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

SET PLAN KEY ACTION N°X[1] - DECLARATION OF INTENT - "HIGH VOLTAGE DIRECT CURRENT – HVDC AND DC TECHNOLOGIES"

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CONTENTS

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[1] To be defined

1. PURPOSE OF THIS DOCUMENT

This document is intended to record the agreement reached between representatives of the European Commission services, representatives of the EU Member States, Iceland, Norway, Turkey and Switzerland, and representatives from the SET-Plan stakeholders most directly involved in energy systems activities, on setting-up a new Working Group (WG) within the SET-Plan on High Voltage Direct Current (HVDC) and setting targets for HVDC technology development to make the energy systems fit for the future with the need to transport and integrate large scale renewable electricity in the EU energy system. The activities of the Working Group will concentrate on HVDC systems and their interconnection to the AC grid and potentially to other DC sub-systems, which could be developed for the grid of tomorrow. Therefore, MVDC systems will also be addressed by a Sub-Working Group (SWG) on MVDC within the WG on HVDC:

- to foster a harmonious development of the energy system structure as a whole – the architecture - which can include layers at different voltage levels (HVDC and MVDC);
- in consideration of its potential application for facilitating the deep penetration of Renewable Energy Sources (RES) in any of these layers and of Electric Vehicles (EVs).

Wherever MVDC is encountered in this Declaration of Intent, it is meant to be specifically pertinent and developed by the SWG on MVDC.

This agreement takes into consideration the development of HVDC and DC Technologies and Systems in the past decade, which makes them potential candidates to complement the AC electrical network, optimising the overall energy system.

A dedicated Working Group on HVDC and DC Technologies and Systems would help aligning the ongoing research, development and innovation actions at national and EU level and focus new actions. The WG will also raise interest in DC systems and related Power Electronics (PE) at national and EU level to support this key technology for the energy transition. Furthermore, the creation of a WG on HVDC and DC Technologies and Systems is intended to increase the collaboration and coordination within SET Plan countries and to ensure their active involvement in the technology development.

Brussels, 29th March 2021

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2. INTRODUCTION

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. Transmission and distribution networks technologies need to be adapted to these new requirements. DC technologies at high and medium voltage can provide solutions to tackle these challenges. HVDC is a key technology for grid interconnection, power transmission as well as offshore integration. MVDC, used for renewable generation - such as Photovoltaics (PV) and wind - as well as industry and the public transport, is becoming attractive also for future distribution network segmentation and applications towards an improved distribution grid controllability that can facilitate the integration of local renewable generation, while also exploiting the inclusion of fast recharge units for Electric Vehicles.

DC Technologies - HVDC and/or MVDC - 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.

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3. 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 transport 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 group on HVDC. The steadily increasing rollout of renewable energy both offshore andonshore, 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.

4. CHALLENGES TO ADDRESS

4.1. Technical

The growing penetration of renewables in the electricity system has presented integration issues linked to the volatility of energy generation from RES. Many actions and strategies have been put in place aiming at accommodating the growing share of renewables in the electricity grid (smart grids, demand response, energy conversion and storage systems, etc.).

DC trunks and layers (HVDC, MVDC) integrated in the AC system, offshore or onshore, can contribute and accelerate further the accommodating capability of RES in the grid. Thanks to the modularity of

DC systems, such integrations can be implemented gradually on the basis of a designed system architecture.

4.1.1. Short-term challenges

- From the Offshore RES strategy, the deployment of offshore wind and other RES generation far away from coast will generally, but inevitably imply a grid infrastructure that goes beyond the point-to-point HVDC connection we are used to today, to other more complex typologies (radial, ring and meshed or through a DC power hub). The number of interconnections with integrated DC systems will increase, thereby raising the need of standardised and extendable solutions covering multi-terminal, multi-vendor and multi-purpose capability including **interoperability among different vendors' HVDC stations**[2]. This will be very important also towards the future realisation of multiple, coordinated VSC HVDC links, embedded within the continental HVAC system (onshore). Moreover, the integration of HVDC links requires the investigation of: active power control for large perturbations (i.e. means to control power flows in embedded HVDC corridors, based on power flow dynamics in the parallel AC corridors, in order to increase stability) and for small perturbations (i.e. means to control the embedded HVDC links so as to damp inter-area oscillations); reactive power control; harmonic issues in case of nearby HVDC terminals. Other topics relate to HVDC cables, such as: the ageing phenomenon of dielectric materials under DC; the relevant measurements to be acquired through monitoring systems; the standardisation of HVDC cable testing.

- 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.

- The ability to seamlessly interconnect many different vendors' converters will lead to a more complex AC / DC hybrid grid architecture and topology. CBA and ROI when selecting AC or DC solutions shall be accurate and based not only on the distance covered, but also on key elements such as, for example, the flexibility of control and management they can provide. There is a centenary experience and knowledge of AC systems; more **studies and knowledge of complex DC and AC / DC hybrid systems** and their control and management are needed to anticipate and address the related

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[2] One of the main conclusions of the EC funded project 'PROgress on Meshed HVDC Offshore Transmission Networks' (PROMOTioN).

challenges. Interactions and behaviour of complex AC / DC hybrid systems are linked also with frequency control & management of the AC, protection schemes, reliability, planning and operation, etc.

As the Northern Seas represent a huge potential source of clean energy, in Southern Europe initiatives[3] emerged to harness the high availability of wind and solar energy in Northern Africa or Southern Europe Countries. Similarly, such objectives cannot be reached without the use of HVDC (or UHVDC)[4].

4.1.2. Long-term challenges

With the current deployment trend and in light of the offshore strategy objectives, the percentage of RES share in the energy system will increase significantly and, as a consequence, new control concepts for grid connections are needed to cope with the stability management of Power Electronics dominated power systems to **avoid critical situations and poorer manageability**[5]. **We, as community, can not afford to continue installing RES and other PEIDs without a plan to avoid grid disruption in the long-term**[6].

The solution to these challenges should bring an immediate benefit today facilitating the integration of RES. Moreover, such solution should contribute in the long-term to deliver capabilities to enable stable operation of the power system with up to 100% share of RES.

High Voltage Direct Current (HVDC) technology in its latest version based on **Voltage Source Converters (VSC HVDC) in cooperation with new stability management concepts (e.g. Grid Forming capabilities**[7]**)** can play a key role in addressing the above-mentioned challenges (two birds with one stone), as well as the following:

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[3] Desertec, Sahara Wind

[4] UHVDC Ultra High Voltage Direct Current is defined as DC voltage transmission of above 800 kV (HVDC is generally 100 to 800 kV) used for very long transmission lines (generally above 1 km). As of 2020, no UHVDC line (≥ 800 kV) exists in Europe or North America.

[5] The traditional AC electricity system is based on thermal power generation with rotating mass generators providing the inertia that keeps the frequency synchronisation and the stability against disturbances, spikes or faults. The generation from renewables is interfaced to the energy system through Power Electronics, which, contrarily to the traditional rotating mass generators, do not provide inertia. Therefore, in the current situation, the inertia of the electricity system diminishes proportionally as the share of RES increases in the system, hence reducing gradually its stability and manageability. The decrease of inertia implies the decrease of regulating energy (or power frequency characteristic of primary control), which is key for the manageability of the electrical system. The decrease of both inertia and regulating energy bring greater deviations of the power frequency response in case of large disturbances (loss of generations or loads), which can lead to the cascading tripping of generators and, in the worst case, to blackouts. One of the main conclusions of the EU funded project "MIGRATE (**M**assive **I**nte**GRAT**ion of power **E**lectronic devices). Simulation performed according to a probabilistic approach to harmonic propagation, showed that an increased PE penetration (from 60 to 90%) leads to a tripling of frequency variations and an increase of the total harmonics distortion (THD) above the 3% in 5% of substations.

[6] The installation of synchronous condensers can avoid/limit the inertia reduction due to RES, but the continuous increase of RES penetration in the grid calls for investigating more incisive and planned actions for the long term.

[7] The Grid Forming Converter's main feature is that it is able to generate the voltage waveform with the related electrical parameters (frequency, phase, etc.), hence it is independent of / does not follow the grid voltage. The converter contributes to shape the voltage waveform and as a result, it contributes to the stability of the grid.

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- Multi-vendor compatibility of HVDC systems and other PEIDs;
- Stability management in Power Electronics dominated systems (a grid with a high share of renewables);
- Assessment of a widespread AC/DC hybrid system including a provision of new electrical simulation modelling methods and tools that allow to improve the overall system behaviour and to mitigate adverse interactions between AC and DC parts;
- Electricity transmission over long distances, including interconnections with North Africa and eastern neighbouring systems (also in a post-2030 perspective)[8];
- De-risk of investments and ensured provision of security, controllability and dynamic stability in the whole system, which could theoretically accommodate up to a 100% share of renewables in the long term;
- Operation of HVDC links as ‘‘firewalls’’ against propagation of cascading outages originating from faults, disturbances or cyberattacks[9].
- Back-to-back HVDC applications for internal continental AC grid segmentation and controllability as well as for asynchronous systems interconnection with eastern neighbouring grids (also in a post-2030 perspective)[10];
- Segmentation of distribution networks by DC technologies, facilitating grids controllability as well as RES and Distributed Generation (DG) integration and manageability[11];

All the above developments and improvements are possible if the proper speed of technology evolutions in crucial areas of AC/DC hybrid systems assessment, stability management and interoperability is ensured with support of proper regulation and market framework (including sand boxes for first time demonstrations) on cross border dimension.

In summary, a **Multi-Vendor Multi Terminal VSC HVDC with complimentary future proof AC/DC hybrid systems assessment and stability management approaches is a top priority to fulfil climate-neutral Europe needs with ambitious aims for offshore renewable energy.**

4.2. Non-technical

The level of penetration and integration of HVDC systems prospects a series of non-technical issues such as regulatory, grid code, governance, market conditions, environmental, circular economy, roles and responsibilities, social acceptance, which can constitute a barrier for the deployment of HVDC systems and needs to be addressed.

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[8] This includes the use of classic LCC-HVDC, not only VSC-HVDC

[9] - J. Duncan Glover et al., “Power System Analysis & Design, fifth edition, SI”, Cengage Learning, 2012
- G. Mazzanti et al., “Extruded Cables for High-Voltage Direct-Current Transmission: Advances in R&D”, IEEE Press Series on Power Engineering, Wiley, 2013

[10] The application of Back-to-back HVDC for asynchronous systems interconnection will play an important role in a mid-to-long term perspective also towards the integration of eastern neighbouring systems (in primis Moldova’s and Ukraine’s).

[11] - Some MVDC projects have been carried out in different places worldwide. It is important to highlight the Angle-DC MVDC project implemented in UK at 33 kV MVAC / +- 27 kV MVDC (https://www.spenergynetworks.co.uk/pages/angle_dc.aspx).
-Two projects have been funded under the H2020 call LC-SC3-ES-10-2020: DC – AC/DC hybrid grid for a modular, resilient and high RES share grid development: TIGON and HYPERRIDE
- Flexible Electrical Networks (FEN) is a pilot project for MVDC developed in Aachen university campus in Germany. Other pilot projects are under study or testing in other European countries.

5. 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 the WG is to support the development of HVDC, MVDC and DC Technologies and Systems within the AC grid, including the assessment and management of a wide-spread AC/DC hybrid system which will allow a high onshore and offshore RES penetration , as well as foster the resilience of the grid, so as to make both the offshore and onshore grid fit-for-purpose in 2050. The work of the WG will entail the following wider impacts:

- Provide the grounds to decision-makers and investors to make better-informed decisions regarding the DC systems as an important grid development option. These decisions usually concern major investments and require multiple analyses of the benefits that can be provided.
- Increase interest and acceptance of DC systems among professional engineers, investors and decision-makers.
- Stimulate R&D to increase the interoperability, controllability, security, dynamic stability and efficiency of the electricity grid.

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6. STRATEGIC TARGETS

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

At the latest, by 2023 (and continue afterwards): developed modelling, planning and operational methods and tools (including a comprehensive reliability features assessment) for widespread AC/DC hybrid systems with the aim to de-risk investments and to ensure global system security, controllability and wide frequency range dynamic stability in the new grid architecture with higher shares of renewables offshore and onshore.

Once the demonstration of the full-scale MV MT HVDC system is commissioned, such modelling, planning and operational methods and tools should address the integration of the 5 GW MT HVDC system into the multi-TSO operating systems and procedures. Moreover, it would be necessary to demonstrate the grid-forming capability of the system in such a real multi-area scenario (multi-area black start, multi-area Power Oscillation Damping (POD), multi-area stability improvement, multi-area faults firewalling, etc.)

- **KPIs**: knowledge of different AC / DC grid architecture behaviour, protection and control schemes, e.g. DC system with one, two, etc. Common Connection Point (CCP) to AC; number of RES generation connected and related power; RES integration facilitation (in %); connection lines or cables length.

At the latest, by 2024: developed system-wide stability management strategies (for example Grid Forming Capabilities) for the future Power Electronics dominated systems. On this content, the provision of new means for long-term network planning, functional requirements and connection rules, grid codes revision on HVDC, load-frequency control procedures and the procurement of ancillary services will be key aspects to be deeply investigated. It will be also important to further assess and understand the phenomena behind HVDC cable system ageing connected to polarity inversion and other physical phenomena.

- **KPI**s: % of RES integration possible with the strategy; % increased reliability of HVDC cable systems.

At the latest, by 2023 - 2024: developed legal framework to define the Multi-Vendor cooperation and general information share in Multi-Vendor Multi Terminal VSC HVDC systems.

- **KPI:** While ensuring protection of IP rights, a document defining the legal framework for multi-vendor MT HVDC is publicly available.

At the latest, by 2024-2025: all technical simulations and HIL completed specifically for the first full-scale implementation so that its procurement can start immediately after targeting 2026-2027 as commissioning dates.

- **KPI**: While ensuring protection of Intellectual Property (IP) rights, a document defining technical simulations and HIL for interoperability of multi-vendor MT HVDC publicly available.

At the latest, by 2026 - 2027: **commissioned** first European full-scale implementation of **Multi-Vendor Multi Terminal VSC HVDC with Grid Forming Capabilities**[12] for power transfer rating of up to 5 GW. It is the first step paving the way to the deployment of the offshore grid and offshore RES development with the possibility to use DC technologies wherever needed, offshore or onshore, with increased reliability.

- **KPI**: the demonstrator itself installed and functioning.

At the latest, by 2028: Multi-vendor MT HVDC technology for power transfer rating up to 5 GW and beyond available commercially for offshore and onshore investments.

- **KPI**: manufacturers make available all the necessary equipment for MV MT HVDC.

At the latest, by 2030: full-scale **deployment** of **Multi-Vendor Multi Terminal VSC HVDC** for the offshore RES development.

- **KPI**: KPIs: number of MV MT HVDC installed.

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[12] With the Grid Forming Capability, we go a step beyond the first multi terminal installation. The world’s first multi-terminal VSC-MTDC system was successfully commissioned on December 2013 in Nan’ao Island in the southern part of the Guangdong province of China. The key objectives of the project were to incorporate the existing and future wind power generated on Nan’ao Island into the regional power grid, both to safeguard future energy supply and to support the transition from coal towards renewable energy sources. Worth of notice: The EU Company DNV GL was involved in the successful commissioning of the world’s first three-terminal VSC HVDC.

At the latest, by 2030: for new or retrofitting electricity systems, **increase of use of HVDC, MVDC and DC Technologies and Systems** to facilitate integration of renewables, new interconnections and AC retrofitting by conversion of existing AC transmission overhead lines to DC. These actions also includes the extension of existing Line Commutated Converter HVDC (LCC-HVDC) (classic HVDC) stations by the implementation of advanced devices such as STATCONs[13] that can improve voltage and reactive power support , with the aim to have almost the same performances as VSC-HVDC. This shall be also oriented to extend the applications and use of HVDC links embedded within the European HVAC system (onshore), to increase its controllability and flexibility, towards the realisation of an AC / DC hybrid grid[14].

- **KPIs**: the % of DC technical solution compared to AC solution; investments in DC Technologies and solutions, % RES integrated by HVDC into the grid.

By 2026-2030 (and beyond): specific targets for the adoption of MVDC in distribution networks to be defined upon support of manufacturers.

- **KPIS**: % RES integrated by MVDC into the distribution grids.

7. NEXT STEPS

A temporary working group (TWG) has been set up with public and private stakeholders. This TWG shall:

- Develop within 6 months a detailed implementation plan for the delivery of these R&I targets, in particular:
  - determine joint and/or coordinated actions; to identify the ways in which the EU and national research and innovation programs could most usefully contribute;
  - identify the contributions of the private sector, research organizations, and universities;
  - identify all issues of a technological, socio-environmental, techno-economic, regulatory or other nature that may be of relevance in achieving the targets;
- Report regularly on the progress with the purpose to monitor the realisation of the targets and take rectifying action where and whenever necessary.

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[13] STATCON (Static synchronous condenser), also known as STATCOM (Static synchronous compensator), is a device belonging to FACTS (Flexible AC Transmission System) technologies, a family of Power Electronics-based technology controllers.

[14] After 2030 the offshore HVDC and the onshore embedded HVDC links could constitute the building blocks of a potential European AC/DC supergrid. These matters have been investigated in several European projects, including GridTech and e-Highway2050. In the long term (2040-2050), the pan-European network may be interconnected via bulk power HVDC corridors to extra-European systems as part of the global grid developments.

8. ANNEX I – POSSIBLE AREAS OF INTERVENTION

1. The R&I and work on interoperability is for the benefit of the whole EU. Before the implementation of the first operational multi-vendor Multi Terminal HVDC with Grid Forming capabilities (to be realised by 2026) within the AC grid, there is the need to coordinate the many stakeholders involved in the organisational process. This preparatory action will support the successive development and planning of the real life demonstration, pilot or industrial project.
2. Identify relevant projects (on going and recent) at EU and national level to jointly contribute to the above points:
   - to collect and analyse the main outcomes (addressed challenges e.g. reliability, interoperability and operation issues, significant benefits, costs, environmental impact etc.);
   - to make the outcomes available to the team that defines/updates the Union list of Projects of Common Interest (PCIs) intended to contribute to the integration of the EU electricity markets;
   - to convene with the manufacturers to find common, standard solutions to interoperability issues.
3. Organize international meetings to share experiences, lessons learned from fault cases, best practises and improvement recommendations by involving experts from several sectors (e.g., manufacturers, designers, commissioning engineers and developers).
4. Identify European common requirements for HVDC inter-compatibility, modelling and performance issues focusing on current and future energy scenarios.
5. Relevant grid codes revision to connect HVDC to the AC system.
6. **Support HVDC/MVDC development/deployment** by creating national mirror groups involving key experts - knowledgeable about integration and planning of offshore-onshore grid development - to **discuss the most important aspects related to HVDC and MVDC applications that still need research, development and demonstration efforts (multi-terminal links, meshed grids, AC/DC hybrid AC/DC systems).** The group on HVDC/MVDC shall play a key role in the interaction with the European Commission, ACER, ENTSO-E (at European and regional level) E.DSO and with NRAs, TSOs (at national level) and also DSOs to foster HVDC/MVDC projects and support the crucial understanding of pros and cons of HVDC/MVDC investments towards a European decarbonisation pattern.
7. **Work at national level on education and social acceptance** of huge infrastructures, while investigating the regulatory barriers.
8. **Investigate the possible interactions with other energy and industrial infrastructures**.
9. **Support and foster the development of HVDC/MVDC technologies** and **planning tools** (including system reliability features assessment) for onshore and offshore applications for control and management, interoperability and resilience to propagation events due to faults, disturbances and cyberattacks of the EU electricity system;
10. In case of HVDC onshore application with construction of new overhead lines (wherever cables and DC gas-insulated lines can not be used), to identify and analyse the impact of Not In My Back Yard (NIMBY) phenomena and how to deal with.
11. **Investigate environmental impact** aspects to account along the life cycle of these kind of structures such as: energy consumption for equipment manufacturing, impacts of copper mining and treatment (before the infrastructure installation); soil occupation

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(during installation and use); equipment disassembly, reuse of components, material recovery *e.g.* reuse or recycling (end-of-life).

12. To take stock of HVDC offshore grids issues and challenges related to the North Seas and Baltic regions and support policymakers in next steps of European offshore strategy, also towards a potential development of an AC / DC hybrid grid in the Mediterranean region (see the recent study performed for the European Commission https://guidehouseinsights.com/news-and-views/offshore-grid-potential-in-the-mediterranean).
13. HVDC would further enable the energy transition requirements of efficient onshore transmission over long distances in north-south, east-west corridors across all European regions, and beyond, considering potential interconnections to extra-European systems (e.g. North Africa and eastern neighbours) in the long-term. The type of interconnection link technology/option (overhead lines or underground cables) depends on the specific situation and in case it involves the construction of new overhead lines, NIMBY phenomena may require complementing the discussion with social impact considerations (assessments, how to deal with, etc.)
14. **Identify potential projects for retrofitting AC with DC lines or AC/DC hybrid lines** on the basis of CBA;
15. The new group shall contribute to education and dissemination on:
    a. Power conversion technology as key for high RES penetration (including grid following and grid forming converters, etc.);
    b. Converter topologies (MLC, MMC,…) and their typical applications;
    c. New components for Power Electronics (using Wide Band Gap (WBG) semiconductors such as Silicon Carbide (SiC), Gallium Nitride (GaN), etc.);
    d. Development of innovative functionalities to support frequency and voltage stability;
    e. Monitoring and communication systems for HVDC/MVDC;
    f. Integration of DC technology into control centres for monitoring and control of AC/DC hybrid systems;
    g. Cables, lines and fittings (including new materials and technologies to increase reliability, resilience and environmental sustainability of HVDC/MVDC grids, etc.);
    h. Reliability, availability and resilience of all HVDC/MVDC components and their integration into the system.
16. Identify overlaps and interfaces with national, European and international activities (e.g. IWG 4 (Smart resilience and Secure Energy Systems), Mission Innovation (Power Mission), IEA (ISGAN) and the wind domain on European level and IEA Wind TCP Task 25 "Design and Operation of Energy Systems with large Amounts of variable Generation" on international level):
    a. synergies can be used and further developed;
    b. coordinate the topics where research is still needed and the topics that are already in focus internationally;
17. Boost **cooperation and alignment of EU and national funding programmes** to contribute to points 1) and 2);
18. Take stock of HVDC implementation projects for a more widespread application of MVDC in real-life distribution grids;

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19. Understand how climate change may affect the evolution and widespread adoption of HVDC technologies across the world. Understand how modifications in the energy system affect the reliability of HVDC cable systems due to changing operating conditions.

In order to implement the above listed actions, specific tasks should be defined:

<u>For points 6 and 7</u>:

- Verification of interoperability (compliance with the standards) should be done without involving other vendors. That is, verification should be done by using qualified non-vendor specific test-facilities where new vendor systems can be tested to verify interoperability in an efficient and transparent way, and where other vendor's systems can be represented in tests and simulations without the use of such other vendors' systems.
  - Agreement on functional requirements for interfaces for control, protection and testing
  - Development of control and protection hardware and software capable of complying with the functional requirements:
    - HIL testing and demonstration of interoperability
    - Application in real projects
    - SIL testing will follow HIL
- Energy system studies based on DC and AC / DC hybrid grid technologies, commissioned/conducted by working group members;
- Communication and dissemination among energy stakeholders;
- Annual workshop on HVDC
- List of possible discussion points to be addressed:
  - Interoperability from different manufacturers for the integration of HVDC in the AC network;
  - The converter as a key component of the energy system with the objective of a high RES penetration (including grid following and grid forming converters, etc.);
  - Converter typologies and development;
  - Error detection, fault clearance and propagation inhibition (e.g. component or AC or DC network and to keep the effects of failures as low as possible);
  - AC / DC hybrid systems control rooms (operation) to detect errors at an early stage to limit their effects;
  - Power Electronics as a key component for the development and deployment of converters for an AC/DC hybrid grid:
    - Development and improvement of Si-semiconductors (e.g. achieve higher short-circuit currents)
    - Beyond Si: development of new materials (Wide Band Gap semiconductors such as GaN or SiC).
  - Passive components;
  - Control systems and communication;
  - Power damping oscillations and frequency stability;
  - Cable systems (including cable monitoring systems, standardisation for cable system testing, stability issues, etc.);

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  - DC gas-insulated substations and lines;
  - HVDC offshore application (including logistics, etc.);
  - Impact of HVDC systems on the resilience of the grid to disturbances, faults and cyberattacks intended as limitation of the affected areas due to the blockage of an HVDC link to the cascading effect (firewall effect);
  - Reliability and maintenance of all HVDC and MVDC components (including Condition & Health Monitoring, etc.);
  - Standardisation: compatibility and interchangeability of components from different manufacturers; voltage levels, etc.;
  - Sustainability: before the infrastructure installation, during installation and use, and at end-of-life stage.
  - Education and training on HVDC (including dissemination among young generation, etc.);
  - Legal and regulatory framework;
  - MVDC technology status and advances;
  - MVDC projects analyses and studies;
  - Further R&D&I.

<u>For points 8, 9 and 10:</u>

- Develop the identified technology needs in a coordinated way among the Commission, MS and the private sector. Itis critically important to secure equal access and a level playing field for all parties (HVDC vendors, TSOs, DSOs and other developers and operators of HVDC/MVDC systems alike). This should ideally be done by:
  - defining open industry standards for multi-vendor multi-terminal HVDC converters and associated systems that ensure interoperability;
  - defining transparent procedures to verify compliance with the standards by testing and simulation;
- Identify existing projects and/or funding programmes addressing:
  - Cost Benefit Analysis of a massive penetration of DC technologies in the AC grid including AC / DC hybrid systems.
  - Cost Benefit Analysis of importing energy from far away sites (offshore, desert) to the consumption areas, i.e. create the basis for further R&I&D.
  - Plan / design the architecture of an AC / DC hybrid system for Europe to enable the growing share of renewables while keeping the grid stable, resilient and sustainable.
  - Envisage adequately the impact of industrial districts hosting the converter stations.
  - Demonstration / development of DC intelligent substations.
- Investigate and develop further the following areas:
  - Deployment of new semiconductor-based components enabling higher power densities, operation voltages, frequencies and temperatures at affordable costs;
  - New control concepts also considering predictive maintenance (methods and tools), particularly for offshore applications;

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- Deployment of suitable monitoring infrastructures for increasing reliability and acquiring the parameters and data correlated with the ageing of the system (pre-fault diagnosis and predictive maintenance);
- Deployment of advanced protection systems integrating fault detection, fault clearing and recovery strategies through local measurement-based algorithms and/or communication-based algorithms;
- MVDC application in distribution networks, also taking stock of HVDC deployment experiences;
- Deployment of a highly reliable and effective telecommunication system interconnecting the terminals of HVDC grids.

9. ANNEX II – BRIEF DESCRIPTION OF TARGETED TECHNOLOGIES

9.1. HVDC

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.

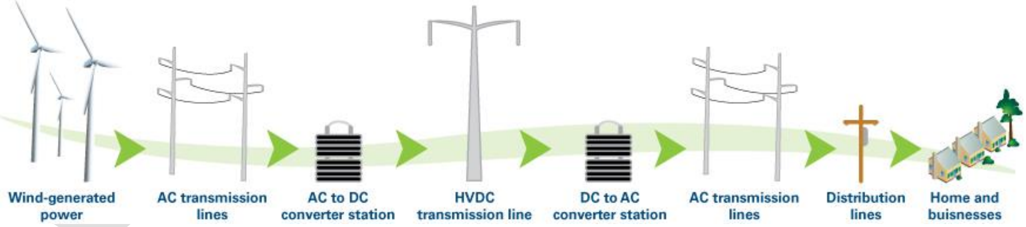

Figure 1 HVDC system integrated in the AC grid Source: Duke-American Transmission Co.

Taking into account the DC transmission technologies available today, the peculiarities of the latest generation of High Voltage Direct Current (HVDC), namely the Voltage Source Converter (VSC) with Grid Forming Capabilities, prospects solutions addressing the challenges highlighted in the introduction.

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

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compensation for the reactive power[15]. 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 - e.g., by means of Virtual Synchronous Machine (VSM)-based approaches - and guaranteeing the manageability of the grid under a high penetration of RES.

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, smoothen wind power fluctuations 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.

9.2. MVDC

The transmission grid uses today HVAC and HVDC wheras 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

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[15] 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.

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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.

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10. ANNEX III - MEMBERS OF THE TEMPORARY WORKING GROUP ON HVDC

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N.		**Name**	**Institution / Company**	**EC, MS, AC / Association**	**Contact**	**Status: Full / Correspondent Member (FM / CM)**
1		Van Hertem, Dirk	KU Leuven, Department of Electrical Engineering	Academia	dirk.vanhertem@esat.kuleuven.be	FM
2		Charalambous, Chrysanthos	University of Cyprus	Cyprus	cchara64@ucy.ac.cy	FM
3		Efthymiou, Venizelos	University of Cyprus	Cyprus	venizelo@ucy.ac.cy	FM
4		Müller, Zdenek	Head of the Department of Electrical Power Engineering Czech Technical University in Prague	Czech Republic	zdenek.muller@fel.cvut.cz	FM
5		Cutululis, Nicolaos Antonio	DTU	Denmark	niac@dtu.dk	CM
6		Baldursdottir, Iris	ENTSO-E	ENTSO-E	iris.baldursdottir@entsoe.eu	FM
7		Butkus, Paulius	ENTSO-E	ENTSO-E	paulius.butkus@entsoe.eu	FM
8		Constantinescu, Norela	ENTSO-E	ENTSO-E	Norela.Constantinescu@entsoe.eu	FM
9		Morollon, Gonzalo	ENTSO-E	ENTSO-E	gonzalo.morollon@entsoe.eu	FM
10		Ndreko, Mario	ENTSO-E	ENTSO-E	Mario.Ndreko@tennet.eu	FM
11		Winter, Wilhelm	ENTSO-E RDIC-WG2 Convenor for Security and operations of tomorrow	ENTSO-E	wilhelm.winter@tennet.eu	FM
12		Wendt, Volker	Europacable	Europacable	v.wendt@europacable.eu	FM
13		DIONISIO, Mario	DG ENER	European Commission	mario.dionisio@ec.europa.eu	FM
14		VAN STIPHOUT, Mark	DG ENER	European Commission	Mark.VAN-STIPHOUT@ec.europa.eu	FM

N.		Name	Institution / Company	EC, MS, AC / Association	Contact	Status: Full / Correspondent Member (FM / CM)
15		SOEDE, Matthijs	RTD	European Commission	Matthijs.SOEDE@ec.europa.eu	FM
16		LIMA DA CUNHA, Carlos Eduardo	RTD	European Commission	Carlos-Eduardo.LIMA-DA-CUNHA@ec.europa.eu	FM
17		SHTJEFNI, Drilona	JRC	European Commission	Drilona.SHTJEFNI@ec.europa.eu	FM
18		TELSNIG, Thomas	JRC	European Commission	Thomas.TELSNIG@ec.europa.eu	FM
19		Montagne, Xavier.	Ministry of higher education, research and Innovation	France	xavier.montagne@recherche.gouv.fr	FM
20		Eickhoff, Ralf	Forschungszentrum Juelich GmbH Project Management Juelich	Germany	r.eickhoff@fz-juelich.de	FM
21		Zsolt Zoltán, LENGYEL	MAVIR Hungarian Independent Transmission Operator Company Ltd.	Hungary	lengyelz@mavir.hu	CM
22		Palsson, Magni	Landsnet, Iceland	Iceland	magnip@landsnet.is	FM
23		Ging, John	Sustainable Energy Authority of Ireland	Ireland	John.Ging@Eirgrid.com	FM
24		Basosi, Riccardo	MUR - Italian Ministry of University & Research	Italy	riccardo.basosi@unisi.it	FM
25		Capra, Marcello	MITE – Italian Ministry for Ecological Transition	Italy	marcello.capra@mise.gov.it	FM
26		L'Abbate, Angelo	RSE	Italy	Angelo.Labbate@rse-web.it	FM
27		Riva Sanseverino, Eleonora	Università di Palermo	Italy	eleonora.rivasanseverino@unipa.it	FM
28		Bikulcius, Ramunas	Head of Strategy and Research Division Litgrid AB (National TSO)	Lithuania	Ramunas.Bikulcius@litgrid.eu	FM

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N.		Name	Institution / Company	EC, MS, AC / Association	Contact	Status: Full / Correspondent Member (FM / CM)
29		van der Meijden, Mart	Technical University Delft	Netherlands	Mart.vander.Meijden@tennet.eu	FM
30		Le, Khanh Tuan	The Research Council of Norway	Norway	ktl@forskningsradet.no	FM
31		Collombet, Rémi	Oceanenergy	Ocean Energy Europe	r.collombet@oceanenergy.eu	FM
32		Pirttimaa, Lotta	Oceanenergy	Ocean Energy Europe	l.pirttimaa@oceanenergy.eu	FM
33		Andrade, Ana	Directorate-General of Energy and Geology	Portugal	ana.andrade@dgeg.gov.pt	FM
34		Zachia, Oana	CNTEE Transelectrica S.A.	Romania	oana.udrea@gmail.com	FM
35		Cruz, José Ignacio	Faculty of Electrical Engineering	Spain	ignacio.cruz@ciemat.es	FM
36		Rodriguez, Pedro	Universitat Politècnica de Catalunya	Spain	pedro.rodriguez@upc.edu	FM
37		Vinson, Paul	Supergrid	Supergrid	paul.vinson@supergrid-institute.com	FM
38		Barker, Carl	GE	T&D Europe	carl.barker@ge.com	FM
39		Lundberg, Peter	Hitachi ABB Powergrids	T&D Europe	peter.lundberg@hitachi-powergrids.com	FM
40		Schettler, Frank	Siemens Energy	T&D Europe	frank.schettler@siemens-energy.com	FM
41		Peereboom, Diederik	T&D Europe	T&D Europe	secretarygeneral@tdeurope.eu	FM
42		BİLGİN, Hazım Faruk	Tubitak	Turkey	faruk.bilgin@tubitak.gov.tr	FM
43		YILDIRIM, Çağrı	SET Plan country representative of Turkey	Turkey	cagri.yildirim@tubitak.gov.tr	FM
44		Bray, Morris	National Grid Ventures UK	Wind Europe	morris.bray@nationalgrid.com	FM
45		El-Khatib, Walid	Vattenfall	Wind Europe	walidziad.el-khatib@vattenfall.com	FM
46		Klonari, Vasiliki	Wind Europe	Wind Europe	Vasiliki.Klonari@windeurope.org	FM
47		Marshall, Benjamin	National HVDC Centre	Wind Europe	Benjamin.Marshall@sse.com	FM

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N.		Name	Institution / Company	EC, MS, AC / Association	Contact	Status: Full / Correspondent Member (FM / CM)
48		Sharifabadi, Kamran	Equinor	Wind Europe	kamsh@equinor.com	FM
49		Sørensen, Troels Stybe	Ørsted	Wind Europe	TROSO@orsted.dk	FM

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11. ANNEX IV: DEFINITIONS, ACRONYMS

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

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N.	Acronym	Description
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

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