



**How to unlock
investments for the
first full-scale multi-
vendor HVDC
systems
demonstration**



ABOUT READY4DC

The future electricity network envisioned by READY₄DC will be characterized by a growing role of multi-terminal multi-vendor (MTMV) HVDC solutions within the current AC transmission networks both onshore and offshore. READY₄DC is contributing to this synergistic process by enabling commonly agreed definitions of interoperable modelling tools, model sharing platforms, clear processes for ensuring interoperability, and an appropriate legal and political framework.



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How to unlock investments for the first full-scale multi-vendor HVDC systems demonstration

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EXECUTIVE SUMMARY

This whitepaper discusses several aspects to consider for unlocking investments for the first full-scale multi-terminal multi-vendor (MTMV) high-voltage direct-current (HVDC) system demonstration and beyond. Short term, for a first-of-a-kind (FOAK) MTMV HVDC demonstrator, the funding will not only depend on remuneration and on the reliability of being able to recoup investments, but more heavily on long term social and technology benefits. As such, the funding structure and source need to reflect these goals. The project owner needs to be shielded from both the short-term risks of a project and marginal costs to lower project risk (e.g., additional equipment to provide redundancy, etc.) and longer-term risks of over-scaled or redundant infrastructure or equipment. There are funding mechanisms available for such a FOAK demonstrator. However, these could be improved and/or simplified from an administrative viewpoint.

In the longer term, given the anticipated total funding requirement and the complexity of meshing grids, we may anticipate a potential shift in equity ownership from TSOs to new parties entering the offshore grid infrastructure market. These are both strategic and financial infrastructure investors. It may be in the form of partial or complete asset ownership. This may lead to new models for operation.

To date, there are still only limited examples of multi-terminal infrastructure constructed. It can be argued that most FOAK proposals have faced non-financial barriers (e.g., lack of relevant staff, preference to let others move first) and have not been implemented, despite the reasonable costs and benefits of meshing. In this whitepaper, how the funding of a FOAK project may be realized is considered, and the boundary conditions to achieve this, i.e., which blocks need to be removed to gain a go-ahead.

Looking ahead, this whitepaper gives a rough back-of-the-envelope style idea of the enormous investment required in HVDC components and systems to achieve the integration of EU offshore wind generation targets, potentially consuming an unrealistically high portion of the yearly turnover of the primarily concerned North Sea transmission system operators – each year in the coming decades.

Marginal costs of DC meshing offshore are anticipated to be limited compared to the total planned infrastructure investment. Depending on the distance between two offshore DC platforms, additional cable costs and appropriate protection are a very small part of the total costs when connecting two P2P HVDC connections offshore-offshore. Yet this interconnection offshore may bring significant benefits in grid performance and commercial benefits to both national and Europe-wide systems.

Through the course of the Working Group, it also became clear that implementing new technologies may be delayed by the pressed staffing situation in the HVDC sector. Notably, a poll of stakeholders in READY4DC indicated their high workload already today, as well as an overall need for more staff in the close future. This may require growth in the output of universities and also retraining of existing staff.

Furthermore, the view of the HVDC community is that raising capital for a FOAK demonstrator is less about technology but more about clear organization. This view aligns with investor input. Still, technology de-risking must be included in a MTMV project as a pre-condition for investments. This technology de-risking includes multi-vendor HIL testing using replicas (see companion whitepaper [1]). Furthermore, liability questions have to be solved (see second companion whitepaper [2]). Fall-back options could be a suitable approach to MTMV where a system is split into a “core task” (e.g., wind_energy to shore) and “extra functions” (MT/MV), for example, using a DC-connection for parallel point-to-point HVDC links. If in such a setup, interoperability does not work, the fallback options are separate single-vendor systems.

Similarly, technological de-risking should be addressed with separate “crucial” (mandatory) and “nice-to-have” (performance-improving) functional specifications (see third companion whitepaper [3]).

Finally, it is neither possible nor necessary to find a one-fits-all approach to financing MTMV HVDC projects. To build more efficient and effective grids, it is also highlighted the needs for (a) changes in regulatory regimes to allow anticipatory investments, less restricted use of cable infrastructure, and multilateral agreements, and (b) more widespread political support for the development of MTMV HVDC systems.

1. INTRODUCTION

The Delivery of Multi-terminal (MT) and multi-vendor (MV) aspects is a critical foundation to achieving the HVDC networks of the future due to;

- **Environmental and cost reasons:** a MTMV DC network is one which requires less submarine cable, less onshore converter infrastructure than present day point-point HVDC projects and which is able to concentrate the maximum amount of offshore wind power capacity within the minimum transmission infrastructure as a result. This leads to societal benefits in being able to deliver the energy transition more rapidly than would otherwise be the case to a lower cost and environmental impact than would otherwise be the case¹. MTMV will increase the availability of offshore wind energy and therewith increase the total RES portion in generation mix and reduce the CO₂ emission.
- **Practical reasons:** the required DC networks will be grown over time, constructed in stages. Over this same time period HVDC supply capability will grow to meet demand, but as DC networks grow it will not be possible to guarantee that the originating vendor delivering the first stage will be appropriate to deliver all further phases, and an open competitive environment across vendors will be desirable to maintain the growth of offshore wind in the most appropriate manner. In this regard, achieving interoperability for HVDC systems provided by different vendors (multi-vendor interoperability) will be key to facilitate grid expansion and offshore wind integration.
- **Technical reasons:** for similar reasons to why onshore AC transmission systems are built as multi-terminal networks of infrastructure, there are strong reliability, security of supply² and operational flexibility reasons that support the delivery of MTMV delivering efficiency to the end consumer.
- **Financial reasons:** A key challenge is to both incentivise construction and improve the bankability of MTMV HVDC networks. The European developments in MTMV HVDC systems must speed up to support the EU offshore goals- and to date no MTMV project has been delivered in practice.

MT and MV aspects of high-voltage direct current (HVDC) systems in Europe have been discussed and researched for many years. The respective research and innovation projects include the BestPaths³ project focusing, e.g., on converter control and protection including real-time simulation, the MIGRATE⁴ project focusing on massive integration of power electronics into the electricity grid, and the PROMOTioN⁵ project focusing on demonstration of key technologies (including protection) and the regulatory framework. While it can be argued that many aspects of HVDC multi-vendor interoperability have been addressed to some degree, still the European developments in multi-terminal multi-vendor (MTMV) HVDC systems have to speed up massively to support the EU ambitious energy and climate goals. In 2020, these goals amounted to 60 GW offshore wind by 2030 and 300 GW by 2050⁶[4]. In 2022, at the North Seas Energy Cooperation (NSEC) meeting in Dublin, the eight NSEC countries agreed to reach at least 76 GW (2030) and 300 GW (2050) of offshore wind energy in the North Sea, an amount that represents more than 85% of EU ambition for 2050 [5]. To accommodate this infeed of electricity, international cooperation and coordinated planning, to facilitate incremental grid build-out, provide critical infrastructure resilience (e.g., against natural catastrophes), achieve greater energy efficiency and speed

¹ One WG member would like to add that this is true if the MTMV grid is connected to different price zones.

² One WG member would like to add that security of supply requirements may be less strong for offshore grids with pure generation, cmp. Section 5.3.

³ 2014-2018, 62.8 M€, 23 partners

⁴ 2015-2019, 17.9 M€, 23 partners

⁵ 2016-2020, 42.8 M€, 33 partners

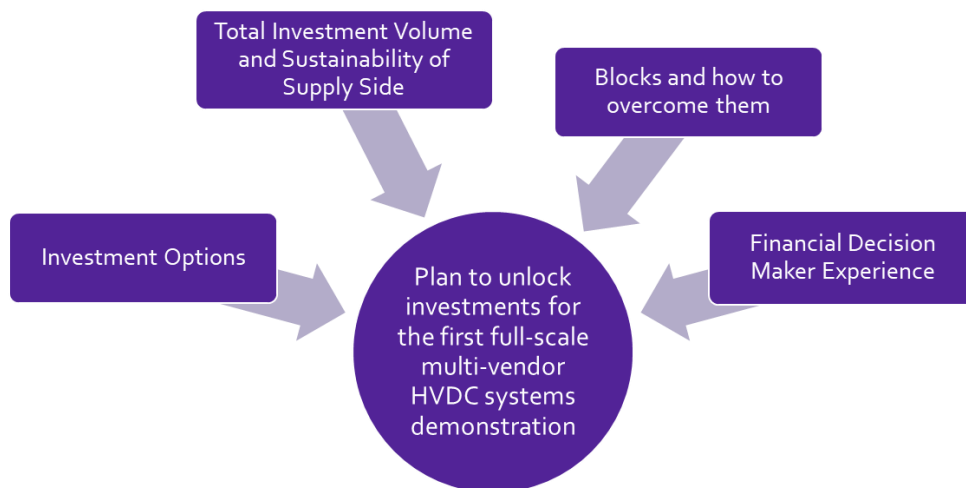
⁶ Compared to 14.6 GW offshore wind capacity installed in 2021.

up electricity market integration process, MTMV HVDC systems are essential. Therefore, incentivizing investments in such systems is crucial for the future European energy system.

The actual investment decision for the first full-scale multi-vendor HVDC system in Europe has to be seen in light of four aspects as indicated in Fig. 1, namely, (a) the investment options and funding mechanisms (Section 2), (b), the total investment volume and sustainability of supply side (Section 3), (c) the blocks for investing into the first MTMV HVDC demonstrator (Section 4), and (d) the experience of financial decision makers (Section 5). This whitepaper analyses these four aspects and aims to propose a plan to unlock investments for the first full-scale multi-vendor HVDC system demonstration in Europe.

FIGURE 1

Structure of this whitepaper



2. INVESTMENT OPTIONS

2.1 Context

As a general statement, we can optimistically state that if there is a clear and demonstrated need for funding of the infrastructure for electricity transmission, the transmission system operators (TSOs) (in Europe) or other stakeholders (the offshore wind farm (OWF) developers, offshore transmission owners (OFTOs), etc.) will fund and/or construct the infrastructure.

For mature and available technology, such as point-to-point HVDC, there are established mechanisms (national grid development plans, ten-year network development plan (TYNDP) and offshore network development plan (ONDP), procurement, procedures for Projects of Common Interest (PCI), etc.).⁷ Projects identified as PCIs are cross-border infrastructure projects that are deemed crucial for linking EU energy systems and have the right to apply for funding from the Connection Energy Facility (CEF) [6]. This will also apply to MTMV HVDC projects.

In the early phases of building a new MTMV HVDC project, where first of a kind (FOAK) is relevant or where technology is not perceived as mature in Europe, the process is similar to mature and available technology (an infrastructure need is identified, and the project may be agreed upon and/or proposed under the

⁷ TYNDP will be combined with ONDP 2026.

TYNDP/ONDP and PCI mechanism). However, for a FOAK, the evaluation for funding should not only depend on remuneration and on reliability of being able to recoup investments, but it should also take into account longer term social and technical benefits. As such, the funding structure and source needs to reflect these goals and investments should be incentivised despite the risks related to a FOAK. The project owner therefore needs to be shielded from both short-term and marginal costs to lower project risk (e.g., additional equipment to provide redundancy, etc.) and longer-term risk of over scaled or redundant infrastructure or equipment (compare, e.g., problematic anticipatory investments for TSOs).

Integrating offshore renewables in the most efficient way brings several benefits that should be taken into account for facilitating investment decisions in this direction. Such benefits include:

- Increasing renewables share in the energy mix and achieving higher offshore wind energy integration in the system
- Creating redundancies in terms of the n-1 criteria to enhance security of supply, and achieve a better electricity flow to support the onshore transmission network
- Improved redispatch leading to overcoming grid bottlenecks, arising from the direct controllability of the multi-terminal network.
- CO₂ reduction by supporting the increase of offshore generation into the onshore transmission system via minimisation of overall transmission losses,
- More efficient usage of the offshore space and thereby limiting the environmental impact of the grid connection,
- In case of bi-or multilateral interconnection, European market integration and price convergence is enhanced, providing long term benefits in consumer price, noting the variability of the wind resource that needs to be “pooled” across European networks

Building an interconnected offshore power grid benefits not only the countries of project promoters but may also several neighbouring countries. An increasing number of mechanisms⁸ to share the benefits and the occurring costs are either already applied, like the CBCA for PCI projects, or under development. When using these tools, it is crucial to reflect all existing cost sharing agreements, be it MoUs between project partners or EU-level mechanisms and avoid double counting or double compensation. These tools must avoid creating a massive administrative burden and potential complexity in remuneration to investors. Equally, intense cost contributions that are not connected to the ownership of dedicated assets on the balance sheets bear a risk in terms of ratings and financial health of the organizations involved. Therefore, transparency and predictability must be ensured wherever possible and significant liabilities avoided for benefits which cannot be tracked.

In the holistic (coordinated international) planning and probable incremental build of multi-terminal and meshed grids offshore, there are a number of considerations that may impact investment and the above processes: the interplay of asset purpose and operation as well as regulation, must be considered in the project assessment and accordingly in the cost-benefit analysis (CBA). This broader perspective may change the value of a project for different and potentially new stakeholders. Also, these aspects must be

⁸ The CBCA (cost benefit cost allocation) mechanism is an applied method for PCI projects. The methodology has just been revised by ACER. According to the TEN-E regulation, an CBCS (cross-border cost sharing) methodology shall be developed until 2025 which covers the new offshore infrastructure per sea basin. This shall be for information only without a compensation. Another mechanism announced might also cover the EU-wide benefit sharing with landlocked countries.

considered in the inter-regional / country and EU-level planning requiring coordination and cooperation. Questions may also arise as to:

Who is the initiator/anticipated owner of the asset: TSO⁹ or Government institution; OWF developer or OFTO; Merchant/Commercial investors? Current grid investment for transmission assets within Europe, is led mainly by the TSOs with the UK exception. As put forward by ENTSO-E [7] there are many reasons why countries have in the past tended towards TSO-led investments, such as holistic system planning to strengthen security of supply, general national security, reliability, grid resilience, control and management of grids, price control, etc. In the Staff Working Document accompanying the EU Strategy on offshore renewables, the European Commission states that there are alternatives to the traditional TSO model (where it is only the TSO that builds and operates the network) that can fully comply the unbundling rules [4]. It is still to be investigated and defined which approach works better for offshore grids.

How should investment costs and benefits be shared? This is already complex for a bilateral project. Given the complexity of the new projects (for example, offshore hybrid projects or energy islands) and the different stakeholders involved, it is very important that there is a clear framework on how costs and benefits should be allocated among different countries, sectors and stakeholders involved.

What revenue streams are anticipated? Without having a clear image of the regulatory framework that it is going to be applied, it is difficult to identify the revenue streams for investors. However, transparency on how the regulatory framework is going to be formed is necessary to enable future investments¹⁰.

Who will own, manage, and control potential offshore hubs, compare [7]? Asset ownership varies from country to country even through Europe, with different models in EU as well as in the non-EU countries, the UK and Norway. Current grid investment for evacuation assets within Europe, is led mainly by the TSOs with the UK exception. However, even in the UK bootstrap offshore connections North-South and offshore "landing points" equivalent to a "socket in the sea" as promoted in Belgium are being classed as "Onshore Assets, to facilitate these being built as a part of the national grid infrastructure rather than a part of the offshore generation infrastructure. In the UK, interconnection assets, remunerated with congestion revenue are owned and managed by non-regulated entities, but even here these assets are mainly TSO initiated and owned. The interconnector assets theoretically rely on price differences between bidding zones. As such, each increase in capacity between bidding zones may result in a reduction in congestion and likely lower revenue and higher volatility. Therefore, for a meshed grid, the interconnector model may not be the most appropriate business model.

New forms of assets such as offshore hubs and offshore hybrid projects (assets combining transmission of offshore wind energy and interconnection of bidding zones) will add further complexity to the system. These assets bring significant socio-economic welfare benefits, but they also require a clear framework on cost-benefit and cost-sharing issues for all the stakeholders and countries involved. Additionally, they

⁹ TSOs are often perceived as Government-owned, but we should be aware that in some countries, these are private companies with a concession for geographic areas, e.g. Germany, Belgium, the UK. They do receive a regulated income for capacity provision and service quality, and in many cases have Government shareholders, but in many cases act as independent companies. However, as their income is dependent on a regulated asset base, any investment is controlled by the national Government (1 or more ministries) and a Regulator. If a TSO is given an offshore concession and is asked to build assets offshore as a part of its asset base, these need to be justified to the local Government. In theory, the current interconnectors fall outside this regulation and are built as commercial assets [not if based on TYNDP and/or national development plan]. It is possible in the future therefore to consider an offshore-to-offshore connection in a similar way.

¹⁰ Regulatory revenue is currently "Capacity-based" – where the asset is a part of the regulated national grid; an OFTO or equivalent investment remunerated as a part of the OWF consent. For current merchant interconnectors, it is "Congestion- or flow-based" Other possible models could be a utilisation-based remuneration which is potentially required for hybrid interconnection. However, to attract public or private investments the revenue scheme and associated risks need to be understood. See also glossary in appendix.

pose a challenge for regulators. If an offshore asset in one country is connected to a hub in another and then to multiple onshore locations, how should this connection be remunerated? At the same time, unbundling requirements pose a challenge to competitive developers of infrastructure. On the other hand, in the accompanying Working Document of the EU Strategy on offshore renewables it is stated that for offshore grids alternative models to the traditional TSO model can be applied while fully complying with unbundling rules and avoiding incentives for discriminatory behaviour [4]. Grid connection must be provided non-discriminatorily to all users. In this context new centralised codes and standards supporting the non-discriminatory common approaches for offshore interfacing are an important area to be developed. These provide important clarity over what assets need to do, how they are operated and managed which in turn lower investment risk, and help frame the nature of investment, see also [8].

Given the anticipated total funding requirement and the complexity of meshing grids, we may anticipate a potential shift in equity ownership from TSOs to new parties (both regulated and non-regulated) entering the offshore grid infrastructure market. These are both strategic and financial infrastructure investors. It may be in the form of partial or complete asset ownership. Whilst the scale and cost of these new HVDC networks and their available flexibility in interfacing TSO areas may drive different and new asset ownership models, technically these DC networks need to be able to operate as one DC system with one operational paradigm which provides security of supply to all, and does not result in its operation favouring individual connections or TSO areas over another. Asset ownership should therefore ensure it complements efficient operation.

Where the revenue streams are not based on a nominal return on investment for the total grid infrastructure (a regulated income for specific infrastructure), the definition of revenue streams becomes important as this defines the Return on Investment for the potential investors. However, in the application of new technology, investors are likely to require protection from failure. "Failure" may represent not just equipment failure, but also failure to deliver assets to conform to a given intended form of operation. Thus, it is most likely that investments in the newest and unproven technology will require Government and EU support to de-risk the investment. It is also challenging to include the risk of delivering such assets to the planning and operation of a larger network.

De-risking includes short term mitigation in case of failure, marginal cost increases required, e.g., for bypass of new equipment, additional protection equipment, additional costs required to test multi-vendor solution testing and implementation, etc. If the assets are later proven to work, there may be consideration of refinancing the assets. For (partially) stranded or unused assets, a method is also required to minimise (financial) impact on investors.

2.2 Magnitude of an Example FOAK HVDC Component Investment

The size of investment for initial FOAK projects may be high and outside many individual National and International support schemes, requiring different streams of funding.

All projects have to fulfill the grid codes¹¹. In terms of system protection, there are different options proposed, e.g. full-bridge converter-based solutions or solutions using DC circuit breakers (DCCBs), and these need investments. As a simple and relatively "cheap" example we use a case study made in PROMOTiON. In order to implement MTMV-systems there is an identified need for DC Switching stations

¹¹ Today only available for AC side

[9][10][11][12], to switch between equipment and routing. This is anticipated to precede testing of bypass solutions utilizing (DCCBs). As a project cost example, within PROMOTioN [13] an opportunity was evaluated to connect two HVDC cables on the DC side. By using such a bypass arrangement, the aim was to leave proposed infrastructure in place in case of project failure, and to add a DCCB-protected HVDC link around the various converters. This opportunity was onshore and therefore there was no need for expensive platforms and additional offshore infrastructure. The estimated investment was approximately €17 million (mechanical DCCB) to €58 (hybrid DCCB) million [14]. These costs were in some cases synthesized using assumptions and may require review as more data becomes available which will be refined at procurement. Savings on size and ratings of planned investment were not changed, but in a commercial situation there would be scope for savings in the size and ratings of planned converters.

However, the above example assumes testing a single piece of new equipment that connects two HVDC projects from different vendors. Under EU procurement law multiple vendors, where available must be able to participate in the procurement process which makes steering a project more complex. The costs of the underlying equipment (and supplier development cost) are probably too high to provide multiple suppliers for a single project. Therefore several (incremental) projects may be needed to fully test different vendor combinations [3][15].

Positioning a link offshore would require materially more investment in platform infrastructure and connections. While the subject in earlier projects is offshore multi-terminal [READY₄DC scope is both offshore and onshore] and meshed grids, it may be perceived prudent to consider initial testing of DCCBs and other equipment onshore.

In the example proposed above, over the projected lifetime of the device, the proposed investment provided a positive economic as well as social benefit. Yet the risk of the project remained too high for stakeholders in this specific or in a parallel equivalent situation to consider supporting such a project (compare block survey in Section 4).

Notably, the DCCB example put forward here is just one option playing a role in the operation and protection of MTMV HVDC systems, with more options including, e.g., full-bridge converter-based solutions [15] and more¹². These new technologies will need FOAK investments. It is noteworthy though that the above DCCB FOAK example with favourable conditions (onshore, one new component, fall-back option available) is hard to justify.

2.3 Potential Subsidy and Funding Options for FOAK and Early Development Projects

Considering the level of investment required and the risks related to such innovative technologies financial and political support from national governments and the EU will be essential for the first projects. There are several EU programmes that they could potentially be used to fund part of a first-of-a-kind project in MTMV HVDC technology as shown in Table 1..

¹² For a holistic (not technology-specific) interconnection approach, many technologies have to be considered. These furthermore include, e.g., large H2 generation units near the onshore HVDC asset. These can reduce the need for DCCBs as the offshore HVDC converter can trip under DC fault scenarios, while the wind power generation (also during no wind condition) is replaced. Amonia or H2 generation may be required to ensure the security of supply to support the grid under contingencies. The cost for such generation has to be weighed against cost for a DCCB offshore.

TABLE 1

Overview of relevant EU programmes

	Horizon Europe Cluster 5	Innovation Fund	Cohesion Policy, (ERDF, ESF, Cohesion Fund and Just Transition Fund)	Connecting Europe Facility (CEF) (Transport and Energy)	InvestEU Programme	Recovery and Resilience Facility
Type of instrument	Grants	Grant and project development assistance	Grants, loans, guarantees	Grants	Fund: Budgetary guarantee (Debt and equity financing); advisory/project development support under the Advisory Hub	Grants and loans
Focus/Project Lifecycle stage	Research and Innovation	Scaling up innovative clean tech and to finance the demonstration of first-of-a-kind highly innovative projects	Co-financing direct investments Supports projects at any stage of the value chain, depending on the specific priorities/objectives selected by the programmes and ultimately to the calls for projects.	Mature technologies	Leveraging (mainly) private investments economically viable projects with high EU value added Research and innovation, demonstration, deployment of mature tech	Co-financing direct investments for technologies in all stages of development

CEF Energy aims to enable PCIs and to support the development of high-performing and well-interconnected trans-European networks.

InvestEU Fund, as the centrepiece of the InvestEU programme, provides risk-bearing capacity to support financing for investment in the EU priority policy areas.

The Innovation Fund is designed to scale up innovative clean tech and to finance the demonstration of first-of-a-kind highly innovative projects. For the time being, one of the criteria for award is the level of CO₂ avoidance, making it difficult accessible for an enabling technology.

Horizon Europe Cluster 5 aims to fight climate change by better understanding its causes, evolution, risks, impacts and opportunities and by making the energy and transport sector more environmentally friendly, more efficient and more resilient.

Forward grid planning is perceived by both TEN-E and the EU strategy on offshore RES as essential to optimise long term asset usage. Incremental building and investment in early MTMV Potential asset owners of HVDC grid elements or systems require a positive cost benefit. Early grid elements will need to consider the lifetime use of the asset and as a part of the holistic system. In the case of anticipatory assets, usage will change over time. Minimising risk is vital: e.g., a simple use case such as described in Section 4.2,

onshore installation, the funding of hardware-in-the-loop (HIL) replicas by the regulator, etc. These early or FOAK assets may also require positive backing by international stakeholders like ENTSO-E, vendors, and national and international governments, e.g., for connection of non-national or 3rd party assets to national infrastructure. With new technology, the additional cash flow timing risks further EC and national funding may be required to kick-start such projects.

The most likely finding for a FOAK will be with EU CEF/PCI support. Under the EU regime to 2020, the FOAK project needs to be classified as a “project of common interest” (PCI) by the EU. A PCI is open to funding under the Connecting Europe Facility (CEF) [16]. The CEF system has a combination of Debt and Equity instruments and acts as a short-term funding for projects. Questions still remain how suitable these instruments are especially when the value of an asset may change over time a so-called anticipatory asset and where assets may have a different value for different potential owners (multi-lateral or bilateral projects).

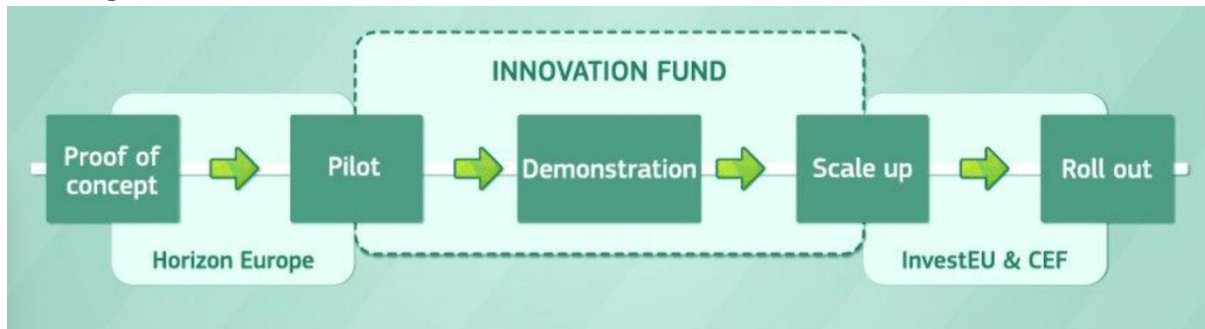
Anticipatory investments will be needed to, e.g., accommodate future grid expansion or for de-risking in multi-vendor setups. The latter is especially important in FOAK projects. Today, point-to-point single-vendor HVDC systems are thoroughly optimized in terms of efficiency by one party (the vendor). Multi-vendor setups, however, need a combination of different technologies which in turn will require hardware over-dimensioning for de-risking. This could include, e.g., the cable ratings, or the converter semiconductor limits (e.g., current and voltage capability). Where over dimensioning is necessary, EC or national support may be necessary, to extract the risk from the project for more commercial investors. Within Horizon Europe, valuation of potential projects has 3 pillars: Excellent Science; Global Challenges and European Industrial Competitiveness; Innovative Europe. Funds (totalling EUR 95.5 billion) will be allocated based on factors related to these pillars. Energy transmission falls under the cluster “Climate, Energy and Mobility” and is a core area of interest. There are similar and parallel initiatives in the UK and Norway to promote innovation (albeit with different budgets). Until the UK has formalised its participation in the Horizon Europe Programme UK companies may apply and their costs will be remunerated by the UK Research and Innovation (UKRI) programme. Specifically for this sector cooperation and interconnectivity is important for both economic and geographic reasons, and therefore we propose a close monitor of the situation.

The Horizon Europe funding programme continues investment in Global Challenges and European Industrial Competitiveness: Climate, Energy and Mobility. There is a focus on funding high technology readiness level (TRL) projects where (large) infrastructure is industrially tested. In project proposals it is important to take into consideration the factors below as this will influence contract structures with suppliers, and development of intellectual property. It is likely that a budget may cover marginal investment and operational costs. It is unlikely to cover specific additional risks the TSOs and infrastructure investors are taking. In the latest reference [16] pilot and demonstrators (as discussed here) will be in the European Innovation fund, it is still not clarified as to whether funds will cover redundant investments, additional costs specific to broadening the vendor base, etc.

How actual funding of a “real” project will be realized and recouped is still unclear. One idea could be to extend “FOAK” into “FOAK in Europe” for strategically important technologies for Europe. This also could consider technology integration aspects (touching upon, e.g., IP or regulation [3]) that can be different to solutions outside Europe. As time passes, some specific technology deployments elsewhere in the world will become more widespread, and this position may become untenable. Utilisation of this fund for a specific project, may be best achieved with a selection of stakeholders and partners.

FIGURE 2

Funding mechanism overview EU



- 1) European Innovation Council: Support for innovations with potential breakthrough and disruptive nature with scale-up potential that may be too risky for private investors. This is 70% of the budget earmarked for small and medium-sized enterprises (SMEs).
- 2) Missions: Sets of measures to achieve bold, inspirational and measurable goals within a set timeframe. There are 5 main mission areas as part of Horizon Europe.
- 3) Open science policy: Mandatory open access to publications and open science principles are applied throughout the program Factsheet: Open science in Horizon Europe
- 4) New approach to partnerships: Objective-driven and more ambitious partnerships with industry in support of EU policy objectives

Other funds available include EEEF (for energy efficiency), COSME (for SMEs), InvestEU, but these seem more appropriate for smaller enterprises and projects, and not for MVMT HVDC.

In particular, the “Open Science Policy” will be of importance to decide how to combine and share new intellectual property between manufacturers [which new scientific solutions and new IP must be publicly available, and which remains with the IP owners]. This needs to be bridged and is discussed in [16].

Also, if a project is treated as a “normal” project it will fall under procurement regulation that requires open tender. In a test situation, it is attractive to test equipment from multiple manufacturers – and specifically those participating in the FOAK project.

Especially for projects that are very complex, public-private partnership could be a good option for financing and sharing risk. Public-private partnerships include collaborations between government agencies and private sector to finance build and operate projects. Neuconnect, a UK-German interconnector reached a financial close in 2022 under such a scheme [17].

In any case, having a foreseeable-forecastable cash flow is crucial for investors. Given that defining market risk in the energy sector for the long-term can be very challenging, regulatory stability and transparency are necessary to facilitate investments.

2.4 Project Funding and the Long Term

Most infrastructure for electricity transmission is being planned, developed, built and owned by the TSOs in Europe (terms are different but it is essentially classed as Critical Infrastructure and excluded from competition). The interconnectors between countries (including the UK) varies in structure from country to country, either: 1. inside or 2. outside the regulated grid operator remit and structured as private companies. In both cases many have been built by the respective TSOs. Also, there are the combination

of OWF developers and OFTOs (coordinated by the onshore operators (NG, SSEN, SP)). Norway has some HVDC connections to offshore oil & gas platforms built by the oil companies. Some new interconnectors between the UK and Europe have independent private sponsors.

There is a necessity to proceed with more holistic and efficient offshore grid planning, rationalising the use of offshore cable infrastructure (avoiding the “spaghetti” effect). There are more cooperative projects in Europe, still mainly led by TSOs, albeit new initiatives like the energy islands have mixed public-private ownership. While the funding of energy islands has been opened to public-private partnership, the proposals for remuneration are yet to be publicly disclosed. The transmission to shore is anticipated to be a part of the transmission infrastructure and built by the respective TSOs with appropriate cross-border cost allocation (CBCA).

Point to point funding from offshore substation to shore for transmission is mostly single country, with well-established regulation and thus transparent to assess revenue and income. Interconnectors to date have been built based mainly on Congestion Revenues. As the amount of interconnection increases, the (theoretical) congestion will decrease (compare Section 2.1) and there is a diminishing return for increased interconnection and the congestion rents are subject to higher volatility. This discourages interconnection for non-financial aspects such as security, redundancy, etc. Also, in the case of the construction of an MTMV offshore grid, interconnection may be a part of a bigger grid system. Evaluating the congestion revenue may be complex for each individual link. These meshed links may also facilitate longer term international supply contracts and an international energy market²³. When the use of a grid element is offshore to 2nd country onshore, Offshore to Offshore across international borders or crosses multiple borders, it becomes an interconnector or a hybrid interconnector/evacuation cable. Regulation and remuneration for these assets will of needs differ from current models, but also potential shareholders. Funding these by an asset owner will depend on purpose, potential revenue streams, availability, and management of the asset. As a meshed grid evolves and each element has new functions the management of this may become complex and revenues mixed. This may result in a plea for limited or national shareholders (e.g., national TSOs, an offshore TSO, other specific structures) to avoid financial control issues – but other structures may speed or facilitate a build out. While potentially more expensive these are possible if properly regulated. Most TSOs have communicated a desire to retain ownership of the grid assets. However, with choices to be made by National Governments and the sheer size of total investment, Governments may be open to new or public-privately funded models similar to the TenneT structures in Germany. While a fully private initiative remains theoretically possible, it will require full cooperation with the relevant offshore grid operator [16].

Today, there are several potential institutional funding sources available. For example, these are investing in Denmark in the construction of the energy islands, the proposed North Sea Wind hub and the UK OFTOs. These experienced and often global companies understand the market (in the UK a number have received pre-qualification for investment). However, given a reasonable opportunity, it is anticipated that funding will be available if required.

Another funding issue will be for payment of the protection and hub equipment required to connect a link to a hub. Who will be responsible for access to the hub, any HVDC bus, protection strategies, etc.? This discussion may become complex where build is incremental and where ownership and responsibility are

²³ We should consider locating wind energy in the best possible locations: e.g. it is known that Denmark has excellent wind generation possibilities whereby it may generate a surplus of wind energy. An OWF developer may consider building a farm in Denmark specifically to supply the Dutch market – and have long term contracts to supply the Dutch market directly through the grid rather than via the Danish mainland grid.

assigned to multiple parties. There may also be technical issues and risks linked to an incremental build out (multi-vendor and equipment generational development over time). CBCA methodologies are available specifically to solve this. The European Union Agency for the Cooperation of Energy Regulators (ACER) has defined this for the energy sector, but this may require revision for incremental development of an offshore grid and consideration is needed in the allocation of costs which may be perceived as needed by one country and unnecessary for the connected country (arbitration methodology). However, over the question remains how to fund so-called anticipatory assets: e.g., if a cable is “over-scaled” it may be used at lower power, there remains a risk of stranded assets that needs to be minimised. Despite these problems, it may be of interest to fund each link as a commercial activity. The regulation, ownership and market model have an influence on how fast the investment can be recovered.

The institutions involved (TSOs, infrastructure funds, offshore wind developers (OWDs)) have funding mechanisms utilizing combinations of equity, debt, (Green) bonds, and other instruments. The TSO structure in Europe is often linked to national ownership, and levels of debt and equity may be linked to Government targets as much as investment need, which may limit investments (albeit cost of debt is probably lower for a nationally owned asset). Also traditionally, the European TSOs try to retain full control of assets, but if the regulatory structure is appropriate, it may be possible to loosen ownership rules to admit more infrastructure investors (compare [7]). While these are unlikely to have an appetite for untested infrastructure, they may be attracted by regular income from the future asset projects. Therefore, the opportunity exists for TSOs to leverage their position providing additional alternatives to funding through e.g., sell down on TSO infrastructure to financial investors. This may give scope for accelerated build out of infrastructure. This is a parallel to how offshore oil & gas projects are financed, where a consortium “evolves” over time from Project Build through early-stage operation to late-stage operation and eventual decommissioning. It is already tested in point-to-point projects in Germany (CIP has invested in TenneT’s Borwin and Dolwin HVDC platforms in Germany). Regulation has opened opportunities in Denmark (the North Sea energy island is funded by a consortium including CIP) and Norway (HVDC lines have been constructed by Equinor and AkerBP connecting oil platforms Valhall and Johan Sverdrup to the Statnett onshore grid). The UK structure also accepts financial ownership of similar assets.

Selling down TSO infrastructure may require quite strict definition of each element in a grid – with identifiable boundaries of responsibility, what substation equipment is a part of the new asset, which is required by the existing infrastructure. There is also the option to split the functions of Service Operation and ownership. This may simplify revenue allocation. Also 3rd party investors will demand a commensurate return on investment. They are less interested in non-quantified benefits. Therefore, for these, the revenue model requires clear definition.

3. INVESTMENT VOLUME FOR OFFSHORE TARGETS AND SUSTAINABILITY OF SUPPLY

Enormous investment is required to build the offshore infrastructure required for full energy evaluation. In this section a “back of the envelope” calculation has been made for total investment in systems. The actual investment in MTMV systems is unlikely to decrease this amount substantially, and required protection is a factor that will reduce any cost advantage – albeit that meshing may only represent 5-10% of total investment costs. These costs are mitigated by the benefits described in Section 2.1.

3.1 Required Investments – A Very Rough Estimate

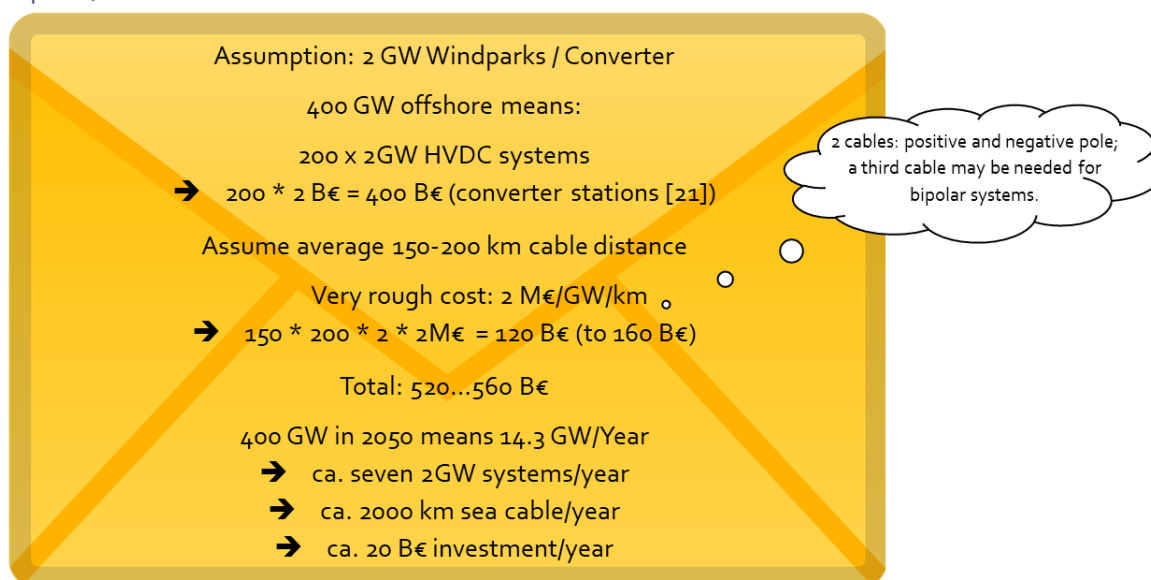
The EU targets 300 GW offshore wind generation by 2050 [4]. The North Sea Wind Summit targets 260 GW in the North Sea by 2050 [5]. Given the rapidly increasing offshore targets, let us assume 400 GW offshore wind generation connected to shore via HVDC. Using contracts for 2GW HVDC systems as reference (only converter stations) [18], the back-of-the-envelope calculation in Fig. 3 estimates the required total HVDC investment costs with app. 520 B€ (converter stations and cables) amounting in investment per year of app 20B€ (if built point-to-point) until 2050.

Additional cost of DC meshing is mainly driven by cable costs and additional space for DCCBs on the platforms. For example, two converter platforms 20 km distance would require (using the assumed cable cost in Fig. 3) $20 \text{ km} * 2 * 2 \text{ M€}/\text{km} = 80 \text{ M€}$ for cables, as well as additional four DC bays incl. DC switch equipment (~20Mio€, not including the additional platform space), thus in total 100 M€ extra for DC meshing (20 km distance). For the same approach with 5 km distance, the extra cost would be 40 M€. In the hypothetical case that each converter platform has one mesh of 20 km distance, the total for 200 converter platforms can be estimated in the range of 5B€ which is negligible compared to the total investment volume. Note, that additional cost for protection has been estimated with 5% (of the total grid cost) for non-selective strategy to 9% for a fully selective strategy using fast DCCBs [19].

Obviously, a proper analysis of the required investments would have to consider many more aspects, e.g., scaling effects. The rough estimation put forward here not meant as a detailed analysis, but rather as illustration of the enormity of the challenges ahead. Notably, the yearly investments (each year until 2050) are in the range of some of the North Sea TSO revenues (e.g., TenneT: 9.8 B€ in 2022; National Grid \$B 20.8 in 2022).

FIGURE 3

Back-of-the-envelope calculation of anticipated investments for offshore HVDC systems (if built point-to-point)



3.2 Difficulties to Ensure Supply Chain and Sufficient Staff

Given this back-of-the-envelope estimation, the following statement is not a surprise:

"Among the key risk regarding T&D investment, supply chain occupied a central position- T&D assets, technologies require a high volume of raw materials-diversification of raw material supply, and stronger supply chains will be crucial." *Investors Dialogue on Energy 2022*

Additional to the blocks for the first MTMV demonstrator in Section 4, the supply chain for the longer term has to be addressed. Compared to the above blocks – that can be mitigated - a sustainable supply chain of materials and goods needed for HVDC installations (multi-vendor or not) has become a big uncertainty.

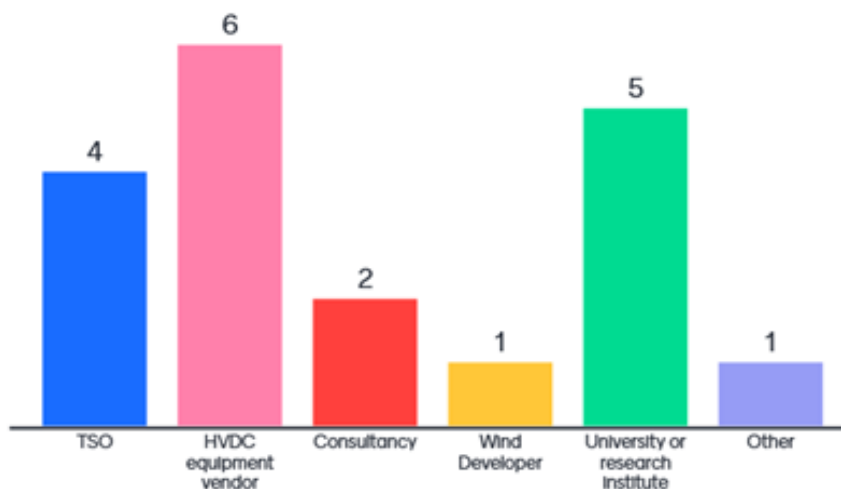
Since the pandemic, economic and political situation (2023) comes with associated new and/or worsened supply chain difficulties and uncertainties, in general it can be assumed that previous reports are not entirely applicable anymore. Still for completeness it is referred to [20][21][22]. Notably, additional to the above challenges in supply and financing, staff shortage in all areas relevant for HVDC technology, is a real problem – in particular taking into account several years needed for education and training on any of the involved sectors:

"The challenges to the supply chain however do not purely reside within production but on the scale of available skilled resources available to the HVDC sector to design, construct, deliver, install, commission and maintain the HVDC infrastructure associated." [20]

A staff scarcity survey was conducted among the members of READY₄DC working group⁴. The individuals were asked to judge the staff situation in their team. The distribution of participants per HVDC sub-sector are presented in Fig. 4.

FIGURE 4

Distribution of survey participants per sub-sector [person/sub-sector]



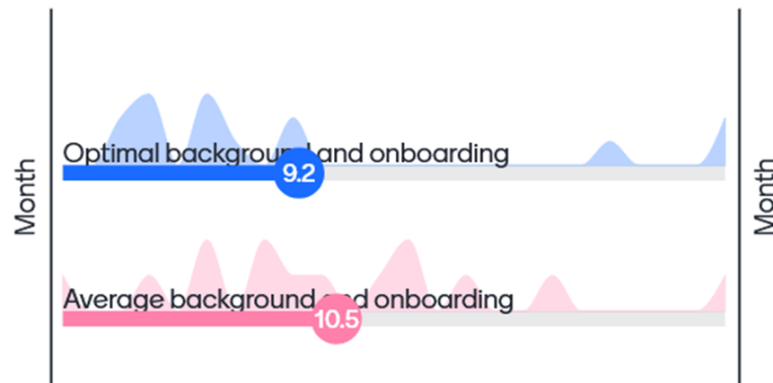
The survey results presented in the following are not sub-sector-specific:

- The teams' workload (during writing of this paper) ranges from 60% to 250% with
 - 15% of employees judging their team being loaded 200-250%
 - 20% of employees judging their team being loaded 130-150%
 - 41% of employees judging their team being loaded 90-120%
- More than half the teams are currently hiring 20-40% of their size.
- One year from now, most teams need 0%-60% extra staff.
- Five years from now, the teams need between 0%- up to more than 200% extra staff.
- It is getting harder to hire.

Furthermore, the time (in months) before a new colleague can work independently is judged between 9.2 (optimal) and 10.5 (average) months as shown in Fig. 5.

FIGURE 5

Time until a new co-worker can work independently (scale from 0 to 24 months)



Among the proposals to improve the staffing situation in the HVDC sector, (1) more interaction between universities and companies, and (2) dedicated HVDC education or doctoral training programs were found to be the most promising. Furthermore, the companies must actively search for suitable recruits. On the short term, also a re-positioning of existing staff or making existing work processes more efficient can help deal with the workload. Still, the HVDC sector acknowledges that they will only be able to support the offshore renewable targets if enough qualified staff is available.

4. BLOCKS FOR INVESTING INTO THE FIRST MTMV HVDC DEMONSTRATOR

While funding options are available, the European HVDC sector perceives several blocks that delay or complicate the investment decision for the first MTMV HVDC demonstrator in Europe. A survey (not the same survey as in Section 3) among the READY4DC WG4 members was conducted to identify and prioritize these blocks.

4.1 Survey Results

First, the WG members were separated into the stakeholder groups “TSOs”, “vendors” (with academia and consultants equally spread over these groups). These two groups then conducted separate brainstorming on identifying blocks, resulting in ten topics identified by the TSOs and five topics identified by the vendors. After that, the complete list of blocks was ranked by three mixed groups (with mixed stakeholder representatives) in terms of importance and difficulty as indicated in Fig.6. Only the blocks that were identified as both important and difficult were kept for more detailed discussion.

The blocks perceived as difficult and important for the first European MTMV HVDC demonstrator investment decision are summarized in Fig. 7, where 0 indicates low perceived criticality and 6 indicates high criticality. Notably, while there are minor absolute differences in the perceived criticality, in relative terms, “Unclear agreements and division of different parties” and “national vs. cross-border project specificities” stand out.

FIGURE 6

Template for block prioritization

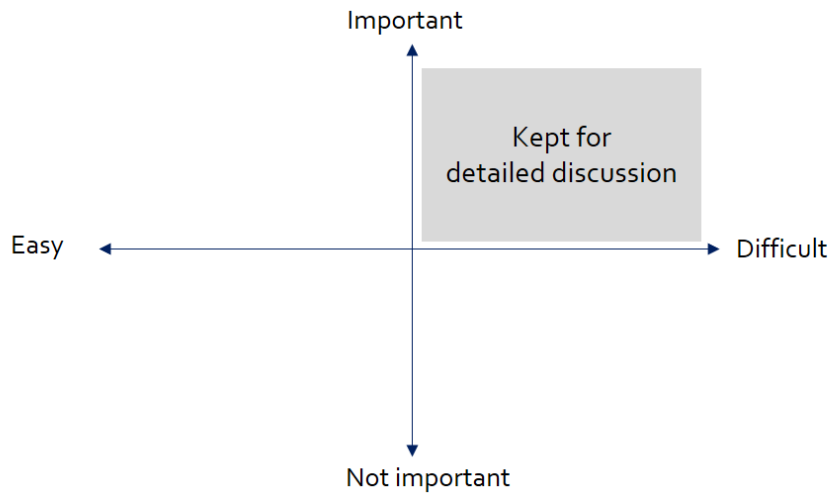
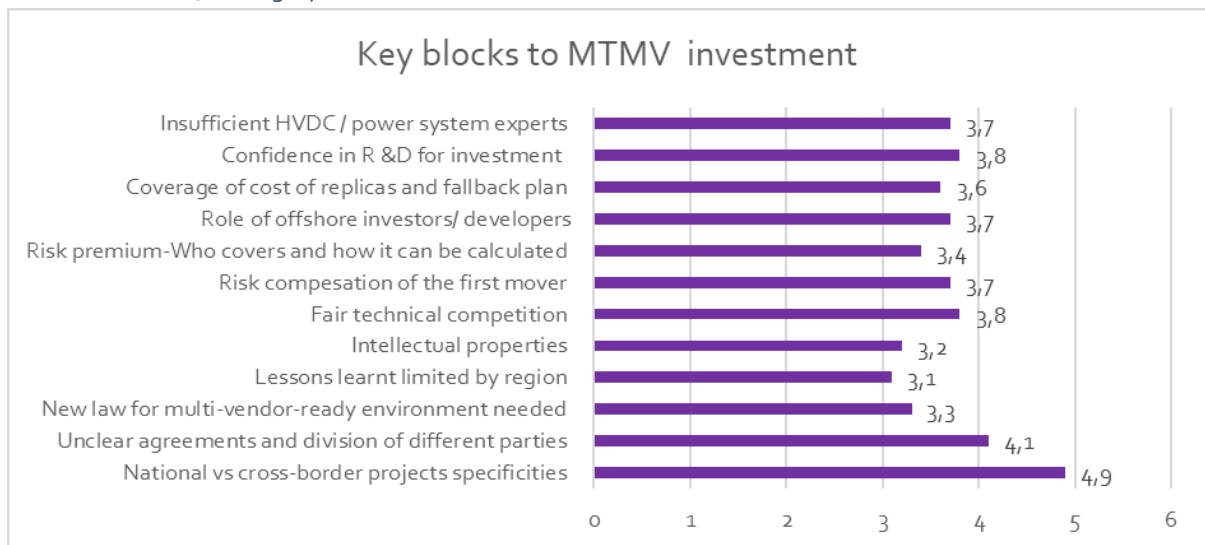


FIGURE 7

Survey results on key blocks for the first MTMV HVDC demonstrator investment
(0 = not critical, 6 = highly critical)



Furthermore, when the blocks are sorted by categories “organizational”, “economic”, “technical”, and “overall sector development”, as shown in Fig. 8, the following can be noted. The technical risks are covered by one topic, namely “Confidence in R&D for investment”, whereas on the other hand the organizational and economic blocks include 6 or 5 topics respectively, confirming that an MTMV HVDC investment decision is perceived as being less about technology but more about clear organization and risk compensation.

FIGURE 8

Blocks per category



4.2 Detailed Discussion

Of the identified 12 difficult and important aspects blocking an investment decision for an MTMV HVDC demonstrator (Fig. 8), the eight most critical are discussed here. Notably, *“Intellectual property”*, *“Lessons learnt limited by region”*, *“New law for multi-vendor ready environment needed”*, and *“Risk premium – who covers it and how can it be calculated”* were perceived as less critical in relative terms, however, with a small absolute difference compared to the discussed blocks.

“National vs Cross-border projects specificities” is perceived as one of the most relevant blocks for investment in the first MTMV demonstrator (Fig 4). Different local laws that have requirements, which do not fit together, is one of the main risks associated with this block. Additional challenges can be found with regard to market design due to technical implication, the need of well-implemented cost-benefit allocation between countries, different parties, and finding possibilities that combine all legal requirements. A way of mitigating the block could be to establish a multilateral agreement between the countries involved in the project, and that implies developing different types of regulations, cost-benefit analyses and a fit-for-purpose market design. For this, it is also important to have dialogue between TSOs, vendors and wind developers considering the defined relationship between them in terms of solid procurement to also facilitate proposed market development and define clear responsibilities from different parties in the market. In addition, to enhance the formal dialogue between developers and TSOs, it could be necessary to define additional functionality in terms of remuneration to the developers.

“How can three European vendors be included while allowing for maximum technical advantage and competition?” was perceived as second-most important block. The main risk associated with this block is to exclude vendors that are not part of the MTMV demonstrator project. In particular, the risk is identified that a development in a specific project context (which will be realized after the common development phase) - and not in a generic demonstrator project - the vendors which are involved in this development work will not be allowed to bid on the following building/execution phase for this infrastructure project. This is not a problem if a HVDC system owner is tendering a whole project which includes development and execution phase in one bid!

More generally speaking, there could also be the possibility that the first vendor that was part of the project builds the first part of the system and, therefore, could have the advantage to build the second one. Similarly, another challenge to overcome is to achieve the maximum performance with the maximum number of competitors with the lowest cost and assure that there is no violation of competition law.

Finally, the timing of the bids is also a block to be considered, and with it raises the question *what if two independent tenders end up with same vendor?* According to the vendors, it could be possible to learn from MTMV HVDC projects in Asia; however, information is hardly accessible, and the general conditions of Asian projects are different from Europe's, e.g., in terms of law, market type, and context. In order to mitigate the challenges, the following actions could be taken: Consider the ways that are being developed in InterOPERA - which includes intellectual property aspects and information sharing. Public tendering and respects rules in terms of competition, decide the number of vendors at the first stage according to the location of each vendor and check the legal barrier for vendors to cooperation within a consortium to build the first MTMV project. In addition, this is also an important block that needs to be addressed in order to achieve complete transparency and open access for all vendors to minimize the risk from an investment point of view.

Another important block regarding investment is related to the need for the “*confidence in R&D for investment*”. Vice-versa, the risk for R&Ds is to develop products and services that the market is not asking for and that could lead to a waste of time and money. It is important to find customers that are committed to build or buy a certain technology and have a clear idea of capitalizing on returns. The challenges associated with this block are for example, that different parties have different needs, and it is difficult to invest in customizing the projects and assure some similarity without having grid codes. In addition, good cooperation with vendors and control developers is necessary to guarantee clear responsibilities and how and what to build to not affect the DC grid stability since control and protection systems and their implementation are specific for every vendor. In this sense, functional specifications are needed. Finally, considering the role of Wind Turbines Vendors, the OWFs may be asked to provide grid-forming capability. Thus, if this impacts the turbines' design and cost, it may be that the farm developers would ask for additional compensation. Therefore, to reduce the risk, a suggestion for vendors and wind developers is to sign a contract for a real and specific project or even better several projects to increase the maturity and reliability of the technology.

Next, the block “*Risk compensation for the first mover*” reflects that the first movers face the risk of project delays due to unexpected problems during project implementation. Challenges in this regard include appropriate margins within the schedule and limiting penalty payments to a fair level. From the vendors' perspective, a joint effort from all stakeholders is crucial to realize the first successful demonstrator projects, which can provide sufficient assurance. The wind developers add the inclusion of risk compensation to create a risk appetite as a challenge. As the TSOs point out, it is questionable that the few countries realizing a first MTMV HVDC project should cover all the cost and risk while possibly enabling advancements benefiting the entire EU. Possible resolutions might be a legal liability exception in case of delay or failure of a first mover project to reduce the risks and anticipatory investments.

Another block for an MTMV investment decision is the “*Role of offshore investors and developers*”. The wind developers point out that risks arise from the OWDs not being involved in the early phases of a project since they cannot make relevant contributions to parts of the design from their perspective, e.g., voltage levels. In particular, it depends on the country whether OWDs have an influence on design specifications. For example, in the UK, the OWDs are involved in the development and design process of HVDC substations, whereas in Germany, they are not. In the Netherlands, OWDs participate in

consultations to influence project development. The unclarity of the OWDs' role in development poses a challenge for MTMV HVDC projects, potentially involving multiple countries. Public consultation involving bilateral dialogue between all parties during all project phases could be a possible resolution; the OWDs should be able to participate in such consultation before essential design parameters are determined. The TSOs see an additional challenge in the definition of grid forming. While the TSOs also see the cooperation of all parties, including the OWDs, as a solution approach, they also suggest introducing and harmonizing grid codes that map the discrepancy between different requirements. The vendors state that they rely on guidance from the TSOs and the OWDs and that the guidance depends on the needs of different countries, leading to the urge for functional requirements.

Next, the investment block "*Insufficient HVDC / power system experts*" is discussed. From the vendors' perspective, there is a risk of development delay due to a lack of resources. Missing experience in the HVDC field leads to the additional effort of investigating topics from scratch. On-site training of experts remains challenging as it might take years. The wind developers add that the HVDC sector needs to gain an understanding of how parties in different legal and market conditions can collaborate and be coordinated and get insights into design decisions and challenges for de-risking projects. Increasingly motivating students to join the HVDC world should be focussed on mitigating the described risks. The TSOs perceive final stage management as a risk, as managing an MV environment poses a challenge during a lack of experts. Further, procurement strategies in an MV environment need to be developed. Approaches to mitigate the block include implementing strategies to attract and hire more skilled workers in HVDC and clarifying the requirements of operation and maintenance in MTMV systems.

Lastly, the block "*Coverage of investments, cost of fallback plan and replicas*" is analyzed. According to the TSOs, the investors face the risks of overinvestment in additional simulation capacity and stranded assets. Arising challenges are implementing a fallback plan in parallel to an MTMV project and selecting a project where other grid elements do not necessarily depend on the developed interconnector/HVDC system. Further, the high expenses for simulation tools need sound justification for coverage. Approaches to cope with the described risks and challenges are improving the funding environment, e.g., by more flexible use of grants and developing a regulation business case [23][24][25]. Regarding the cost of replicas, the vendors remark that replicas are not part of the core business and that the required effort for building and testing such control & protection system is similar to a full HVDC project. Therefore a development towards offline testing may be beneficial given the upcoming volume of HVDC projects.

5. FINANCIAL DECISION-MAKER EXPERIENCE

Without claiming to cover all financial decision-maker experiences, this section summarizes some aspects that were obtained through interviews and brainstorming sessions.

5.1 Investor View

In general, investors consider several aspects before making a financial decision. These aspects concern (1) Technology, (2) Equity financing and bankability, (3) Regulatory environment, (4) Supply chain and contracting, and (5) Revenue. In terms of renewable energy investments with new technology, it can be noticed that the appetite for investments has grown – as compared to earlier years when only proven technology would have been bankable. Still, innovation funding is seen as a necessary tool for first demonstrators. Regarding the regulatory environment, it can be argued that it does not have to be the

most favourable regulatory regime as long as it is stable (“predictability of regulatory regime”). For supply chains and contracting, questions about what protection and warranties a contractor offers (even for unproven technology) are relevant. Finally, regarding the revenue, e.g., fixed-income tariffs are not necessarily the only option if a project’s long-term revenue perspective is promising. To reach that conclusion, transparent risk analysis and de-risking are seen as key. Furthermore, it is important that investor concerns are considered.

Examples of de-risking of other renewable energy technologies (than MTMV HVDC) include, e.g., floating offshore platforms that were first demonstrated downscaled using a mix of EU innovation funding with equity investment, after which a full-scale project was developed that was officially bankable with some EIB funding. Larger battery storages, for example, can use a 5-year contract with grid operators leading to financial decision-making based on partial feasibility – an approach that can make sense in an uncertain market with a promising long-term perspective.

While down-scaled demonstrators and partial feasibility are not applicable to MTMV HVDC systems, here, a reasonable oversizing for better availability, as well as fall-back options to single-vendor point-to-point systems appear as useful proposals.

5.2 TSO View

For TSOs, political support of specific grid development projects and investments in those is crucial. As TSOs are regulated entity due to their characteristic as regional natural monopoly, the regulatory framework defines the requirements for their build-out activities. The administrative framework conditions are driven by political guidance.

Some TSOs are facing lacking political support for investments in new and innovative technology, which only realize their benefits over time. HVDC grids and offshore interconnection have shown net benefits, compared to radial AC connection, in various studies. Results, first experiences and learnings shall be shared among the TSOs.

In order to invest in projects, that only show benefits over longer time, and assets, that are future-proofed for a MTMV system, TSOs must be allowed to do so called anticipatory investment. Here, TSOs invest in assets, which anticipate future needs to avoid stranded assets in the future.

It must be ensured that the national regulatory set-ups allow for sufficient flexibility and adequate parameters in the CBA project assessment and investment can be recovered e.g., via grid tariff although the full range of benefits do not materialize yet (compare also [26] as example analysis for a specific region).

Good examples can be found in the Maritime Spatial Plan of Germany, which states, that all future offshore grid connection platforms shall be designed as hybrid-ready. To speed up the development process the German Offshore Act foresees TSOs to plan and develop the grid connection once the areas for offshore wind are assigned. In the Netherlands the TSO is allowed to build slightly larger platforms to ensure that additional space for extension is reserved.

To develop a meshed offshore grid with MTMV interconnections requires a massive amount of investment capital will be necessary. The opportunity to construct MTMV connections may provide opportunities to save or delay investments and may provide operational and commercial benefits, but overall will not materially impact the overall grid investment cost. The availability and accessibility of funding differs between TSOs, also depending on their ownership structure. Especially when accessibility to financial

markets is necessary as funds need to be obtained externally, it's important that the risk structure and class of the project to be funded is reflected in its potential yield. When innovative technology is applied and new solutions are tested, various risks occur that increase the risk profile.

5.3 Wind Developer View

When building the offshore HVDC infrastructure it is important to consider the revenue stream for the offshore wind developers. The visibility of the revenue stream is determined by the regulatory framework. Therefore, having a clear regulatory framework on ownership, governance, and operation issues relating to infrastructure is an essential enabler. Cost-benefit and cost-sharing practices between stakeholders should also be defined clearly.

Without deciding whom will build the infrastructure or own it, an important question is who will be the operator. Keeping the onshore TSO as offshore grid operator is one option but is not seen as an ideal solution from the wind developer perspective. For an offshore wind owner, it is desired to sell their power to the highest price zone, while the onshore TSO may have other objectives. This will have both financial and security of supply amplifications.

Offshore wind owners would not be interested in a solution that will impact their revenue. Consequently, some new form of revenue should be in place to attract the generation owner. This touches upon questions whether offshore grids really need to be built with N-1 design for which the associated cost can be hard to justify. Alternatives can be to, e.g., allow converter trips while keeping it under critical generation disconnection.

6. PLAN TO UNLOCK INVESTMENTS

Even though unlocking investments appears to be more about organizational aspects than about technological aspects, still technology de-risking must be included in a MTMV project as pre-condition for investments. This technology de-risking includes multi-vendor HIL testing using replicas as presented in the READY₄DC companion whitepaper [1]. Furthermore, liability questions have to be solved as presented in another READY₄DC companion whitepaper [2]. Fall-back options could be a suitable approach to MTMV where a system is split into a "core task" (e.g., wind energy to shore) and "extra functions" (MT and/or MV), for example using a DC-connection for parallel point-to-point HVDC links. If in such a setup interoperability does not work day one as expected, the fallback options are separate single-vendor systems and the first demonstrator would not depend 100% on its multi-vendor aspect as necessary condition [2][3]. Similarly, technological de-risking should be addressed with separate "crucial" (mandatory) and "nice-to-have" (performance-improving) functional specifications as discussed in the third READY₄DC companion whitepaper [3].

Regarding the organizational aspects underlying an investment decision, it can be observed that political support (such as is the case for energy islands in Denmark) appears to boost the decision-making for a first (potentially multi-vendor) multi-terminal HVDC demonstrator. If a strong HVDC industry and government (financial) support is available - such as the case in other initiatives and industries – also MTMV HVDC demonstration projects will appear. This political support must be complemented with a stable regulatory regime, a simplified permitting (compare Hydrogen permitting in Germany), innovation funding, and a transparent process including all stakeholders.

7. CONCLUSION

This whitepaper presented and discussed several aspects regarding unlocking investments for the first full-scale MTMV HVDC systems demonstration and beyond. Firstly, there are funding mechanisms available for such a FOAK demonstrator, however these could be improved and/or simplified from an administrative viewpoint. The view of the HVDC community (that contributed to this whitepaper) is that financing a FOAK demonstrator is less about technology maturity and more about clear organization. This view aligns with investor interviews. Advantages of MTMV HVDC like higher grid availability and accordingly higher RES penetration, flexibility, redundancy etc. have been addressed. Looking ahead, this paper gave a rough back-of-the-envelope style idea of the enormous investments needed in offshore HVDC infrastructure. This challenge was put into perspective with an analysis of the pressed staffing situation in the HVDC sector. Finally, while it is neither possible nor necessary to find a one-fits-all approach to financing MTMV HVDC projects, a need is raised for (a) changes in regulatory regimes to allow anticipatory investments, and (b) more widespread political support for development of MTMV HVDC systems.

ABBREVIATIONS AND ACRONYMS

	Text
ACER	Agency for the Cooperation of Energy Regulators
CBA	Cost-benefit analysis
CBCA	Cross-border cost allocation
CEF	Connecting Europe Facility
DCCB	Direct current circuit breaker
EEZ	Exclusive economic zone
EIB	European Investment Bank
FOAK	First of a kind
FSD	Fast separation device
HIL	Hardware-in-the-loop
HVDC	High-voltage direct current
MT	Multi-terminal
MV	Multi-vendor
MTMV	Multi-terminal multi-vendor
OFTO	Offshore transmission owner
ONDP	Offshore network development plan
OWF	Offshore wind farm
OWD	Offshore wind developer
PCI	Project of common interest
SMEs	Small and medium-sized enterprises
TRL	Technology readiness level
TSO	Transmission system operator
TYNDP	Ten-year network development plan

GLOSSARY OF TERMS USED

	Meaning
Anticipatory Investments	These are investments in assets built that are scaled larger than for their initial purpose and as such anticipate future expansion. E.g. a 2 GW point-to-point cable may be laid for a 1GW offshore wind development, in the knowledge that a second wind park will be constructed later delivering a further 1 GW of power.
Bidding Zones	Bidding zone is the largest geographical area within which market participants are able to exchange energy without capacity allocation, i.e. this defines areas or countries where the energy price is constant.
Capacity-based	Capacity-based revenues are based on provision/availability of cable capacity for the potential transmission of power.
Congestion revenue	<p>Congestion revenues are dependent on and generated by the existence of price differences between markets at either end of an interconnector between 2 bidding zones.</p> <p>All interconnection capacity is allocated to the market via market-based methods, i.e. auctions, and the trading arrangements on electricity interconnectors are governed by Access Rules and Charging Methodologies as noted in each interconnector’s licence.</p>
Cost Benefit Analysis	<p>Cost benefit Analysis is a general method to evaluate a project. While the method and certain factors are potentially different for each stakeholder, the evaluation of project should be the sum of the discounted cash flows over the lifetime of an asset. In terms of the incremental build of a grid, the benefits (revenue streams) may change over time.</p> <p>ENTSO-e has developed a more nuanced CBA methodology mentioned in Section 2.1 which includes additional non-financial benefits, which are evaluated but are not quantified. These may influence a TSO decision to build an asset.</p>
Flow-based	Flow-based revenue would be based on the actual power flow transmission through a cable asset. At present this is not used as a remuneration method.
Grid element	Traditionally, HVDC infrastructure has been constructed as semi-closed systems (point to point connections). Interaction with other power systems has been only on the HVAC side. In the future MTMV world we anticipated smaller and different grid elements to be considered, each end of a point to point may be from a different vendor, switching stations and protection elements. A Grid element is a single or group of these individual grid components.
Grid forming	Grid Forming is the ability to perform a decentralized “black start” of a grid, rapidly and safely – crucial for the ability to stabilise grids where a base load with inertia (think of coal gas or nuclear) is no longer available. Market models are now evolving to enable monetization for this crucial capability.
Grid resilience	The resilience of a grid has no exact definition. It includes the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents. If extended to Renewable energy generation, it requires the grid to operate where supply is distributed and potentially irregular.

Grid stability	Grid stability is the ability of a grid to maintain a constant voltage and frequency where both power infeed may vary, and consumption may vary.
Holistic planning	This refers to a system view of a grid covering all or a section of the region. The objective of a Holistic planning would be to predict a potential end situation for a grid requirement. It may never be perfect, but should reflect long term infrastructure needs (30+ years)
Hybrid Assets	Hybrid assets are those with multiple purpose. Currently the EC defines, regulates and remunerates assets based on their purpose, e.g., for evacuation and for interconnection. In the future, it is anticipated that transmission assets may be multiple purpose whereby either new revenue streams need definition or multiple revenue streams will be available, but which need to add to a commensurate remuneration for investment in the asset.
Incremental build	Incremental build is how one anticipates that a grid will be needed in both the short term but also in the long-term holistic plan. The incremental build should reflect the anticipated functional needs (rather than the short-term requirements).
Merchant Interconnector	A Merchant Interconnector is a commercial interconnection between two bidding zones. Here the revenue is determined by commercial flows of power through the cable. In most cases this results in congestion revenue.
Regulated Revenue	The regulated revenue is revenue defined by the national regulator and paid for transmission infrastructure
Utilisation based	Utilisation-based is similar to and may include “flow based” but it may be related to time in use rather than physical flows.

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APPENDIX

As a continuation of Section 5.2, further, more detailed, aspects were raised by the TSOs:

- Currently, in most countries no feasibility study (technical viability and positive CBA) or project pipelines are available; these needs to be developed as these are the basis for investment decision; the precondition for an investment decision is evidence for net-benefit of interconnection project.
- Holistic grid planning processes need to be further developed.
- Higher cost is feared for first demonstrator compared to radial connections; a positive CBA not always assured; higher cost risk also occurs due to potential higher unavailability of connection and remuneration of lacking infeed; however, in the long term, meshed HVDC grids are expected to decrease cost.
- Mandatory cost sharing per sea basin has to be developed.
- Voluntary cost sharing including land-locked countries has very complex administration because all project net benefits have to be included.
- It is difficult to recover cost and raise capital; yield of projects is comparably low with regards to the massive amounts of investment necessary; the yield should address the risk class of the project
- There are differences in availability / accessibility of funding amongst TSOs; for some, funding is an issue as funds need to be obtained externally, some (state-owned) have a less limited access to funding, where the yield is of lower relevance.
- Technology for DC infrastructure is not readily available on the market so far and not ensured that all components work together in a reliable way; in contrast, TSOs are responsible for assuring a defined/max. level of security of the overall system.
- EU funding for new technology and its application should be extended (volume), not only funding for R&D; EU funding should be treated equally by the NRAs of the EU and allow for a level-playing field of all TSOs; An open question is: how do you operationalize the funding? Complex administration to operationalize EU funding vs. little volume.
- The sector suffers from lack of “right” staff, or fluctuating staff; at the same time there is limited availability of experience and expertise with DC grids and components.
- The definition of lacking specification is challenging; there are no structured interfaces towards vendors yet. DC so far was part of the vendor’s sphere, TSOs have only defined the interface towards the AC system; learnings from single-vendor projects will help to identify the specifications, that would work securely together; it is expected that InterOPERA will develop these specifications.
- The dynamics of the power system have been mainly based on basic physics with limited amount of non-linear equipment in the system. The rapid increase in wind power generation, HVDC links, solar generation and batteries is changing the system dynamics. There is a lack of understanding of these new stability phenomena, simulation tools to analyze them, and solutions to handle them. At the same time the secure system operation and power availability have to be ensured; it is referred to READY₄DC WG1 whitepaper [1] **Fehler! Verweisquelle konnte nicht gefunden werden.**
- The definition of liabilities and accountability in case of failure is required; standards will help to set-up a robust project framework which gives visibility of costs and risks; it is referred to READY₄DC WG2 whitepaper [2] **Fehler! Verweisquelle konnte nicht gefunden werden.**