voltage and temperature	4-6		Control and protection	
53	RSE - RdS C.4 T&D-CC ("Trasmissione e distribuzione in corrente continua")	2015-2018	RSE S.p.A.	Italian Ministry of Econon	2.155 M€	Analyses of HVDC systems integration in tradition: Study of HVDC technology evolution Assessment of control logics of HVDC system components, al: Analyses of MVDC and LVDC systems integration in AC distrit Investigation on conductors for HVDC transmission Techno-economic assessment of new SACOI interconnection Evaluation of AC-to-DC transmission OHL conversion Analyses and development of LV DC breaker prototype	4-6	Simulation validation Development of DC gr Testing and simulatio Analyses and develop	Planning RES Integration Control and protection Technology Economics/market integration	http://rse-web.it/progetti/progetto/714 http://rse-web.it/progetti/progetto/764 http://rse-web.it/progetti/progetto/795 http://rse-web.it/progetti/progetto/907
54	RSE - RdS 2.2 Systems and grids architecture models for RES integration - Task on AC-to-DC	2019-2021	RSE S.p.A.	Italian Ministry of Econon	0.0473 M€	Evaluation of AC-to-DC transmission OHL conversi Techno-economic assessment of new HVDC interconnections	4-6	Simulation validation	Planning RES Integration	
55	Definition of test procedures for HVDC components and cables (Definizione di procedure	Jul. 2018-Jul. 201	University of Palermo	Prysmian S.p.A.	0.030 M€	HVDC application analyses	4-6			
56	Pulsed Electro-acoustic Space Charge Apparatus (PESCA)	Oct.2018-Oct.202	University of Palermo	Italian Ministry of Educati	0.070 M€	HVDC application analyses	4-6			
57	Pre-Fault Investigation by Space Charge Electric Release (P-FISHER)	Apr. 2020-Apr. 20	University of Palermo	Prysmian S.p.A.	0.185 M€	HVDC application analyses	4-6			
58	ENSIEL ST 203	2021-2022	University of Naples Federico II	TERNA S.p.A.	0.0742 M€	HVDC tie links in smart power grids: A versatile control strategy of VSC converters	4-6		Control and protection	