Pan-European interoperable AC-DC HYbrid electricity NETworks

D6.5: Expanding HYNET: Scalability, replicability, and valorisation of DC for pan-European implementation (Initial version)

Lead beneficiary:	BME	**Contributors:**	BME
Reviewers:	CIRCE, NKUA		
Type:	R - Report	**Dissemination:**	PU - Public
Document version:	V2.0	**Due date:**	M18, 31.03.2026.

Funded by the European Union

Project information

Project title:	PAN-EUROPEAN INTEROPERABLE AC-DC HYBRID ELECTRICITY NETWORKS
Project acronym:	HYNET
Grant Agreement No:	101172757
Type of action:	HORIZON Research and Innovation Actions
Call:	HORIZON-CL5-2024-D3-01
Topic:	HORIZON-CL5-2024-D3-01-13 DC and AC/DC hybrid transmission and distribution systems
Start date:	1 October 2024
Duration:	36 months

Document information

Associated WP:	WP6
Associated Task(s):	T6.2
Main authors:	Bence Bereczki (BME)
Contributors:	István Vokony (BME), Bálint Hartmann (BME)
Reviewers:	Marta Bernal Sancho (CIRCE) Maria Teresa Villen Martinez (CIRCE), Leon Nielsen (CIRCE), Pavlos Katsivelis (NKUA)
Type:	R - Report
Dissemination level:	PU - Public
Due date:	2026.03.31.
Submission date:	2026.03.31.

Funded by
the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Document revision history

Version	Date	Changes	Contributor(s)
v0.1	2026.02.02.	Table of Content	Bence Bereczki (BME)
v0.5	2026.02.16.	First draft	Bence Bereczki (BME)
v1.0	2026.03.11.	Peer Review Version	Bence Bereczki (BME) István Vokony (BME) Bálint Hartmann (BME)
v1.1	2026.03.23.	Reviewed Version	Marta Bernal Sancho (CIRCE) Maria Teresa Villen Martinez (CIRCE), Leon Nielsen (CIRCE), Pavlos Katsivelis (NKUA)
v2.0	2026.03.27.	Final Version	Bence Bereczki (BME)

Disclaimer

Copyright message

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Table of contents

Table of contents 4
List of acronyms and abbreviations 6
List of Figures 8
List of Tables 9
Executive summary 10
1. Introduction 12
1.1 Purpose and scope of Deliverable D6.5 12
1.2 Role of scalability, replicability and standardization within HYNET 12
1.2.1 Role of Scalability 13
1.2.2 Role of Replicability 13
1.2.3 Role of Standardisation 13
1.3 Positioning of D6.5 within WP6 and links to other work packages 14
2. Methodological Framework 15
2.1 Adaptation to hybrid AC/DC systems 15
2.1.1 Changing trends in TYNDP of Europe 16
2.1.2 DC connections in TYNDP 2024 17
2.1.3 HYNET Solutions Supporting the Hybrid AC/DC Networks in Europe 18
2.2 Overall assessment approach 18
2.2.1 Literature and SRA methodology review 18
2.2.2 Demonstration-based expert interviews 20
2.2.3 Questionnaire on the scalability, replicability and standardisation of tools developed within the project 20
2.2.4 EU-wide stakeholder questionnaire 21
3. HYNET Demonstrations as Input to the SRA 25
3.1 Overview of HYNET demonstration environments 25
3.1.1 Demonstration 1a Mitigating Frequency issue on Caribbean Island weak grid 25
3.1.2 Demonstration 1b – Contingency issues in a distribution grid facing mass EV integration 26
3.1.3 Demonstration 2 – Montenegro Cross-Border Grid Resilience and Renewable Energy Synergy 28
3.1.4 Demonstration 3 – Norwegian HVDC corridors: interconnections and offshore RES integration 30
3.1.5 Demonstration 4 – Validating HVDC interconnection via real-time digital twin emulation for the Cyprus power system 32
3.2 Diversity of technical contexts 33
3.3 Role of demonstrations in supporting pan-European scalability 35

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

4. Interview-Based Scalability and Replicability Assessment 38
4.1 Interview methodology 38
4.1.1 Questions asked during the interviews 38
4.2 Summary of qualitative findings 39
4.3 Influence of Interview Findings on the Stakeholder Questionnaire Design 40
5. Cross-Demonstration Analysis 42
5.1 Identified barriers and limiting factors 42
5.2 Tool-Level Replicability and Scalability Assessment Across European Power Systems 43
5.3 Power Systems 43
5.3.1 Transferability Across Locations 43
5.3.2 Scalability Potential 47
6. Standardization and Interoperability Perspectives 50
6.1 Alignment with existing standards and initiatives 50
6.1.1 Technology Readiness Level (TRL) 50
6.1.2 HYNET as an agnostic innovation effort 51
6.1.3 Relevant Standards 51
7. Conclusions and Outlook 55
7.1 Key SRA findings 55
7.2 Implications for large-scale European deployment 56
7.3 Future work and finalization of Deliverable D6.5 57
8. References 58
9. Annexes 60
9.1 Annex A – Interview guidelines 60
9.1.1 Project Introduction 60
9.1.2 Scalability, Replicability, and Standardization 60
9.1.3 Regulatory and Physical Constraints 61
9.2 Annex B — Tool-Leader Barriers Questionnaire: Responses from Tool Developers 62
9.3 Annex C – EU stakeholder questionnaire 70
9.3.1 General questions 70
9.3.2 Specific questions towards stakeholders 70

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

List of acronyms and abbreviations

Abbreviation	Description
AC	Alternating Current
API	Application Programming Interface
BESS	Battery Energy Storage System
CBA	Cost-Benefit Analysis
CENELEC	European Committee for Electrotechnical Standardization
CGMES	Common Grid Model Exchange Standard
CIGRE	International Council on Large Electric Systems
CIM	Common Information Model
CSV	Comma-Separated Values
DC	Direct Current
DER	Distributed Energy Resource(s)
DNP3	Distributed Network Protocol 3
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EV	Electric Vehicle
FMU	Functional Mock-up Unit
GPU	Graphics Processing Unit
GUI	Graphical User Interface
HIL	Hardware-in-the-Loop
HPC	High-Performance Computing
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Abbreviation	Description
IP	Intellectual Property
JSON	JavaScript Object Notation
JRC	Joint Research Centre
KPI	Key Performance Indicator
LCC	Line-Commutated Converter
LVAC	Low Voltage Alternating Current
LVDC	Low Voltage Direct Current
MMC	Modular Multilevel Converter
MVAC	Medium Voltage Alternating Current
MVDC	Medium Voltage Direct Current
OPF	Optimal Power Flow
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
RES	Renewable Energy Source(s)
ROCOF	Rate of Change of Frequency
RTDS	Real-Time Digital Simulator
SCADA	Supervisory Control and Data Acquisition
SGAM	Smart Grid Architecture Model
SRA	Scalability and Replicability Analysis
TCP/IP	Transmission Control Protocol / Internet Protocol
TRL	Technology Readiness Level
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
VSC	Voltage Source Converter
WIP	Work in Progress
WP	Work Package

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

List of Figures

Figure 1. HYNET methodology 13
Figure 2. Comparison of energy losses in AC and DC lines 15
Figure 3. Comparison of TYNDP 2022 and TYNDP 2024 Transmission Projects 16
Figure 4. Planned HVDC connections according to TYNDP 2024 17
Figure 5. Microgrid overview in demonstration 1a 25
Figure 6. Existing and planned Italy-Montenegro interconnections 29
Figure 7. HVDC interconnector between Cyprus, Greece and Israel 32
Figure 8. HYNET Workbench 36

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

List of Tables

Table 1. Comparative Overview of HYNET Tools 33
Table 2. HYNET Workbench categories........ 36
Table 3. Qualitative Assessment of HYNET Demonstrations (++ Favourable; -- Challenging)........ 40
Table 4. THEMATIC COMPARISON OF HYNET DEMONSTRATIONS BASED ON INTERVIEWS........ 42

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Executive summary

The accelerating deployment of renewable energy sources, the growing need for cross-border electricity exchange, and the structural shift away from synchronous generation are fundamentally transforming European power systems. Hybrid AC/DC networks — combining high-voltage DC transmission corridors with existing AC infrastructure — are emerging as a central technological response to these challenges.

Deliverable D6.5 presents the Scalability and Replicability Analysis (SRA) conducted under Task 6.2 of Work Package 6 of the HYNET project (Grant Agreement No. 101172757), whose overall objective is to establish a pan-European framework for interoperable hybrid AC/DC electricity networks. The purpose of this deliverable is to systematically evaluate the conditions under which the tools, methodologies, and validation outcomes developed within HYNET can be scaled to larger systems, replicated in diverse regulatory and operational environments, and valorised in the context of European strategic grid development objectives.

The work carried out for this deliverable is structured around three complementary methodological pillars. First, a comprehensive literature review established the conceptual foundations of scalability and replicability and surveyed SRA methodologies applied in prior EU innovation projects, including Platone, IElectrix, EUniversal, RESPONSE, and FLEXITRANSTORE. This analysis confirmed the relevance of the BRIDGE initiative guidelines and the Smart Grid Architecture Model (SGAM) as reference frameworks, while identifying a persistent gap in harmonised SRA reporting formats and hybrid-AC/DC-specific assessment methods. Second, semi-structured interviews were conducted with the leads of all five HYNET demonstration environments — the French Caribbean island grid (Demo 1a), the French distribution grid under EV integration stress (Demo 1b), the Montenegro cross-border transmission corridor (Demo 2), the Norwegian HVDC and offshore RES planning environment (Demo 3), and the Cyprus real-time digital twin platform (Demo 4). These interviews provided structured, evidence-based qualitative insights into the scalability, replicability, standardisation readiness, and regulatory maturity of each demonstration. Third, a tool-level barrier questionnaire was administered to the developers of all thirteen HYNET tools, covering ten thematic categories (C1–C10) spanning software dependencies, computational performance, geographic transferability, data availability, hardware infrastructure, interoperability, knowledge requirements, validation robustness, regulatory alignment, and scalability potential. The work will be extended with an EU-wide stakeholder questionnaire targeting TSOs, DSOs, research institutions, and technology providers. The questionnaire has been designed and is being deployed; results will be integrated in the final version of this deliverable, that will cover the second half of the project as well.

The cross-demonstration analysis and tool-level assessment yield several key findings. The HYNET tool portfolio — spanning planning tools, reliability and resilience tools grid-forming and inertia support tools, and DC distribution tools — demonstrates a generally positive scalability profile at the design level. Planning and stochastic security tools are explicitly designed for large-scale, multi-area transmission systems and exhibit strong transferability across European contexts. Real-time monitoring and control tools show high replicability potential in similar system contexts, but their deployment depends critically on the availability of synchronised PMU infrastructure, robust communication backbones, and configurable converter control interfaces. Distribution-level tools are well-suited to their demonstration environments, but face barriers related to the high cost and limited commercial availability of MVDC protection equipment, particularly DC circuit breakers, which currently represent the most significant hardware bottleneck for broader deployment of medium-voltage DC architectures.

Across all demonstrations, three structural barriers were consistently identified. At the technical level, DC fault management and protection coordination in meshed or multi-terminal configurations remain unresolved at the equipment and methodology level: conventional AC protection schemes are insufficient for hybrid environments, MVDC circuit breakers are not yet commercially accessible at scale, and protection coordination frameworks for multi-terminal DC environments are absent from current standardisation. At the regulatory and market level, grid codes, ancillary service market designs, and cross-border coordination frameworks have not yet been updated to accommodate hybrid AC/DC operation at scale, and this regulatory lag was identified in multiple demonstrations as an equally significant constraint as technical immaturity. At the standardisation level, significant gaps persist in the areas of multi-terminal DC protection schemes, grid-forming converter interoperability requirements, MVDC voltage level harmonisation, and multi-vendor data exchange protocols — gaps that collectively impede the structural integration prerequisites for large-scale deployment.

The HYNET Workbench integrates the validated tools into a modular, vendor-agnostic interoperability ecosystem, enabling consistent and repeatable deployment across heterogeneous European system environments; its architecture, standardisation alignment, and tool migration pathway are detailed in Deliverable D2.3, also due M18.

The deliverable concludes that the HYNET tool portfolio provides a sound and strategically relevant analytical foundation for supporting the pan-European hybrid AC/DC transition, with planning and stochastic security tools ready for near-term wider adoption, and real-time operational tools requiring targeted infrastructure investments and regulatory enablers to reach deployment at scale. Priority recommendations for standardisation engagement focus on multi-terminal DC protection, grid-forming interoperability, and MVDC voltage harmonisation, aligned with ENTSO-E Network Code development and IEC/CENELEC work programme priorities.

This initial version of D6.5 will be finalised upon incorporation of the EU-wide stakeholder questionnaire results, which will provide the quantitative ecosystem-level validation required to complete the SRA framework and strengthen the policy and deployment recommendations.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

1. Introduction

D6.5 adopts a structured assessment logic building upon the outcomes of demo-leader interviews, the SRA methodology, tool developer questionnaire and a planned EU-level stakeholder consultation.

The objective is not limited to evaluating technical performance at demonstration scale – instead, it extends to determining the conditions under which HYNET solutions can evolve into pan-European deployment pathways.

1.1 Purpose and scope of Deliverable D6.5

D6.5 is the strategic consolidation output of Task 6.2 within WP6. It moves beyond demonstration-specific validation to systematically determine the conditions under which hybrid AC/DC solutions developed within HYNET can be deployed across heterogeneous European regulatory, geographical, and operational contexts. Its scope is explicitly broader than technical performance: system integration constraints, interoperability requirements, and gaps in existing standardisation frameworks are treated as first-order assessment dimensions alongside tool-level performance metrics.

The analysis is structured around three principal axes. Scalability is assessed in terms of technical robustness, computational performance, and operational viability when transitioning from pilot demonstrators to transmission- and distribution-level implementations, including multi-terminal HVDC and MVDC/LVDC architectures. Replicability is examined through cross-demonstration synthesis and contextual mapping against European DC corridor developments, enabling the identification of transferable implementation patterns and candidate replication regions. Valorisation extends the analysis toward stakeholder acceptance and contribution to European strategic objectives, including resilience enhancement, renewable integration, and cross-border system flexibility.

The remainder of this chapter is organised as follows. Section 1.2 defines the roles of scalability, replicability, and standardisation within the HYNET project. Section 1.3 positions D6.5 within WP6 and documents its cross-work-package dependencies. The methodological framework underpinning the SRA — including the literature review, demonstration interviews, tool-leader questionnaire, and EU-wide stakeholder survey — is presented in Chapter 2. Demonstration environments and their contribution to pan-European scalability are described in Chapter 3, followed by the interview-based qualitative assessment in Chapter 4 and the cross-demonstration analysis in Chapter 5. Standardisation perspectives are addressed in Chapter 6, and conclusions with deployment recommendations are presented in Chapter 7.

1.2 Role of scalability, replicability and standardization within HYNET

Within the HYNET project, scalability, replicability, and standardisation constitute three structurally interdependent pillars that determine whether validated hybrid AC/DC solutions can transition from controlled demonstration environments to large-scale, pan-European implementation. These dimensions are not treated as auxiliary evaluation criteria, but as core enablers of systemic impact aligned with HYNET's objective of establishing interoperable AC/DC hybrid electricity networks across Europe.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

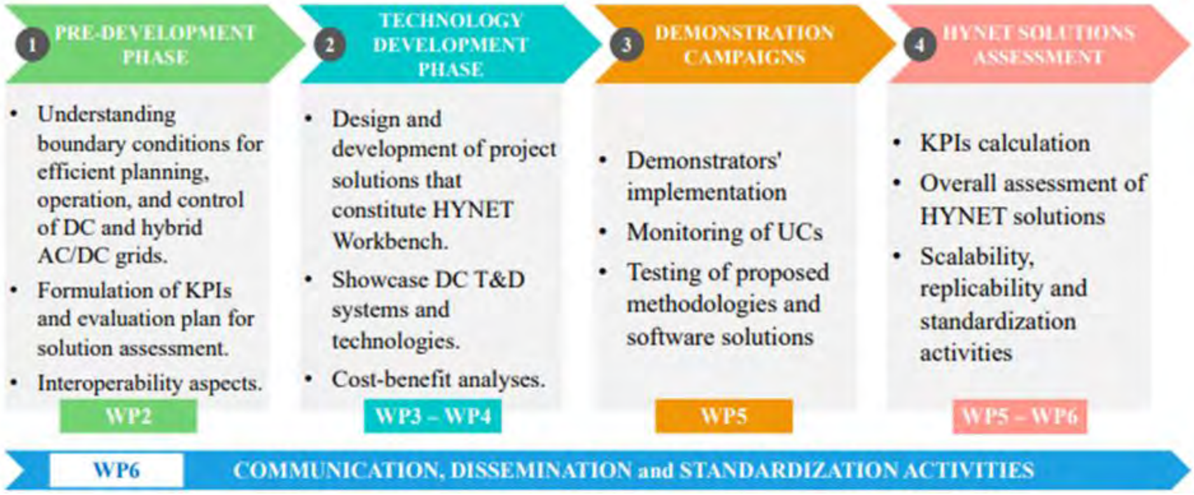

Figure 1. HYNET methodology

1.2.1 Role of Scalability

Scalability in HYNET refers to the capability of the developed tools to maintain technical robustness and operational stability when deployed beyond pilot-scale demonstrators. The project validates solutions across multiple voltage levels and system configurations; however, their long-term relevance depends on their ability to function under increased network complexity, higher penetration of power-electronics-based resources, and multi-terminal AC/DC couplings [1].

From a technical perspective, scalability encompasses:

- Computational scalability of planning and operational assessment tools.
- Interoperable operation of multi-vendor converter technologies.
- Stable control performance in grid-forming and grid-following hybrid configurations.

1.2.2 Role of Replicability

Replicability in HYNET addresses the transferability of validated solutions across heterogeneous European contexts, including differences in regulatory frameworks, grid topology, RES penetration levels, and market structures. Given that European power systems range from islanded configurations to highly meshed cross-border networks, demonstrator-specific success does not automatically imply broader applicability [1].

HYNET therefore incorporates a structured assessment of replication potential by combining:

- Qualitative insights from demonstration environments.
- Quantitative stakeholder input through an EU-wide questionnaire.
- Mapping of existing and planned DC interconnectors in Europe to identify candidate replication regions.

Replicability ensures that the project outcomes generate transferable implementation blueprints rather than context-dependent technical proofs. It provides the analytical bridge between demonstration validation and the European deployment strategy [1].

1.2.3 Role of Standardisation

Standardisation plays a foundational role in enabling both scalability and replicability. Hybrid AC/DC networks introduce new interoperability challenges related to converter interfaces, DC protection schemes, grid-forming functionalities, data exchange protocols, and multi-vendor system integration.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Without harmonised technical frameworks, large-scale deployment would be fragmented and vendor-dependent [1].

HYNET explicitly targets the establishment of standardised methodologies and interoperability frameworks for multi-terminal, multi-vendor MVDC and LVDC systems. Within WP6 activities, stakeholder consultation identifies priority areas for standardisation and barriers to AC/DC integration, with the objective of informing contributions to European and international standardisation bodies such as IEC, CENELEC, and IEEE/PES [1].

In this sense, standardisation within HYNET is not limited to dissemination, it functions as a structural integration mechanism that aligns technological innovation with normative frameworks, ensuring compatibility, system security, and long-term market uptake [1].

1.3 Positioning of D6.5 within WP6 and links to other work packages

Deliverable D6.5 constitutes the strategic consolidation output established in Task 6.2. The activities performed provide the analytical backbone for the scalability and replicability assessment presented.

D6.5 moves beyond isolated demonstration-level evaluation and systematically examines the conditions under which hybrid AC/DC architectures can be scaled across heterogeneous European regulatory, geographical, and operational contexts. Its scope encompasses the integration of qualitative insights from demonstrations with quantitative stakeholder validation, ensuring methodological robustness and cross-context comparability. Importantly, the deliverable does not restrict its analysis to technological performance metrics. It explicitly addresses system integration constraints, interoperability requirements, and gaps in existing standardisation frameworks that currently limit the accelerated deployment of DC-based solutions [1].

Within WP6, D6.5 is closely aligned with standardisation and interoperability activities, particularly those targeting multi-terminal, multi-vendor DC systems. Technical challenges to be identified during the demonstrations are translated into structured recommendations for future large-scale implementation and standardisation engagement [1].

From a cross-work-package perspective, D6.5 integrates key inputs from:

- WP2 (T2.4), providing interoperability and integration principles, including common data exchange formats and interface definitions that enable scalable tool deployment,
- WP3-WP4, supplying the technical tools and modelling frameworks whose replication potential is evaluated under diverse system conditions,
- WP5, contributing validated demonstration results and lessons learned that ground the scalability assessment in empirical evidence.

2. Methodological Framework

2.1 Adaptation to hybrid AC/DC systems

The rapid transformation of the European power system – driven by large-scale renewable integration, sector coupling, and increasing cross-border electricity exchange – requires a fundamental evolution of transmission infrastructure. Within this context, HVDC technology and hybrid AC/DC architectures are emerging as key enablers of long-distance bulk power transfer, offshore wind integration, and enhanced system controllability. This subsection examines the growing strategic importance of HVDC in European grid development, analyses recent trends in the ENTSO-E Ten-Year Network Development Plan (TYNDP) framework, and positions HYNET solutions within this evolving landscape of hybrid transmission systems.

HVDC is positioned to become a central element of European grid development because it directly addresses the dominant structural drivers of the transition: large-scale renewable integration, long-distance bulk transfer, and controllability under stressed operating conditions. The HVDC technology supports the "smooth integration" of new renewable sources and can function as a controlled transfer channel during AC system issues (e.g., voltage instability, frequency deviations, faults) by maintaining constant power flow and providing damping through AC/DC decoupling. It also becomes cost-competitive for long distances, as seen in Figure 2, due to lower losses and reduced infrastructure requirements compared with AC alternatives [2].

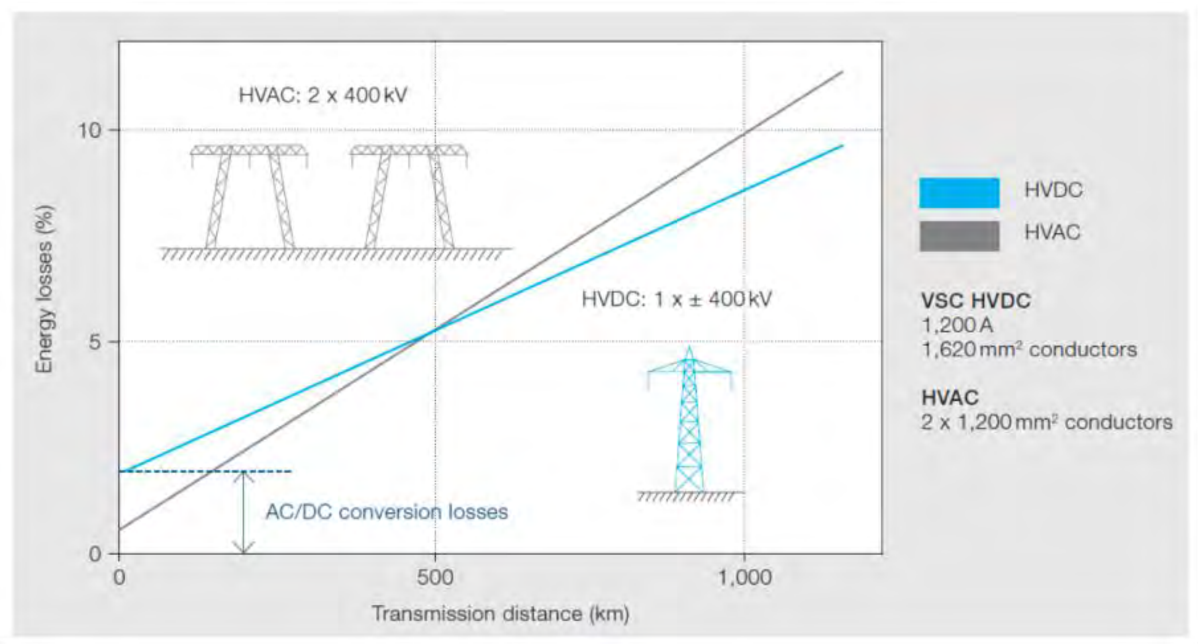

Figure 2. Comparison of energy losses in AC and DC lines

Hybrid HVAC-HVDC grid development is simultaneously reinforced by system-level advantages: improved voltage stability and resilience in high-RES systems, efficient long-distance transmission, and asynchronous interconnection capability; VSC-HVDC in particular enables fast and accurate power-flow control and can contribute grid-support services (e.g., synthetic inertia, oscillation damping, frequency support, black-start), which becomes increasingly valuable as synchronous generation is displaced [3].

In market terms, the HVDC interconnectors enhance European decarbonization by improving market efficiency through stronger cross-border coupling. The interconnectors increase transfer capacity,

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

reduce structural congestion, and thereby narrow persistent price differentials between zones. This effect promotes competition and can lower overall system costs by enabling more efficient cross-border use of generation and flexibility resources [4].

The disadvantages are primarily concentrated in cost, complexity, and integration constraints. The JRC document notes high upfront cost structures (converter substations and materials dominating project cost) and highlights supply-chain constraints and long lead times (e.g., cables, transformers) as non-trivial deployment risks [1]. At the technical-operational level, hybrid AC/DC deployment faces protection and interoperability challenges: DC fault behaviour differs fundamentally from AC (no natural current zero crossings), DC breakers are more complex and expensive (due to the absence of a natural current zero crossing, requiring active interruption mechanisms), and harmonization across operators (software/communication/security standards) remains a key barrier. Finally, the financing/regulatory dimension is itself a bottleneck: traditional TSO-led, tariff-based development models are argued to be increasingly insufficient for the required scale and pace; regulatory complexity and uncertainty deter new entrants and slow project delivery [4].

2.1.1 Changing trends in TYNDP of Europe

The TYNDP 2024 [5] includes 177 pan-European transmission projects to be assessed. Of these, 72 are HVDC connection plans and 87 are AC transmission line projects; the remaining projects cover supporting infrastructure such as substations and phase-shifting transformers. A particularly strong shift toward HVDC is visible in offshore transmission: 46 offshore projects are DC-based, while only 6 are AC-based. This highlights HVDC as the dominant technology for offshore connections, especially where long submarine distances, controllable power transfer, and the efficient integration of offshore generation make DC solutions preferable for linking islands and continental grids.

A comparison between TYNDPs clearly indicates that DC technologies are becoming increasingly significant within European transmission planning, as also illustrated in Figure 3. While conventional AC transmission lines remain numerically dominant, their growth between TYNDP 2022 [6] and TYNDP 2024 is moderate. In contrast, DC-related categories show a visibly stronger upward trend, particularly in offshore developments.

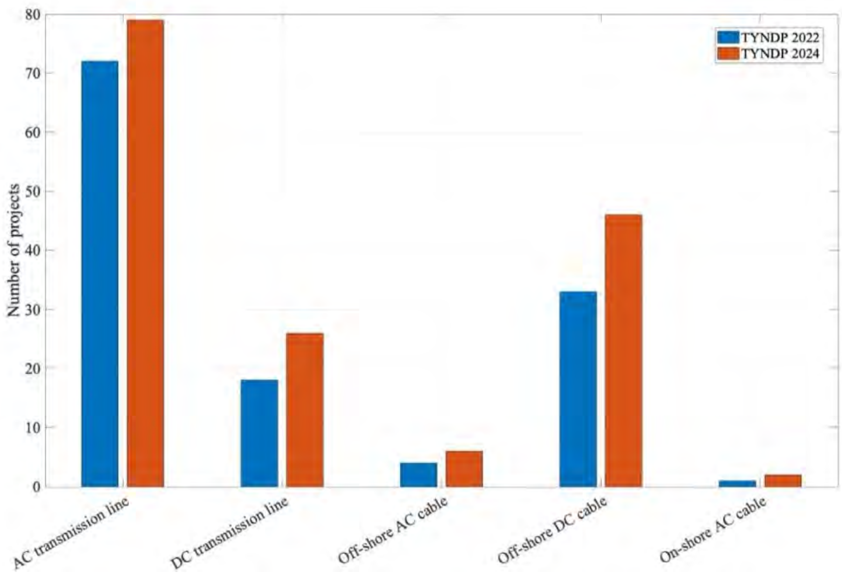

Figure 3. Comparison of TYNDP 2022 and TYNDP 2024 Transmission Projects

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

The most pronounced structural shift appears in offshore transmission, where DC solutions clearly dominate over AC alternatives. The increase in offshore DC projects reflects the accelerating integration of offshore wind generation and the technical preference for HVDC over long submarine distances. At the same time, onshore DC transmission lines also exhibit a noticeable rise compared to the previous TYNDP cycle, indicating that HVDC is no longer confined to niche interconnections but is progressively embedded into the core transmission backbone.

Overall, the figure suggests not merely quantitative growth, but a qualitative transition in planning philosophy: while AC reinforcement continues to support meshed grid strengthening, DC infrastructure is increasingly positioned as the strategic technology for long-distance transfer, offshore integration, and cross-border exchange. This reinforces the broader trend toward hybrid AC/DC transmission architectures across Europe.

2.1.2 DC connections in TYNDP 2024

TYNDP 2024 reveals a clear geographic concentration and structural pattern in planned European transmission development (see Figure 4). The most prominent cluster appears in the North Sea region, where multiple high-voltage DC corridors interconnect the United Kingdom, the Benelux countries, Germany, Denmark, and Scandinavia. This area is evolving into a major DC hub driven by offshore wind integration and reinforced cross-border exchange. The density of planned links indicates a transition from isolated bilateral interconnectors toward a more meshed, hybrid AC/DC backbone in Northwestern Europe.

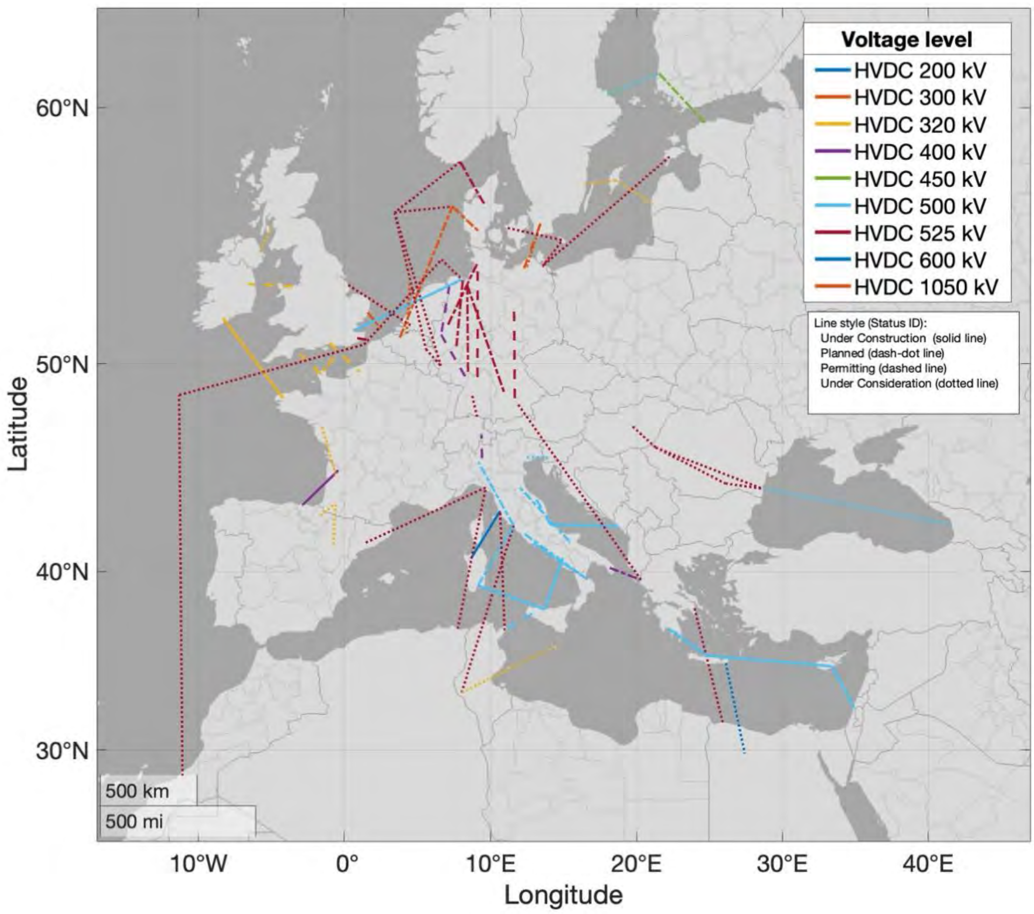

Figure 4. Planned HVDC connections according to TYNDP 2024

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

A second key concentration can be observed in the Mediterranean and Southern European region, particularly around Italy, the Balkans, and Greece. Several planned HVDC links connect Southern Italy with North Africa and Southeastern Europe, strengthening interregional exchange and integrating previously weakly connected market areas. These projects contribute to the physical and economic integration of Southern European and Mediterranean electricity markets, enhancing transfer capability between regions with differing generation portfolios and demand profiles.

The map also highlights the strategic role of HVDC in connecting islands and geographically peripheral systems to the continental European grid. Planned links involving Great Britain, Ireland, and Mediterranean islands illustrate how HVDC enables long submarine connections that would be technically or economically inefficient with conventional AC technology. By integrating island systems and remote renewable generation zones into the European transmission network, HVDC supports market coupling, security of supply, and the structural transition toward a hybrid AC/DC architecture at the continental scale.

2.1.3 HYNET Solutions Supporting the Hybrid AC/DC Networks in Europe

The TYNDP clearly indicates a growing deployment of HVDC corridors and hybrid AC/DC infrastructures across Europe. In this context, HYNET directly supports these developments by addressing the technical, operational, and planning challenges associated with large-scale DC integration. The integrating DC grids into existing AC systems requires advanced control, protection, stability, and interoperability solutions, particularly for multi-terminal and hybrid configurations. HYNET's technology repository and Workbench architecture provide a structured and interoperable framework to define functional specifications and validate solutions for hybrid AC/DC systems, ensuring that these future DC deployments can operate securely and efficiently.

Tools such as Tool#3 (multi-energy planning) and Tool#4 (TEA-based adequacy and security assessment) enable techno-economic assessment, adequacy evaluation, and optimal long-term planning of hybrid AC/DC networks, including HVDC interconnectors and offshore hubs. These tools support TSOs in evaluating new HVDC corridors under normal and contingency conditions, performing OPF-based analysis, security assessment and cost-benefit studies. This is directly aligned with TYNDP-type projects, where the integration of new DC links requires comprehensive evaluation of cross-border flows, system adequacy, and resilience before implementation.

At the operational level, HYNET strengthens the stability and controllability of future system through grid-forming control, inertia estimation, and adaptive synthetic inertia provision via HVDC interconnectors. Tools such as Tool#12 and Tool#13 enable real-time inertia estimation and coordinated frequency support across HVDC links, which is critical when interconnecting weak and strong grids. In parallel, reliability and protection-oriented tools (e.g., Tool#6 and Tool#11) address the specific protection and resilience challenges of hybrid AC/DC architectures. Altogether, HYNET provides the analytical, control, and validation framework necessary to de-risk and technically enable the large-scale HVDC expansion foreseen in European planning documents, accelerating the transition toward secure and resilient hybrid AC/DC networks.

2.2 Overall assessment approach

2.2.1 Literature and SRA methodology review

The literature review conducted within Task 6.2 establishes the conceptual and regulatory foundation for assessing scalability, replicability, and standardisation of hybrid AC/DC and HVDC networks in the HYNET project. Existing European and international standards already provide partial guidance for the planning, operation, and protection of AC/DC systems; however, the rapid evolution of multi-terminal,

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

multi-vendor HVDC and MVDC architectures reveals substantial methodological and regulatory gaps [7].

From a standardisation perspective, communication and interoperability frameworks are primarily governed by IEC 61850, which enables structured data exchange and real-time coordination in substations and HVDC environments. Voltage level harmonisation is addressed by IEC 60038, ensuring compatibility across transmission and distribution systems. DER integration requirements are defined in IEEE 1547 and relevant EU network codes, including Regulation (EU) 2016/631 and the HVDC Network Code (2016), which specify functional and performance obligations for converter-based resources [8].

Despite this normative landscape, the literature highlights persistent challenges in HVDC system expansion, particularly in three domains:

- Technical limitations, including the absence of fully mature HVDC circuit breaker solutions and interoperability constraints between different converter technologies (LCC/VSC, MMC-based systems).
- Protection complexity, resulting from the lack of natural current zero-crossing in DC systems and the need for ultra-fast fault detection and isolation.
- Cybersecurity and control vulnerabilities, due to increasing digitalisation and reliance on communication-intensive architectures.

These challenges underscore the necessity for structured Scalability and Replicability Analysis (SRA) frameworks that extend beyond pure technical validation and integrate regulatory, economic, and stakeholder dimensions [9].

Conceptual Foundations of Scalability and Replicability

Within the smart grid domain, scalability refers to the ability of a system to maintain operational stability, performance integrity, and economic viability when expanded in size, geographical scope, or functional complexity. Replicability, in contrast, concerns the transferability of validated solutions across heterogeneous regulatory environments, grid topologies, and market structures.

Both concepts are interdisciplinary and inherently linked: scalability ensures that innovations can operate under increased system stress and penetration levels, while replicability ensures contextual adaptability. In the context of hybrid AC/DC systems, these dimensions are further complicated by multi-voltage interactions, converter-dominated dynamics, and cross-border interoperability requirements.

Review of SRA Methodologies in EU Innovation Projects

To define a robust methodological basis for HYNET, several Horizon 2020 and Horizon Europe projects were examined, including Platone, IElectrix, EUniversal, RESPONSE, and FLEXITRANSTORE [9][10][11].

Across these projects, common methodological characteristics can be identified:

1. Alignment with BRIDGE Guidelines – Most projects structured their SRA around the BRIDGE initiative recommendations, ensuring consistency across EU-funded smart grid projects [12].
2. Use of the Smart Grid Architecture Model (SGAM) – SGAM served as a reference framework to map scalability and replicability across business, functional, information, communication, and component layers [13].
3. Mixed-method approach – Quantitative simulations (e.g., OPF models, Monte Carlo analyses, ICT performance simulations) were combined with qualitative stakeholder and regulatory assessments.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

4. Multi-dimensional evaluation criteria, typically covering:
   - Technical feasibility
   - Economic viability
   - Regulatory compatibility
   - Stakeholder acceptance
   - ICT interoperability and cybersecurity [9][13][14][15][16][17]

Projects such as Platone and IElectrix implemented simulation-based quantitative SRA across multiple distribution networks, while EUniversal and RESPONSE emphasized ICT-layer scalability using API compliance metrics and communication performance indicators. FLEXITRANSTORE focused more strongly on qualitative questionnaires addressing regulatory and market conditions.

A recurring limitation identified in the literature is the lack of harmonised SRA reporting formats, which complicates cross-project comparison and aggregation of results. Data availability constraints and proprietary ICT solutions further restrict replicability assessments at European scale [9].

2.2.2 Demonstration-based expert interviews

Semi-structured interviews were conducted with the leads of all five HYNET demonstration environments — the French Caribbean island grid (Demo 1a), the French distribution grid under EV integration stress (Demo 1b), the Montenegro cross-border transmission corridor (Demo 2), the Norwegian HVDC and offshore RES planning environment (Demo 3), and the Cyprus real-time digital twin platform (Demo 4). The interviews provided a structured, evidence-based qualitative foundation for assessing the scalability, replicability, and standardisation readiness of each demonstration, complementing the quantitative tool-level and stakeholder assessment layers of the SRA.

Each interview was organised around four thematic areas: (i) scalability and replicability potential, (ii) critical technical enablers for large-scale deployment, (iii) system interoperability and standardisation alignment, and (iv) regulatory, infrastructural, and market barriers. The full interview guideline is provided in Annex A. The complete methodology, structured findings per demonstration, and their influence on the design of the EU-wide stakeholder questionnaire are presented in Chapter 4.

2.2.3 Questionnaire on the scalability, replicability and standardisation of tools developed within the project

The tool-leader barriers questionnaire was administered to the developers of all thirteen HYNET tools as a systematic internal assessment instrument designed to capture tool-level barriers and enablers of replicability and scalability. Unlike the EU-wide stakeholder questionnaire, which targets the broader ecosystem of transmission and distribution system operators, research institutions, and technology providers, this instrument focuses specifically on the technical, operational, and institutional characteristics of each individual HYNET tool. By collecting structured responses directly from tool developers, it grounds the scalability assessment in first-hand implementation knowledge and complements the qualitative insights derived from the demonstration-based interviews.

The questionnaire was distributed to representatives of the tool-developing organisations within the HYNET consortium, covering institutions including INESC TEC, CIRCE, ART, SGI, GEPC, and UCY. The thirteen tools addressed span all four HYNET Workbench functional categories: planning tools, reliability and resilience tools, grid-forming and inertia support tools, and DC distribution modelling and operational tools. This coverage ensures that the barrier assessment is representative of the full technical portfolio and not confined to a specific tool category or operational layer.

The questionnaire is structured around ten thematic barrier categories (C1-C10), each subdivided into six subcategories, yielding sixty assessment dimensions per tool. The categories are defined as follows:

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

- C1 – Software dependencies: addressing commercial software reliance, programming language portability, operating system compatibility, licensing restrictions, version sensitivity, and third-party library dependencies;
- C2 – Time-domain constraints: covering real-time execution requirements, computational scalability with problem size, simulation-to-real-time ratio, data processing speed, parallel processing capability, and memory and hardware requirements;
- C3 – Transferability across locations: assessing grid topology flexibility, voltage-level applicability, data format standardisation, sensitivity to national regulatory frameworks, documentation language, and organisational workflow assumptions;
- C4 – Data availability and quality: examining temporal and spatial resolution requirements, reliance on proprietary or confidential data, historical data needs, measurement infrastructure prerequisites, sensitivity to data quality issues, and real-time data access dependency;
- C5 – Hardware infrastructure: evaluating Hardware-in-the-Loop (HIL) requirements, high-performance computing needs, communication infrastructure dependencies, sensor and measurement hardware requirements, laboratory or testbed facility needs, and cloud versus on-premise deployment constraints;
- C6 – Interoperability and integration: covering API availability and documentation, communication protocol support, multi-tool workflow compatibility, containerisation support, model exchange format compatibility, and vendor lock-in risks;
- C7 – Knowledge and expertise: addressing domain expertise requirements, programming skill levels needed for deployment, training duration and learning curve characteristics, documentation quality and completeness, technical support and community availability, and tacit knowledge dependencies;
- C8 – Validation and benchmarking: assessing benchmark availability, validation against real-world systems, uncertainty quantification capability, result reproducibility, standardisation of performance metrics, and cross-validation potential with other tools or methods;
- C9 – Regulatory and standardisation: covering grid code assumptions, implemented technical standards, certification requirements, intellectual property constraints, cybersecurity compliance, and open versus closed development models;
- C10 – Scalability potential: addressing maximum network size handled, multi-area and multi-operator support, technology diversity accommodation, scenario and uncertainty analysis capacity, modular architecture design, and readiness for future technologies.

The full questionnaire responses for each tool are provided in Annex B. The synthesised findings, organised by barrier category and cross-referenced against tool characteristics, are presented in 5.2.

2.2.4 EU-wide stakeholder questionnaire

The questionnaire instrument presented in this section, and provided in full in Annex C, has been finalised within Task 6.2 and is currently being prepared for distribution to the target stakeholder population. Distribution is planned for Q3 2026, with data collection and analysis to be completed prior to the final submission of Deliverable D6.5 at Month 36. The present initial version of D6.5 therefore establishes the complete methodological and analytical framework, with the stakeholder validation layer to be incorporated in the final version.

The EU-level stakeholder questionnaire developed under Task 6.2 is designed to systematically capture stakeholder perspectives on scalability, replicability, standardisation, interoperability, and deployment readiness of hybrid AC/DC electricity networks.

The questionnaire is structured into two main layers:

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

1. General cross-stakeholder questions, applicable to all respondent categories
2. Stakeholder-specific blocks, tailored to:
    - Transmission System Operators (TSOs)
    - Distribution System Operators (DSOs)
    - Research institutions
    - Technology providers

The structure ensures both horizontal comparability across stakeholder types and vertical depth within each technical domain.

General Cross-Stakeholder Questions

The general section addresses strategic perception, organisational positioning, and ecosystem involvement related to hybrid AC/DC systems.

The following thematic areas are covered:

Strategic Necessity of Hybrid AC/DC Systems

Respondents are asked to evaluate the perceived importance of hybrid AC/DC power systems in meeting future grid flexibility and resilience requirements (5-point Likert scale).

This question captures high-level strategic alignment with the hybridisation paradigm.

Participation in Interoperability-Related Initiatives

Organisations indicate whether they are currently involved in projects addressing interoperability in AC and/or DC system components.

This provides insight into ecosystem engagement and technological maturity exposure.

Relevance of Replicability Across EU Member States

A Likert-scale question assesses how relevant cross-border replicability of technical and regulatory solutions is for the organisation.

This dimension directly supports the SRA objective of identifying transferable hybrid AC/DC architectures.

Standardisation as Barrier or Enabler

Stakeholders evaluate whether current standardisation frameworks (IEC, IEEE, ENTSO-E guidelines) act primarily as a barrier or as an enabler for AC/DC hybrid deployment.

This provides qualitative insight into regulatory-system alignment.

Grid-Forming and Black-Start Requirements

The questionnaire assesses organisational involvement in defining requirements for grid-forming or black-start capabilities in converter-based systems.

This dimension is particularly relevant under inverter-dominated system scenarios.

Feasibility of Large-Scale Deployment by 2030

Respondents rate the perceived feasibility of large-scale, multi-vendor hybrid AC/DC infrastructure deployment by 2030.

This captures forward-looking deployment confidence.

Adoption of European R&I Outcomes

Organisations indicate whether they contribute to or adopt outcomes from European research and innovation projects (e.g., HYNET, OneNet, TDX-ASSIST, TwinEU).

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

This allows assessment of innovation diffusion within the sector.

Backwards Compatibility Requirements
Stakeholders evaluate the importance of ensuring backward compatibility with legacy systems.

This dimension addresses transition constraints and integration complexity.

Openness to Shared Validation Platforms
Respondents are asked whether they would participate in shared validation environments (virtual or real-time testbeds) for hybrid AC/DC systems.

This supports the assessment of collaborative scalability frameworks.

Collaboration with Standardisation and Regulatory Bodies
The questionnaire evaluates the degree of organisational interaction with standardisation bodies and regulatory authorities.

This captures institutional integration within governance structures.

Stakeholder-Specific Question Blocks
The following subsections summarise the thematic areas covered by each stakeholder-specific block. The full list of questionnaire questions is provided in Annex C.

Transmission System Operators (TSOs)
The TSO block focuses on transmission-level hybridisation challenges, regulatory adequacy, and system readiness.

Main dimensions covered:

- Sufficiency of ENTSO-E grid codes and IEC/IEEE standards for hybrid AC/DC operation
- Adoption of hybrid system designs developed by other TSOs or EU projects
- Importance of reference hybrid architectures
- EMS/SCADA readiness for real-time hybrid grid management
- Consideration of modular HVDC substations
- Participation in cross-border hybrid interconnector projects
- Strategic importance of pan-European hybrid transmission corridors by 2035
- Preferred hybrid transmission topology (radial HVDC, meshed overlay, DC hubs, etc.)
- Testing or validation of grid-forming converter functionalities
- Identification of operational or regulatory barriers for continental-scale deployment

This block addresses system stability, planning architecture, regulatory alignment, and cross-border integration.

Distribution System Operators (DSOs)
The DSO block focuses on distribution-level hybridisation, MVDC integration, and operational flexibility.

Core themes include:

- Necessity of standardisation frameworks (e.g., IEC 61850, IEEE 2030.5)
- Adoption of solutions developed by other DSOs or EU projects
- Transferability of pilot results across regions
- DMS/SCADA scalability for DC asset integration
- Likelihood of deploying modular DC substations or MVDC feeders
- Consideration of internal MVDC interconnectors

Funded by the European Union
HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

- DSO-TSO hybrid interconnection roles
- Preferred hybrid distribution topology (DC feeder integration, DC microgrids, hybrid substations)
- Testing or simulation of hybrid protection and control schemes
- Technical, economic, and regulatory barriers to AC/DC deployment at distribution level

This block captures local grid transformation readiness and protection/control maturity.

Research Institutions

The research block evaluates knowledge generation, transferability studies, and test infrastructure availability.

The main thematic areas are:

- Participation in AC/DC-related standardisation activities
- Research on replicability and transferability across European grid configurations
- Translation of research outputs into operational practice
- Access to simulation environments or hybrid testbeds
- Importance of scalability analysis in research projects
- Studies related to HVDC or MVDC interconnectors
- Collaboration with TSOs and DSOs
- Priority research topics (AC/DC control, grid-forming converters, hybrid protection, multi-terminal HVDC)
- Alignment with open-source or modular validation architectures
- Identification of scientific or technological gaps

This section supports gap analysis for future R&I prioritisation.

Technology Providers

The technology provider block focuses on product maturity, standard compliance, scalability, and multi-vendor interoperability.

Covered dimensions include:

- Compliance with international standards (IEC, IEEE)
- Design portability across grid topologies
- Collaboration frequency with system operators
- Scalability of deployed technologies (modular substations, plug-and-play converters)
- Development of MVDC/LVDC solutions
- Supply of HVDC/MVDC interconnector systems
- Support for advanced functionalities (dynamic power flow control, fault ride-through, grid-forming capability)
- Targeted hybrid grid segment (substations, converters, control systems, etc.)
- Real-time or HiL validation capability
- Technical and commercial challenges in multi-vendor deployment

This block enables assessment of market readiness and industrial scalability.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

3. HYNET Demonstrations as Input to the SRA

This section is structured to clarify how HYNET demonstrations contribute to pan-European scalability from three complementary perspectives. First, it presents an overview of the HYNET demonstration environments, describing the range of system contexts covered and the tool-driven validation logic applied in each case. Second, it analyses the diversity of technical contexts addressed by the tool portfolio, highlighting how planning, operational, and dynamic control functions are combined across different system layers. Finally, it explains the role of the HYNET Workbench in structuring, integrating, and scaling these validated tools into a coherent interoperability ecosystem capable of supporting hybrid AC/DC deployment pathways at European scale.

3.1 Overview of HYNET demonstration environments

HYNET demonstrations provide a coherent set of validation environments spanning weak and islanded power systems, distribution networks undergoing electrification stress (e.g., mass EV integration), and transmission-scale HVDC corridors supporting offshore renewable integration and cross-border exchange. Together, they form a structured ladder of complexity – ranging from local hybrid AC/DC microgrid behaviour up to national and interregional transmission interactions – so that HYNET tools can be assessed in realistic contexts and against representative system challenges. The demonstrations are explicitly tool-driven: each demo environment is designed to validate specific HYNET tools and their interoperability within a workflow.

3.1.1 Demonstration 1a Mitigating Frequency issue on Caribbean Island weak grid

This demonstration targets frequency stability limitations in a weak, islanded power system with limited inertia and high sensitivity to disturbances, using the French Caribbean Island grid (Guadeloupe) as a representative case. The system is characterized by a growing penetration of inverter-based renewable energy sources, limited interconnections, and operational constraints on variable generation. These conditions create significant risks related to frequency excursions, reduced short-circuit strength, and diminished dynamic stability margins. The objective of the demonstration is to evaluate and validate grid-forming reinforcement strategies capable of enhancing frequency stability and resilience in such weak-grid environments.

Figure 5. Microgrid overview in demonstration 1a

The system context corresponds to a small-to-medium islanded transmission and distribution system operated by EDF in French overseas territories. The grid exhibits low inertia due to high shares of inverter-based resources and limited synchronous generation. Operational constraints, such as limits on combined RES output, illustrate the structural stability challenges. Hybridization in this demonstration is introduced through inverter-dominated operation and advanced grid-forming

Funded by the European Union
HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

battery energy storage systems (BESS), which emulate synchronous machine behaviour. The demonstration environment combines detailed offline simulation models (DIgSILENT PowerFactory-based grid representation, including topology, protection schemes, and component parameters) with real-time validation via a Power Hardware-in-the-Loop (PHIL) setup using an EDF downscaled microgrid as seen on Figure 5. This two-step validation framework ensures both analytical robustness and experimental verification.

Main technical challenges include:

- Low system inertia and high Rate of Change of Frequency (RoCoF) following disturbances,
- Frequency recovery performance under N-1 contingencies and generation-loss events,
- Operation under reduced short-circuit strength conditions,
- Increasing instantaneous share of inverter-based resources without jeopardizing stability,
- Comparative assessment of reinforcement alternatives (synchronous compensator versus grid-forming BESS).

HYNET tools implemented in Demonstration 1a:

- *Tool#5 – Computational suite for steady-state and dynamic analysis:* This tool provides dynamic modelling and simulation of AC and hybrid AC/DC power systems. In this demonstration, it is used for detailed offline dynamic studies based on the representative "Steak au poivre" island grid model. The tool simulates disturbance scenarios (e.g., generation loss, N-1 events) and compares reinforcement strategies, including no additional support, synchronous compensator installation, and BESS operating in grid-forming mode. Tool#5 evaluates frequency stabilization, inertia contribution, and renewable integration impacts. In the second validation step, Tool#5 results are benchmarked against PHIL experimental data to ensure predictive accuracy under real-time operating conditions.
- *Tool#8 – Grid Forming control of inverter-based resources:* This tool implements a voltage-source, inverter-agnostic grid-forming control algorithm designed for hybrid AC/DC systems. It operates both in offline simulations (MATLAB/Simulink environment) and in real-time through OPAL-RT platforms within the PHIL setup. The tool enables BESS units to operate in grid-forming mode, emulating virtual synchronous machine behaviour, providing fast frequency response, voltage regulation, and synthetic inertia support. In this demonstration, Tool#8 is validated as an alternative reinforcement solution to conventional synchronous compensators, enabling enhanced resilience in weak or islanded grids and supporting higher shares of inverter-based generation.

Stakeholders included in Demonstration 1a:

- *The local system operator (EDF):* provides the operational context, grid data, and validation framework,
- *Technology providers:* responsible for inverter and BESS control implementation,
- *Research partners:* conducting modelling, KPI definition, scenario design, and validation analysis.

The demonstration contributes to defining technical requirements for scalable grid-forming solutions applicable to other weak or islanded systems and establishes a structured validation methodology aligned with the IEC 62559 use case framework.

3.1.2 Demonstration 1b – Contingency issues in a distribution grid facing mass EV integration

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

This demonstration addresses contingency and operational challenges in a distribution network experiencing rapid electrification, particularly due to large-scale EV integration. The increasing penetration of EV charging stations introduces significant variability in load profiles, higher peak demand, and new congestion patterns at medium- and low-voltage levels. The objective of the demonstration is to explore and validate reinforcement and operational strategies capable of maintaining reliability, service continuity, and voltage compliance under these evolving conditions.

The system context corresponds to a representative MV/LV distribution network operated by a DSO. Although geographically local or regional, the challenges addressed are transferable across Europe due to common electrification trends and EV-driven demand growth. The demonstration explicitly investigates hybrid AC/DC distribution architectures, including multi-terminal DC configurations, as structural reinforcement options. Required input data include detailed MV/LV network characteristics, grid topology, AC and DC component parameters, operational modes, and coordinated control strategies. The outputs focus on scalability across a wide range of system configurations and operating scenarios, including islanded operation modes, ensuring replicability beyond the specific pilot grid.

The main technical challenges addressed in this demonstration include:

- Contingency management under highly variable and peak-oriented EV-driven demand patterns.
- Planning and validation of MVDC/LVDC and multi-terminal DC reinforcements to increase hosting capacity.
- Maintaining voltage regulation and power quality within regulatory limits under dynamic load conditions.
- Ensuring coordinated protection, selective fault isolation, islanding capability, and service restoration in hybrid AC/DC architectures.
- Quantifying reliability and resilience improvements enabled by DC-based reinforcement strategies.

Four HYNET tools are implemented in this demonstration:

- *Tool#1 – Power dispatch and voltage control tools*: This tool is designed to support DC distribution and hybrid AC/DC network operation through coordinated power dispatch and voltage regulation functionalities. It enables optimized control of distributed energy resources (DERs), controllable loads, and converter-based assets across both AC and DC subsystems. In the context of Demonstration 1b, Tool#1 manages voltage profiles and mitigates congestion arising from EV-driven load variability by coordinating active and reactive power flows. The tool operates based on detailed grid architecture data, component ratings, and control characteristics of both AC and DC devices. It supports different operational modes, including normal operation and contingency scenarios, and ensures stable voltage regulation within acceptable limits under rapidly changing load conditions. Its role in the demo is primarily operational, enabling real-time or near-real-time dispatch optimization in hybrid MV/LV networks.
- *Tool#6 – Reliability and resilience analysis tool for MVDC and LVDC integration:* Tool#6 focuses on evaluating the reliability and resilience performance of hybrid AC/DC distribution systems, particularly when MVDC or LVDC reinforcements are introduced. It assesses how DC-based configurations impact service continuity, fault propagation behaviour, and recovery capability under contingency events. The tool analyses different reinforcement alternatives and quantifies their contribution to improving system robustness. In Demonstration 1b, Tool#6 is

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

used to compare conventional AC reinforcement strategies with hybrid AC/DC and multi-terminal DC configurations, evaluating resilience improvements in terms of reduced outage impact and enhanced restoration performance. Its primary role is analytical, supporting decision-making through structured reliability and resilience assessment methodologies.

- *Tool#7 – Grid planning tool for HVDC, MVDC, and LVDC integration:* Tool#7 supports long-term planning of hybrid AC/DC networks by assessing candidate reinforcement architectures, including multi-terminal DC topologies. It evaluates different expansion scenarios based on network characteristics, operational constraints, and projected load growth, such as EV penetration. The tool processes input data related to grid topology, AC and DC component specifications, coordinated control strategies, and operational modes. It outputs planning recommendations that ensure scalability and adaptability across a wide range of configurations, including islanded operation modes. In Demonstration 1b, Tool#7 plays a strategic planning role, enabling the DSO to assess whether MVDC/LVDC integration or multi-terminal DC solutions provide a technically and operationally viable reinforcement pathway compared to conventional upgrades.
- *Tool#11 – Islanding, service restoration, and network protection for hybrid AC/DC grids:* Tool#11 addresses protection coordination and restoration logic in hybrid AC/DC distribution systems. It supports the design and validation of protection schemes capable of operating safely in networks that combine AC and DC segments. The tool considers fault detection, selective isolation, islanding strategies, and coordinated reconnection procedures. In Demonstration 1b, Tool#11 ensures that hybrid AC/DC reinforcement solutions can maintain operational security during faults and contingencies while enabling controlled islanded operation when required. Its function is primarily related to protection and restoration management, ensuring safe system behaviour under abnormal operating conditions and facilitating rapid service recovery.

Stakeholders involved in this demonstration include:

- *Distribution System Operator (DSO):* acting as system owner and validation leader, providing network data, operational constraints, and real contingency scenarios.
- *Technology providers:* supplying grid automation, protection, control systems, converters, and DC integration components required for hybrid operation.
- *Research partners:* responsible for system modelling, contingency scenario definition, KPI tracking, and structured validation of the implemented tools.

3.1.3 Demonstration 2 – Montenegro Cross-Border Grid Resilience and Renewable Energy Synergy

This demonstration focuses on transmission-level resilience in a cross-border environment, explicitly addressing the integration of renewable energy and the reinforcement of interconnection corridors under evolving system conditions. The examined Monita HVDC connection can be seen on Figure 6. The core objective is to validate analytical and control tools capable of quantifying the adequacy, security, and techno-economic performance of reinforcement solutions – particularly HVDC-related options – while addressing the dynamic stability challenges introduced by increasing shares of inverter-based renewable generation. Within HYNET, this demonstration bridges strategic planning methodologies with operationally meaningful stability support mechanisms in a cross-border framework.

The system context corresponds to a transmission-level grid with cross-border interconnections, reflecting the interaction between neighbouring systems and regional electricity exchanges. The environment is HV-oriented, incorporating conventional AC transmission infrastructure and prospective HVDC reinforcement concepts. Hybridisation is considered through the interaction between AC network operation and converter-based technologies, including grid-forming and inertia-support functionalities. The demonstration requires detailed transmission network models, generation portfolio projections, cross-border exchange scenarios, and dynamic system parameters to evaluate both long-term adequacy and short-term stability performance. The geographic relevance extends beyond national boundaries, as the validated methodologies are applicable to interconnected European transmission systems experiencing similar renewable integration trajectories.

Figure 6. Existing and planned Italy-Montenegro interconnections

The main technical challenges addressed include:

- Assessing system adequacy under evolving generation portfolios with increasing renewable penetration.
- Evaluating security margins under N-1 and disturbance scenarios in a cross-border operational context.
- Quantifying the techno-economic trade-offs between reinforcement alternatives, including HVDC-based solutions.
- Addressing reduced system inertia and frequency stability concerns due to high converter penetration.
- Integrating planning-level analytics with operational resilience interventions.

Two HYNET tools are implemented and validated in this demonstration:

- *Tool#4 – TEA-based adequacy and security analysis tool for optimal orchestration of hybrid AC/DC networks:* Tool#4 provides a techno-economic assessment (TEA) framework for evaluating reinforcement strategies in hybrid AC/DC transmission systems. It combines adequacy analysis, security assessment, and economic evaluation into a structured planning methodology. The tool processes transmission network data, generation scenarios, cross-border exchange parameters, and contingency definitions to quantify reliability indicators and cost-performance trade-offs. In Demonstration 2, Tool#4 evaluates reinforcement options—including HVDC-related solutions—by assessing their impact on system adequacy, congestion reduction, and security performance. It supports infrastructure decision-making by identifying optimal orchestration strategies for hybrid AC/DC networks under future renewable-rich scenarios. Its role is primarily strategic and planning-oriented, ensuring that reinforcement decisions are grounded in measurable resilience and cost-benefit metrics.

- *Tool#2 – Inertia compensation scheme:* Tool#2 is designed to estimate and monitor system inertia in real time using PMU-based measurements. It retrieves voltage and current phasors, frequency, and ROCOF data from PMUs via a Phasor Data Concentrator (PDC), processes the signals through filtering and dynamic extraction steps, and computes system inertia using a sliding-window methodology. When the estimated inertia drops below predefined thresholds, the tool generates alarm signals to support operator intervention. In the context of Demonstration 2, Tool#2 is validated as an operational support mechanism complementing planning-level reinforcement analysis. It enhances dynamic security by enabling improved awareness of inertia levels in systems with increasing inverter-based generation. Its function links resilience methodology (UC#2) with real-time operational monitoring, supporting adaptive response strategies in cross-border transmission environments.

Stakeholders involved in this demonstration include:

- *Transmission System Operator (TSO):* responsible for defining system boundaries, providing network and operational data, and validating reinforcement and stability scenarios in a cross-border context.
- *Technology providers:* supporting the feasibility of reinforcement concepts and converter-based support functionalities.
- *Research partners:* responsible for techno-economic assessment design, adequacy and security indicator formulation, KPI tracking, and structured validation of both planning and operational tools within the defined use case framework.

3.1.4 Demonstration 3 – Norwegian HVDC corridors: interconnections and offshore RES integration

This demonstration focuses on the long-term planning and security assessment of HVDC transmission corridors combined with large-scale offshore renewable energy integration. The primary objective is to validate an integrated planning and security assessment framework capable of supporting HVDC corridor expansion under uncertainty, while simultaneously evaluating the dynamic implications of high offshore RES penetration and reduced synchronous inertia. Within HYNET, this demonstration represents a transmission-scale hybrid AC/DC environment driven by offshore development and interregional interconnection requirements.

The system context is transmission-level, with sea-basin and interregional relevance. The grid environment reflects HVDC corridor development associated with offshore wind integration and cross-border exchange reinforcement. Hybridisation is significant, as large HVDC links and offshore integration create strong AC/DC coupling at scale, requiring coordinated planning and operational assessment. The demonstration relies on detailed transmission network representations, projected offshore RES deployment scenarios, corridor expansion pathways, and uncertainty parameters affecting generation, load evolution, and cross-border exchanges. The geographic and structural characteristics of the Norwegian context provide a representative test case for future European HVDC corridor development in offshore-dominated regions.

The main technical challenges addressed include:

- Planning HVDC corridor expansion pathways under long-term uncertainty in demand, generation mix, and cross-border flows.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

- Assessing adequacy and security impacts of large-scale offshore RES integration combined with new HVDC interconnections.
- Evaluating stochastic system behaviour and risk exposure in hybrid AC/DC transmission networks.
- Managing reduced inertia and frequency robustness resulting from high shares of inverter-based offshore generation and HVDC penetration.
- Integrating long-term multi-energy system drivers into transmission development strategies.

Three HYNET tools are implemented and validated in this demonstration:

- *Tool#2 – Inertia compensation scheme:* Tool#2 is designed to estimate and monitor system inertia in real time using PMU-based measurements. It retrieves voltage and current phasors, frequency, and ROCOF data from PMUs via a Phasor Data Concentrator (PDC), processes the signals through filtering and dynamic extraction steps, and computes system inertia using a sliding-window methodology. When the estimated inertia drops below predefined thresholds, the tool generates alarm signals to support operator intervention. In the context of Demonstration 2, Tool#2 is validated as an operational support mechanism complementing planning-level reinforcement analysis. It enhances dynamic security by enabling improved awareness of inertia levels in systems with increasing inverter-based generation. Its function links resilience methodology (UC#2) with real-time operational monitoring, supporting adaptive response strategies in cross-border transmission environments.
- *Tool#3 – Multi-energy vector integration tool:* Tool#3 supports long-term system planning by integrating multiple energy vectors and broader system drivers into transmission development analysis. It evaluates interactions between electricity generation, offshore renewable deployment, and cross-sector constraints, enabling a comprehensive assessment of HVDC corridor expansion pathways. The tool processes planning scenarios incorporating projected RES growth, energy demand evolution, and infrastructure constraints, producing strategic insights into optimal development trajectories. In Demonstration 3, Tool#3 plays a strategic planning role, enabling the evaluation of offshore RES integration and corridor development within a multi-energy and interregional framework.
- *Tool#10 – Stochastic security analysis tool for AC/DC hybrid transmission networks:* Tool#10 provides security assessment capabilities under uncertainty for hybrid AC/DC transmission systems. It evaluates system performance across multiple stochastic scenarios, considering variability in generation, demand, and operational conditions. The tool quantifies security margins and identifies risk exposure related to HVDC corridor deployment and offshore integration. In this demonstration, Tool#10 supports robust planning by assessing the adequacy and security implications of candidate HVDC corridor configurations under uncertain future conditions. Its role is analytical and risk-oriented, enabling resilient infrastructure decision-making.

Stakeholders involved include:

- *Transmission System Operator:* acting as corridor planning owner and validation partner, providing transmission network data, development scenarios, and operational constraints.
- *Offshore energy and technology stakeholders:* contributing contextual information on offshore RES deployment and HVDC technology feasibility.
- *Research partners:* responsible for scenario development, uncertainty modelling, security indicator definition, KPI tracking, and integrated validation of planning and stochastic security workflows.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

3.1.5 Demonstration 4 – Validating HVDC interconnection via real-time digital twin emulation for the Cyprus power system

This demonstration validates the impact of HVDC interconnection and advanced dynamic support strategies through a real-time digital twin framework applied to a national-scale island power system. The primary objective is to assess how HVDC interconnection and converter-based support functionalities can enhance resilience, improve frequency robustness, and reduce cascading risks under severe disturbance conditions. Within HYNET, this demonstration represents the main real-time validation environment for stability monitoring, inertia observability, and coordinated HVDC-enabled frequency support in a hybrid AC/DC context.

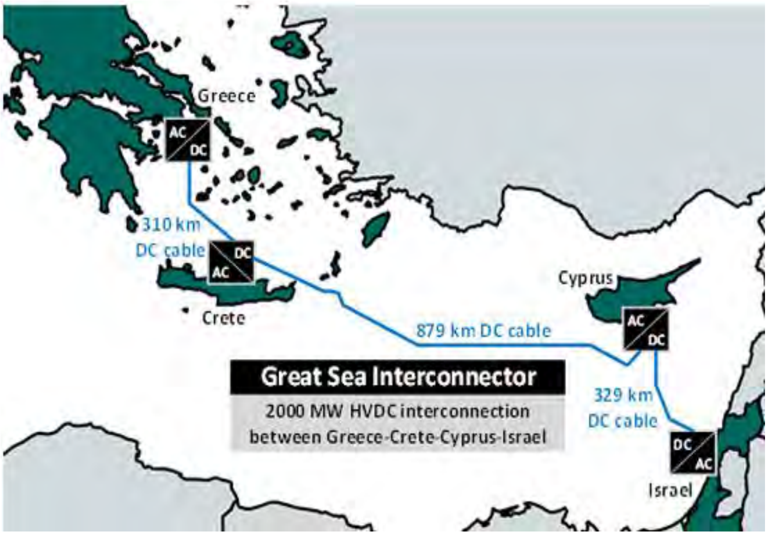

Figure 7. HVDC interconnector between Cyprus, Greece and Israel

The system context corresponds to a national island transmission system with limited synchronous generation and constrained interconnections, making it highly sensitive to generation-loss events and dynamic instability. The grid is transmission-oriented and operated at system level, with hybridisation introduced through HVDC interconnection concepts and terminal-level coordinated control strategies. The demonstration relies on detailed digital twin modelling of the transmission network, including dynamic grid models, measurement-based data streams (PMUs), and disturbance scenarios representative of real operational conditions. The digital twin environment enables the simulation and evaluation of cascading phenomena, inertia variations, and coordinated support actions in near-real-time conditions, supporting a realistic validation of HVDC-enabled dynamic services.

The main technical challenges addressed include:

- Stability risk under severe disturbances, including large generation or interconnection events.
- Static and dynamic cascading analysis to assess propagation mechanisms and system vulnerability.
- Reliable inertia estimation based on measurement-driven methodologies using PMU data.
- Coordinated provision of synthetic inertia and fast frequency response through HVDC terminals.
- Integration of real-time observability tools with control strategies in a hybrid AC/DC transmission environment.

Three HYNET tools are implemented and validated in this demonstration:

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

- *Tool#9 – Static and dynamic cascading analysis of large networks:* Tool#9 evaluates disturbance propagation and cascading behaviour in large-scale transmission systems. It analyses both static and dynamic dimensions of cascading failures, identifying vulnerable nodes and critical contingencies that may lead to widespread instability. In Demonstration 4, Tool#9 is applied within the digital twin framework to assess the resilience of the Cyprus transmission system under HVDC interconnection scenarios. Its role is analytical and resilience-oriented, supporting stability risk assessment and identifying mitigation strategies for large disturbance events.
- *Tool#12 – Quasi real-time estimation of system inertia in AC/DC systems:* Tool#12 provides measurement-based inertia estimation using PMU data streams retrieved via a Phasor Data Concentrator. It processes voltage and current phasors, frequency, and ROCOF measurements, applies filtering and preprocessing techniques, and estimates system inertia through state-estimation methodologies using sliding-window analysis. The tool generates alarms when inertia values fall below predefined thresholds, enhancing situational awareness. In this demonstration, Tool#12 enables near-real-time inertia observability in a low-inertia island system, supporting operator decision-making and the activation of corrective actions.
- *Tool#13 – Provision of adaptive synthetic inertia and frequency support by HVDC systems:* Tool#13 validates coordinated synthetic inertia and frequency support strategies delivered through HVDC converter stations. It enables adaptive control mechanisms that provide fast frequency response and dynamic support at terminal level, improving system stability during disturbances. In Demonstration 4, Tool#13 is used to evaluate coordinated HVDC-based support across terminals within the digital twin environment, ensuring that frequency deviations are mitigated efficiently and that dynamic stability margins are enhanced in a converter-rich transmission system.

Stakeholders involved in this demonstration include:

- *System operator:* providing transmission network models, operational constraints, and disturbance scenarios for validation.
- *Technology providers:* supplying measurement infrastructure (e.g., PMUs), control systems, and HVDC terminal technologies necessary for real-time implementation and testing.
- *Research partners:* responsible for digital twin modelling, PMU-based workflow development, cascading scenario definition, KPI tracking, and comprehensive performance assessment of inertia estimation and HVDC-based dynamic support strategies.

3.2 Diversity of technical contexts

The HYNET tools span a wide spectrum of technical contexts, covering strategic infrastructure planning, reliability and resilience assessment, dynamic simulation, real-time monitoring, and converter-based control. Rather than addressing a single layer of the power system, the tools collectively form a vertically integrated framework that links long-term planning methodologies with operational optimisation and sub-second stability support mechanisms.

Table 1. Comparative Overview of HYNET Tools

Tool	Category	Primary Role	Time Horizon	Methodology	Core Technical Focus
Tool#1 Power dispatch & voltage control	DC Modelling & Operation	Operational optimisation	Operational / Near real-time	Deterministic control optimisation	Voltage regulation, congestion management,

Funded by the European Union
HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

					coordinated DER control
Tool#2 Inertia compensation scheme	Grid-Forming & Inertia Support	Real-time monitoring & alarm	Real-time	PMU-based estimation	Inertia estimation, frequency stability awareness
Tool#3 Multi-energy vector integration	Planning	Strategic planning	Long-term	Multi-energy system modelling	Cross-sector planning, RES-driven infrastructure expansion
Tool#4 TEA-based adequacy & security analysis	Reliability & Resilience	Planning & system assessment	Long-term / Scenario-based	Techno-economic adequacy & security analysis	Adequacy, N-1 security, cost-benefit optimisation
Tool#5 Computational suite for steady-state & dynamic analysis	DC Modelling & Analysis	Dynamic simulation & validation	Scenario-based / Dynamic	Steady-state & transient simulation	Frequency stability, reinforcement comparison
Tool#6 Reliability & resilience analysis for MVDC/LVDC	Reliability & Resilience	Analytical resilience assessment	Scenario-based	Reliability modelling & resilience metrics	Service continuity, DC-based resilience improvement
Tool#7 Grid planning tool for HVDC/MVDC/LVDC	Planning	Network expansion planning	Long-term	Scenario-based infrastructure optimisation	Hybrid AC/DC reinforcement planning
Tool#8 Grid-forming control of inverter-based resources	Grid-Forming & Inertia Support	Dynamic control	Real-time / Sub-second	Control algorithm (voltage-source grid forming)	Synthetic inertia, frequency containment, weak-grid support
Tool#9 Static & dynamic cascading analysis	Reliability & Resilience	Security & risk analysis	Scenario-based / Dynamic	Cascading failure modelling	Disturbance propagation, resilience assessment
Tool#10 Stochastic security analysis for hybrid AC/DC transmission	Reliability & Resilience	Security assessment under uncertainty	Scenario-based / Long-term	Stochastic security analysis	Risk-aware HVDC corridor planning
Tool#11 Islanding, service restoration & protection	DC Modelling & Operation	Protection & restoration management	Operational / Post-fault	Protection coordination & restoration logic	Fault isolation, hybrid AC/DC protection

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Tool#12 Quasi real-time inertia estimation	Grid-Forming & Inertia Support	Real-time monitoring	Real-time	PMU-based sliding-window estimation	Low-inertia observability, stability awareness
Tool#13 Adaptive synthetic inertia & frequency support by HVDC	Grid-Forming & Inertia Support	Dynamic control	Real-time / Sub-second	Converter-based adaptive control	HVDC-based frequency support, coordinated inertia provision

The diversity is reflected across multiple technical dimensions. From a temporal perspective, the tools range from long-term multi-energy system planning and techno-economic adequacy assessment (e.g., corridor development and hybrid network expansion) to real-time inertia estimation and adaptive frequency support. Methodologically, the portfolio incorporates deterministic steady-state analysis, dynamic transient simulations, stochastic security evaluation, state-estimation-based monitoring, cascading risk modelling, and advanced control algorithms. Functionally, the tools address complementary technical challenges, including adequacy, N-1 and stochastic security, voltage regulation, protection coordination, inertia observability, synthetic inertia provision, and HVDC-enabled dynamic support.

This structured diversity ensures that HYNET does not provide isolated analytical components, but rather a coherent set of interoperable tools capable of supporting hybrid AC/DC systems across their full lifecycle — from conceptual planning and infrastructure reinforcement decisions to real-time operation and resilience management in converter-dominated power systems.

3.3 Role of demonstrations in supporting pan-European scalability

The role of demonstrations in supporting pan-European scalability is intrinsically linked to the architectural logic and integration philosophy of the HYNET Workbench developed in Task 2.4. While the demonstrations provide empirical validation environments across diverse system sizes and operational contexts, the Workbench acts as the structural backbone that organises, integrates, and systematises the developed tools into a coherent interoperability ecosystem. In this sense, scalability is not achieved solely through individual tool validation, but through the Workbench's ability to categorise, layer, combine, and redeploy these tools across heterogeneous hybrid AC/DC scenarios.

The HYNET Workbench, as seen on Figure 8, is conceived as a technology repository and integration ecosystem that enables different stakeholders (researchers, system operators, industry, standardisation bodies) to converge on common functional specifications and interoperable models for AC/DC hybrid electricity networks. It is presented as a universal architecture aligned with the Smart Grid Architecture Model (SGAM), underpinned by dedicated components forming the building blocks of HYNET tools and methodologies (the "Tech Repository").

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

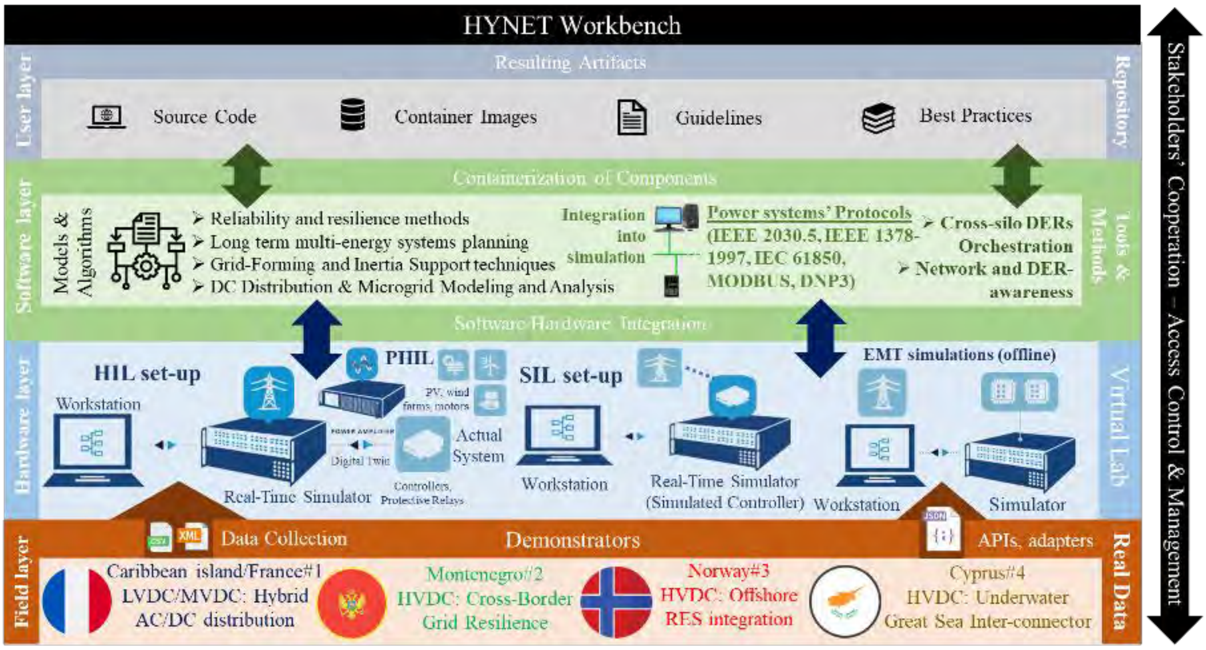

Figure 8. HYNET Workbench

A central Workbench function is tool categorisation and functional layering, enabling a structured view of the portfolio and making it easier to combine tools into end-to-end workflows rather than treating them as stand-alone components. The Workbench portfolio can be explicitly grouped into four categories that correspond to distinct functional needs and analysis layers in hybrid AC/DC systems (see Table).

Table 2. HYNET Workbench categories

HYNET Workbench category	Tools	Typical functional layer/purpose
Reliability & resilience methods	Tool#4, Tool#6, Tool#9, Tool#10	System adequacy/security assessment, resilience and risk evaluation (including cascading and stochastic security)
Long-term multi-energy systems planning	Tool#3, Tool#7, Tool#11	Strategic planning and architecture assessment for grid evolution and hybrid reinforcement pathways
Grid-forming & inertia support techniques	Tool#2, Tool#8, Tool#12, Tool#13	Dynamic stability support and observability (grid-forming control, inertia estimation, adaptive frequency support)
DC distribution & microgrid modelling and analysis	Tool#1, Tool#5	Distribution/microgrid operational analysis, coordination, and modelling tools for DC/hybrid contexts

This categorisation also supports functional layering across the lifecycle of pan-European hybridisation: from planning and orchestration studies, through operational decision support, down to control/protection-relevant functions. In this sense, the Workbench provides a systematic way to position each tool in the broader interoperability stack, rather than defining interoperability narrowly as "data exchange only."

The Workbench's approach to scalability and replicability is built on modularity, vendor-neutrality, and repeatability of deployment across diverse environments. The hybrid AC/DC systems grow in complexity and that portability of services across environments becomes critical; therefore, the

Funded by the European Union
HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Workbench is aligned with practices that allow tools and interoperability components to be packaged and redeployed consistently.

Validation and testing environments are treated as a core Workbench element because interoperability for hybrid networks must be validated under realistic dynamics, communications, and disturbance conditions. The simulation and real-time testing frameworks are necessary to validate controllers, protection schemes, and system interactions before deployment, and it discusses a range of environments relevant to hybrid AC/DC systems: offline simulation, real-time simulation, Hardware-in-the-Loop (HIL)/Power-HIL, and Digital Twin modelling. In parallel, the hybrid AC/DC operation relies on robust communications and that interoperability testing must include protocol integration and multi-vendor considerations, referencing the role of protocols such as IEC 61850 and others in hybrid-grid automation and data exchange. Taken together, these elements position the Workbench as an ecosystem that combines tool artefacts, interoperable interfaces, and validation pathways rather than a simple catalogue of software components.

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

4. Interview-Based Scalability and Replicability Assessment

4.1 Interview methodology

Interviews were conducted with representatives of five HYNET demonstrations: Cyprus, France 1A, France 1B, Montenegro, and Norway. A semi-structured interview format was applied, where core questions were reused across all demonstrations to enable cross-site comparison while preserving the ability to capture site-specific constraints and enabling conditions. The interview guide structured the discussion into three main blocks:

- Project Introduction
- Scalability, Replicability, and Standardization
- Regulatory and Physical Constraints

4.1.1 Questions asked during the interviews

The interviews conducted for the Scalability and Replicability Analysis of the HYNET project followed a structured methodology aimed at evaluating the deployment potential and strategic relevance of hybrid AC/DC solutions. The interview questions were organized into four key thematic areas.

The interview methodology applied in this study follows a semi-structured qualitative approach, aimed at collecting expert insights from demonstration leads within the HYNET project. This method enables a balance between guided inquiry and open-ended exploration, allowing respondents to elaborate on key thematic areas such as scalability, replicability, standardization, and regulatory challenges related to hybrid AC/DC systems. The interviews were conducted using a predefined questionnaire covering technical and operational dimensions, ensuring comparability across cases while preserving the flexibility to capture context specific knowledge.

Scalability and Replicability

The first thematic area focused on evaluating the scalability and replicability of the technologies demonstrated. Scalability refers to the potential for expansion to energy systems of different scales (from large networks to microgrids), whereas replicability addresses the transferability of solutions across different geographic, regulatory, or technical contexts. Interviewees were asked to reflect on performance under scaled conditions, infrastructure constraints, cost implications, and the adaptability of their solutions to diverse grid configurations, climates, and regulatory environments.

Critical Technical Enablers for Large-Scale Deployment

The second thematic area asked respondents to identify the most critical technical conditions for successful implementation of large-scale projects. These include factors such as scalability of power electronics, stability of hybrid AC/DC grids, integration techniques for AC and DC components, deployment of energy storage systems, protection and fault management strategies, real-time communication and data exchange requirements, and overall infrastructure readiness.

System Interoperability and Standardization

A core objective of the HYNET project is to advance common standards for hybrid AC/DC energy systems. This thematic area explored how different subsystems – electrical, control, communication, and regulatory – interact within each demonstration. Interviewees were asked to assess how such interoperability facilitates or constrains the scalability of their solutions and whether their activities are aligned with, or contribute to, formal standardization efforts at the national or European level.

Regulatory, Infrastructural, and Market Barriers

To identify non-technical barriers to deployment, this section of the interviews addresses regulatory challenges, market fragmentation, and the availability and cost of critical components. Respondents

Funded by
the European Union
HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

were asked whether custom-built equipment was required or if commercially available off-the shelf solutions could support broader replication and scaling.

Together, these four thematic blocks enabled a comprehensive assessment of the potential of each demonstration to serve as a replicable and scalable model for future hybrid AC/DC grid systems across Europe.

4.2 Summary of qualitative findings

Scalability and replicability were common goals across all HYNET demonstrations, although specific enabling conditions varied. The French demo's grid-forming battery system was found to be technically scalable owing to the use of standardized low-voltage converters; however, its replicability depends on the precise tuning of control parameters to suit local grid dynamics. The Medium Voltage Direct Current (MVDC) component of the French demo faces more fundamental constraints, particularly the high cost and limited commercial availability of protection equipment, which hinder broader deployment. The Montenegrin demo emphasizes flexibility in tool design; however, replicability will depend on adaptability across various grid configurations and system architectures. The Norwegian demo reports that its planning and simulation tools are inherently scalable, applicable from regional to continental levels, and capable of modelling multi-energy developments. However, real-time control tools, such as inertia estimation, are constrained by the availability of synchronized data, hardware, and communications infrastructure. In the Cypriot demo, the use of a real-time digital twin supports high replicability, particularly in islanded or weak grid contexts, by enabling scenario emulation without the need for physical deployment. However, scalability relies on the presence of PMUs, a robust communication infrastructure, and configurable converter controls.

Regarding technical enablers, all demos identified scalable power electronics and converter technologies as critical. The French demo noted a likely transition from three-level to multilevel converter topologies, as battery systems scale from distribution to transmission levels. Grid stability and inertia management are common concerns. The French, Norwegian, and Cypriot demos addressed the need for enhanced frequency support in low-inertia environments through approaches such as virtual inertia emulation, adaptive grid-forming controls, and real-time inertia estimation using PMUs' data. Hybrid DC/AC Protection and fault management remain major bottlenecks. The French demo highlighted the lack of commercially available MVDC circuit breakers as a key barrier. Similarly, the Montenegrin and Norwegian demos acknowledged that conventional AC protection methods are insufficient for DC environments, particularly in meshed grid topologies. The French and Cypriot demos benefit from access to advanced laboratory environments and controllable testbeds, whereas the Montenegrin and Norwegian demos are still in the process of securing the physical infrastructure required for real-world validation.

With regard to system interoperability and standardization, the demos exhibited varying levels of engagement. Despite its technical maturity, the French demo's grid-forming work has not yet been aligned with formal standardization frameworks. Its MVDC activities explicitly point to the lack of standards for MVDC protection as a structural barrier to broader adoption. The Norwegian and Montenegrin demos are not currently involved in formal standardization processes but anticipate contributing to future frameworks, particularly in grid modelling, adequacy planning, and system coordination. On the other hand, the Cypriot demo demonstrated strong alignment with standardized protocols, integrating PMU-based measurements and testing both droop-based and communication-based HVDC control strategies, supporting HYNET's interoperability objectives.

Finally, regulatory, market, and infrastructural constraints differ significantly. The French demo operates within a more established framework, yet lacks specific market mechanisms for services, such as grid-forming frequency support, which limits commercialization. Additionally, legal separation between Distribution System Operators (DSOs) and service providers constrains asset ownership options. On the contrary, the Norwegian and Montenegrin demos remain at an earlier stage, focusing on simulation and planning. The Cypriot demo faces an underdeveloped electricity market, limited ancillary services, and regulatory gaps related to HVDC, all of which are compounded by geopolitical uncertainties. Regulatory alignment and stakeholder engagement are expected to advance as project scenarios mature.

In terms of technological availability, these conditions remain uneven. The French demo reports commercial readiness for battery-based systems, whereas MVDC components remain expensive and largely custom engineered. The Norwegian and Montenegrin demos possess mature software environments. The Cypriot demo benefits from an extensive PMU network and has access to most HVDC control functionalities, although some adaptation is still required.

In summary, Table 3presents a qualitative evaluation of the HYNET demonstrations. The main findings derived from the interviews are summarized in section 5.1.

Table 3. Qualitative Assessment of HYNET Demonstrations (++ Favourable; -- Challenging)

Theme	Fr. 1a	Fr. 1b	Me.	No.	Cy.
Scalability	++	--	++	+	++
Replicability	++	-	+	-	+
Standardization	-	--	+	+	++
Regulatory Barriers	-	-	+	--	-
Hardware Readiness	++	--	-	+	+

4.3 Influence of Interview Findings on the Stakeholder Questionnaire Design

The qualitative findings derived from the structured interviews with HYNET demonstration leaders were systematically used as a foundational input for the development and refinement of the stakeholder questionnaire. The questionnaire design process was not conducted independently; rather, it was directly informed by recurring themes, identified barriers, enabling conditions, and cross-demonstration patterns revealed during the interview-based analysis.

The stakeholder questionnaire was directly informed by the qualitative findings derived from the structured interviews. The interviews served as the exploratory analytical layer of the Scalability and Replicability Analysis, while the questionnaire was designed to validate and generalise these findings at EU level.

Recurring themes identified during the interviews, including infrastructure dependency (e.g., PMU availability and communication backbone), protection maturity for MVDC systems, converter control configurability, interoperability challenges, and regulatory misalignment, were systematically translated into structured questionnaire items. These themes shaped questions addressing large-scale deployment feasibility, SCADA/EMS readiness, standardisation alignment, grid-forming capabilities, and perceived regulatory barriers.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Demonstration-specific constraints were abstracted into broader stakeholder-level questions. For instance, the dependence of inertia estimation tools on synchronized measurements led to items assessing infrastructure readiness; identified standardisation gaps motivated questions evaluating whether existing IEC, IEEE, and ENTSO-E frameworks are perceived as sufficient; and regulatory barriers observed in certain demos were reflected in open-ended questions on market and legal constraints.

The questionnaire structure mirrors the thematic dimensions applied in the interview analysis: technical scalability, operational readiness, regulatory alignment, and interoperability/standardisation aspects. This ensures methodological consistency and traceability between qualitative demo-level insights and EU-wide stakeholder assessment.

In this way, the interviews did not merely precede the questionnaire but structurally shaped its content, prioritisation, and analytical focus, enabling the extension of demonstration-based findings toward a pan-European perspective.

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

5. Cross-Demonstration Analysis

5.1 Identified barriers and limiting factors

The cross-demonstration assessment highlights both the heterogeneity and the common development pathways of the HYNET pilot sites in advancing scalable and replicable hybrid AC/DC solutions. Although the demonstration areas differ in system size, regulatory environment, and technological maturity, they converge around key principles such as modular design, resilience enhancement, and interoperability across voltage levels and vendors. The analysis confirms that large-scale deployment of hybrid AC/DC architectures requires more than advanced converter technologies and control strategies. Enabling conditions include synchronized measurement infrastructures, real-time emulation and validation platforms, robust protection concepts, and regulatory frameworks that explicitly accommodate hybrid operation. While planning, simulation, and resilience assessment tools are generally well developed, practical deployment readiness varies across sites. Several limiting factors were consistently identified, including protection hardware constraints, gaps in standardization, market design misalignment, and challenges in cross-border coordination. These barriers are not purely technical; they reflect the need for coordinated progress across technology development, regulatory adaptation, and market evolution. Table 4 shows a summary of the findings of the interviews.

Table 4. Thematic comparison of HYNET demonstrations based on interview

Theme	France 1a	France1b	Montenegro	Norway	Cyprus
Focus	Grid-forming battery systems for DSO.	MVDC architecture for DSO reinforcement strategies.	Cross-border hybrid grid resilience and T&D coordination.	Offshore HVDC design and multi-energy planning for RES and inertia estimation.	HVDC interconnection and digital twin validation.
Tool Examples	Grid-forming control algorithms.	Optimal power flow and MVDC protection tools.	Inertia monitoring and techno-economic planning tools.	Techno-economic optimization, grid security assessment, inertia mitigation.	Resilience analysis, PMU-based inertia estimation, HVDC virtual inertia control.
Scalability	Grid-forming solutions are scalable.	MVDC is limited by cost and protection complexity.	Tools designed for generalizability.	Planning tools are scalable; real-time deployment depends on system integration.	Scalable with existing PMU infrastructure and robust communication systems.
Replicability	High for battery-based solutions.	MVDC replication depends on standardization and investment.	Expected to be replicable after validation.	High for simulation; physical deployment requires harmonized infrastructure.	Replicable in similar isolated grid contexts with compatible infrastructure.
Standardization	Technically mature but not standardized.	No formal engagement yet; MVDC domain lacks mature standards.	Advocates early harmonization with EU standards.	Potential alignment via Common Information Modelling (CIM) and grid modelling frameworks.	Applies IEEE protocols and compares HVDC control strategies for future interoperability.
Regulatory Barriers	Mature framework; lack of market	Protection strategies and DCCB technology must be developed.	Regulatory discussions are ongoing.	Regulatory processes not yet in place for offshore HVDC operation.	Immature market design, TSO contribution to the Grid Code,

					geopolitical uncertainties.
Hardware Readiness	Battery systems mature.	MVDC hardware is costly and non-standard.	Prototype-phase hardware; scaling constrained by cost and readiness.	Simulation environment advanced; field-level hardware integration pending.	PMU network in place, HVDC controller tested in emulation.

Overall, the findings support the importance of systemic alignment between innovation, policy frameworks, and operational practices. By identifying shared constraints and enabling conditions across diverse demonstration environments, the project provides structured input to the HYNET roadmap and contributes to the broader European transition toward interoperable hybrid AC/DC grid architectures. Continued monitoring of scalability, replicability, and standardization aspects will remain essential as demonstrations evolve toward higher TRL and pre-commercial deployment stages.

5.2 Tool-Level Replicability and Scalability Assessment Across European Power Systems

This section provides a tool-level assessment of the replicability and scalability of the HYNET solutions across European power systems. The evaluation does not address demonstration sites as a whole but examines each developed tool individually in terms of its transferability and large-scale deployment potential.

5.3 Power Systems

The assessment is grounded in the results of the tool-leader barriers questionnaire conducted under Task 6.2, which systematically captured technical, operational, and institutional barriers across ten categories for each of the thirteen HYNET tools. The findings complement the qualitative insights derived from the demonstration interviews presented in Section 4 and are structured to support the identification of common deployment constraints and tool-specific replication conditions across heterogeneous European power system environments.

5.3.1 Transferability Across Locations

At tool level, transferability refers to the extent to which a given solution can be implemented in a different European grid context beyond its original demonstration environment. The assessment focuses on the following dimensions: required technical adaptations (e.g., parameter tuning, model adjustments, grid topology differences); alignment with national grid codes and operational rules; data availability and measurement infrastructure prerequisites; IT and communication architecture compatibility; and regulatory and market framework constraints. The objective is to identify whether deployment in a different TSO or DSO environment would require minor configuration adjustments or substantial structural modifications.

Software Platform Dependencies and Licensing

Software platform dependency constitutes one of the most structurally significant barriers to tool transferability across European institutions. The questionnaire reveals a clear differentiation between tools with minimal software constraints and those whose replicability is substantially conditioned by commercial platform requirements. Tools #6, #7, and #11 (developed by INESC) are built exclusively on open-source Python libraries and present no software licensing barriers, representing the most portable profile within the portfolio. In contrast, Tool#1 and Tool#5 currently depend on DIgSILENT PowerFactory, while Tool#8 (GEPC) operates across DIgSILENT PowerFactory, MATLAB/Simulink, and OPAL-RT RT-Lab, requiring institutional access to three distinct commercial platforms. Tool#13 (UCY) similarly depends on MATLAB/Simulink and OPAL-RT, with specific version compatibility constraints

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

(MATLAB 2022b and RT-Lab 2023.3) that condition deployment environments precisely. Tool#3 (Artelys) is itself a commercial software product, while Tool#4 (SGI) relies on AMPL in its community version but may transition to an alternative solver during the project lifecycle.

From an operating system perspective, the majority of tools are platform-agnostic; however, Tool#8 requires Windows or specific Linux distributions, and Tool#9 operates exclusively on Windows. Tool#2 requires an environment capable of running Docker containers, which is widely available across operating systems but introduces a containerisation prerequisite. License restrictions that limit the number of concurrent users or geographic installations apply to Tools #1, #2, #3, #4, #5, #8, and #13, meaning that institutional procurement or access agreements with software vendors would be necessary prior to replication. This creates a cost and administrative barrier for smaller or less-resourced organisations wishing to adopt these tools. Tools #6, #7, #11, and #12, by contrast, impose no licensing restrictions and can be installed and operated without vendor-dependent authorisation processes.

Most tools are transitioning toward Python-based implementations, which is a positive signal for long-term portability. Tool#1, for example, is planned to migrate from its current PowerFactory dependency to a pure Python stack. Containerisation support (Docker) has been confirmed or is planned for Tools #2 through #7 and Tools #10 and #11, which will significantly reduce installation friction and improve deployment consistency across heterogeneous IT environments.

Geographical and Topological Flexibility

The questionnaire responses indicate that the HYNET tool portfolio is broadly flexible in terms of grid topology, with no tool being strictly limited to a single network configuration. Tools #1, #3, #4, #5, #6, #7, #10, and #11 explicitly confirm topology-agnostic design, capable of adapting to radial, meshed, AC, DC, and hybrid network configurations. Tool#2 is designed for application in any network configuration with PMU availability, while Tool#9 targets meshed transmission grids, which is the topology most relevant to its cascading analysis functionality.

Voltage-level applicability, however, introduces structural differentiation within the portfolio. Tools #1, #5, #6, #7, and #11 are oriented toward MVAC/MVDC environments, positioning them primarily as distribution-level tools. Tools #4 and #10 target hybrid transmission networks (HVAC/HVDC), making them most relevant for TSO-level applications and HVDC corridor planning. Tool#2 focuses on HVAC systems at any voltage level given PMU availability, while Tool#13 is explicitly designed for HVDC applications. Tools #8 and #9 are MV-oriented and transmission-oriented respectively. Tool#12 (UCY) reports voltage-level independence, as its inertia estimation methodology applies to any grid level where synchronous generation is present and PMUs provide suitable measurements.

Regarding regulatory and organisational assumptions, the questionnaire confirms that no HYNET tool assumes a specific national or regional grid code framework, with the exception of Tool#4, which is aligned with European ENTSO-E methodology (CBA), and Tool#13, which references European grid code provisions for HVDC. No tool presupposes specific organisational structures such as TSO-DSO coordination models that do not exist in other contexts. Documentation will be available in English for all thirteen tools, which is a necessary but not sufficient condition for pan-European accessibility.

Data Requirements and Measurement Infrastructure

Data availability constitutes a significant and differentiated barrier to transferability, particularly for tools whose operation depends on specialised or real-time measurement infrastructure. The most constrained tools in this dimension are Tool#2 and Tool#12, both of which require PMU infrastructure and Phasor Data Concentrators (PDCs) capable of delivering measurements at millisecond temporal resolution. For Tool#2, the absence of real-time PMU data causes the inertia estimation output to be frozen rather than degraded gracefully, which represents an operational risk in regions with limited synchrophasor deployment. Tool#12 can partially mitigate this constraint by operating on historical PMU recordings in offline mode, providing a degree of flexibility for environments where real-time data infrastructure is not yet in place.

Tool#8 (GEPC) requires SCADA-linked commercial data and its grid models are orientation-specific (MV). Tools #4 and #10 both depend on TSO network models and market data, which are by nature proprietary and subject to data-sharing agreements; their availability cannot be assumed across all European contexts, particularly in candidate countries or regions with limited open data policies. Tools #1, #5, #6, #7, and #11 require grid models that are similarly potentially confidential but are typically available to the implementing institution and require only structured access agreements rather than specialised measurement hardware.

Historical data requirements are generally limited across the portfolio. Tool#4 requires historical weather years or typical meteorological year data for scenario construction, which are publicly available through ENTSO-E and Copernicus. Most other tools either operate without historical time-series requirements (Tools #6, #7, #12) or use configurable temporal resolution. Tools that implement Monte Carlo methodologies (Tools #3 and #10) require sufficient scenario data to support probabilistic analysis, but this is handled through parametric scenario generation rather than mandatory access to long historical records.

Data format standardisation is moderately advanced across the portfolio. Tool#4 and Tool#10 support CIM/CGMES import and export, which is the dominant interoperability standard in European transmission system data exchange. The majority of other tools rely on CSV and JSON formats, which are widely accessible but lack the semantic richness of CIM-based exchange. Tool#2 outputs data through Modbus TCP protocol, enabling integration with SCADA systems, while Tool#13 also uses Modbus TCP for data exchange.

Hardware Infrastructure Prerequisites

Hardware dependency is the most heterogeneous dimension across the tool portfolio and represents the most significant barrier to low-cost replication. The majority of tools — specifically Tools #1, #3, #4, #5, #6, #7, #9, #10, #11, and #12 — can run on standard workstations without requiring specialised hardware, which strongly supports replicability in academic, research, and operational environments across Europe.

The principal exceptions are Tool#8 and Tool#13, both of which require OPAL-RT real-time simulation hardware for their intended operation. Tool#8 uses an OPAL-RT platform (model 5707) for its Hardware-in-the-Loop validation, with a fixed-step execution cycle of 50 µs, while Tool#13 relies on OPAL-RT for real-time execution of its HVDC control models and coordination logic. Since OPAL-RT systems represent a substantial capital investment typically available only at well-equipped university or industrial research facilities, the replication of these two tools is structurally constrained to institutions with access to such infrastructure. Tool#2 additionally requires a Real-Time Digital Simulator (RTDS) for testing purposes, though its offline version can operate from CSV files, partially mitigating this dependency.

Communication infrastructure requirements are limited for most tools. Tools #2 and #12 rely on PMU/PDC communication networks, which require specific IEC 60255-118-compliant measurement devices and supporting communication infrastructure. Tool#13 uses Modbus TCP as a coordination interface. The remaining tools do not impose specific communication infrastructure dependencies, operating instead on standard IT networks.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Cloud versus on-premise deployment presents a further consideration for transferability. Tools #4, #5, and #9 are designed for on-premise server deployments, with cloud adaptation requiring additional development effort. Tool#3 supports both cloud and on-premise configurations. Tool#12 is currently an on-premise solution but notes that web-based deployment would require supplementary development steps beyond the project scope.

Interoperability and Integration Capability

The HYNET tool portfolio demonstrates a generally positive profile in terms of inter-tool integration and interface availability, supported by a consistent preference for Python-based APIs across the portfolio. Tools #1, #3, #4, #5, #6, #7, #9, #10, #11, and #13 all expose or are developing Python APIs for programmatic integration. Tool#12 additionally supports cloud-based data sharing (ThingSpeak) and CSV export for integration with external tools, providing flexible connectivity options for both online and offline workflows.

Within the HYNET ecosystem, several integration pathways have been established or planned. Tool#3 (multi-energy planning) exchanges outputs with Tool#10 (stochastic security). Tool#4 is planned to integrate with Tool#9 for cascading analysis and provides results to Tool#2. Tools #5, #6, and #7 form an integrated distribution-level cluster, and Tool#13 coordinates with Tool#12 for inertia estimation feedback. These documented integration pathways demonstrate that the tools are not conceived as isolated components but are positioned within interoperable workflows aligned with the HYNET Workbench architecture.

Model exchange format support is more limited outside Tools #4 and #10, which support CIM/CGMES, IIDM, and netCDF formats. Tool#9 can import/export PowerFactory models, while Tool#8 operates primarily within the DIgSILENT/MATLAB/RT-Lab ecosystem. Most distribution-level tools do not yet support standardised model exchange formats beyond CSV, which constrains automated integration with third-party planning platforms. Vendor lock-in risk is low across the portfolio; no tool introduces proprietary data formats or interfaces that would prevent future migration, with the partial exception of tools dependent on commercial simulation platforms.

Knowledge, Training, and Documentation

The human capacity requirements for deploying HYNET tools vary significantly across the portfolio and represent an important replicability dimension, particularly for potential adopters outside the developing organisations. Tools #2, #3, #5, #6, #7, and #11 require intermediate-level power system knowledge, covering topics such as network simulation, optimal power flow, and reliability analysis, without presupposing specialised expertise in power electronics or HVDC technology. Tool#12 is designed for basic-level users through a graphical interface under development, making it the most accessible tool in the portfolio. Tool#4 requires intermediate knowledge in electricity market simulation and optimal power flow.

The most demanding tools in terms of expertise are Tool#8 (GEPC), which requires expert-level knowledge in power electronics and HVDC systems, and Tool#9 (UCY) and Tool#13 (UCY), both of which require expert-level knowledge in protection, control, and HVDC-specific engineering domains. For these tools, learning curves are estimated at two to six months, compared to a few weeks for the majority of intermediate-level tools. Tool#3 stands out positively with a web-based application accessible to non-programmers, and with training materials already available.

Documentation quality is largely still in progress (WIP) across the portfolio, reflecting the early stage of the project. Tool#3 provides comprehensive documentation including user manuals and API documentation. Tool#4 and Tool#8 have committed to user manuals and API documentation by project end. The absence of user communities or external support structures beyond the developing organisations is a consistent characteristic across the portfolio, which may constrain post-project adoption unless addressed through dedicated dissemination and training activities. Tool#10 benefits from reliance on the open-source PowSyBl framework, which has an active external developer community.

5.3.2 Scalability Potential

This section evaluates the capability of each tool to operate in systems significantly larger than the original demonstration environment, including networks with expanded geographical scope, higher numbers of assets and nodes, increased installed capacity, or substantially greater data volumes. The assessment considers technical, computational, communicational, and operational implications of scaling up and identifies constraints that may influence large-scale deployment across European power systems.

Computational Performance and Time-Domain Constraints

Computational scalability is a critical dimension for tools intended for use in large transmission networks or in real-time operational contexts. The questionnaire responses reveal a binary distribution within the portfolio: tools designed for offline planning or quasi-real-time analysis, and tools subject to hard real-time execution constraints.

For the offline planning and analysis tools, computational performance scales with problem complexity as expected. Tool#3 (ART) reports that computation time grows with the number of nodes, time steps, and uncertainty dimensions, but this is manageable through standard desktop or server infrastructure. Tool#4 can leverage parallel computing through solver configuration, with implementation to be confirmed, and is designed to accommodate large transmission-scale problems. Tool#9 and Tool#10 similarly scale with grid complexity and are suited to large meshed networks, with Tool#10 operating effectively on standard workstations.

Real-time tools face inherently different constraints. Tool#8 operates at a 50 µs fixed-step execution cycle on OPAL-RT hardware, a requirement that cannot be relaxed without compromising the validity of the hardware-in-the-loop validation framework. Tool#13 similarly requires real-time execution for its HVDC coordination models, with the OPAL-RT platform providing 100–500 times faster than offline simulation as an enabling capability. For both tools, scalability is constrained not by software architecture but by the physical limits of the real-time simulation hardware and the number of processing cores available. Tool#2 produces inertia estimates every three to four minutes through its measurement processing pipeline, which is appropriate for its operational monitoring role but would require parallel processing extensions to support simultaneous monitoring across multiple large areas.

Memory and computational resource requirements are modest for the majority of tools. Tools #8, #9, and #10 recommend a minimum of 16 GB of RAM for standard operation. Tool#2 operates within a server environment demanding 2 logical cores of an Intel Xeon Gold processors with 554 MB working RAM for the estimation module, which is easily available on standard institutional computing infrastructure. No tool currently implements parallel computing across multiple cores in an explicit, user-configurable manner, with the exception of Tool#4, where solver-level parallelism is possible, and Tool#8 and #13, where multi-core usage is managed by the real-time simulation platform.

Validation, Benchmarking, and Result Reproducibility

The availability of benchmark cases and validation evidence is a prerequisite for confident deployment beyond the original demonstration context. Across the portfolio, all tools confirm that their results are reproducible given the same inputs, with known sensitivity factors such as random seeds and solver settings documented for stochastic tools. This baseline reproducibility is a necessary, though not sufficient, condition for scalability in European deployment contexts.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Benchmark availability is positive for most tools. Tools #1, #5, #6, #7, #9, #11, and #12 refer to standard benchmark cases available in the literature (e.g., IEEE test systems). Tool#2 has been validated against the IEEE 39-bus benchmark. Tool#3 uses open ENTSO-E TYNDP data as a publicly available reference case. Tool#4 has constructed a standard test case within Task 3.2, and Tool#10 references WIP benchmark development Tool #13 does not yet rely on a standardized or literature-based benchmark case; however, it has been validated through hardware-in-the-loop testing in a dedicated experimental environment.

Validation against real-world systems remains limited across the portfolio, with most tools currently validated in simulation only. This is consistent with the TRL 3–5 scope of the project but represents a gap that must be addressed in post-project deployment phases. Tool#2 has been validated exclusively in simulation; Tools #8 and #13 have undergone hardware-in-the-loop validation, which constitutes the most advanced real-world-adjacent validation environment currently available within the portfolio.

Uncertainty quantification is available in Tools #4 and #10 through Monte Carlo and distributional output methods, while Tools #5 and #6 report WIP implementations. Tools #8, #12, and #13 do not currently provide uncertainty bounds on their outputs, which may limit their suitability for risk-informed operational decision-making in large-scale deployments until this capability is developed.

Network Size, Multi-Area Operation, and Technology Diversity

The scalability potential dimension of the questionnaire directly addresses whether tools can be applied to networks significantly larger than their current demonstration environments. The responses reveal a generally positive scalability profile at the design level, with implementation constraints primarily arising from computational performance and data availability rather than architectural limitations.

Tools #4 and #10 are explicitly designed for large transmission-scale systems and confirm support for multi-area configurations with different operators. Tool#3 is a zonal planning tool, which by design operates at the level of regional or national energy system aggregations and scales naturally to continental scope. Tool#9 and Tool#12 report no fundamental network-size limitations within their respective application domains. Tools #1, #5, #6, #7, and #11 report work-in-progress assessments of their upper network-size limits, reflecting ongoing development activities expected to conclude before project end.

Multi-area and multi-operator support is confirmed for Tools #2, #3, #10, #12, and #13, all of which are designed to handle cross-border or multi-region configurations. Tools #1, #4, #5, #6, #7, and #11 currently assume single-operator control environments, which is consistent with their distribution-level application focus, where multi-operator coordination is less structurally embedded than at transmission level. This assumption would require revisiting if these tools were to be deployed in cross-border distribution scenarios.

Technology diversity accommodation is a strength across the portfolio. All tools that responded to this dimension confirm that diverse converter types, DER technologies, and storage systems can be accommodated, with provision for adding new technologies through modular architecture. Tool#3 explicitly supports multi-energy extensions including gas and hydrogen networks. Tool#4 confirms readiness to extend HVDC modelling capabilities and handles hydrogen vectors. Tool#8 and Tool#13 confirm extensibility through MATLAB/Simulink model modification and Python code adaptation respectively. Scenario and Monte Carlo analysis capabilities are confirmed for Tools #3, #4, #9, #10, #11, and #12, with Tools #3 and #10 having demonstrated these capacities at scale within their current demonstration environments.

Funded by the European Union
HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

The modular architecture dimension is positive across the portfolio. All tools that provided responses confirm modular design allowing the addition of new components, algorithms, or features. This architectural posture is critical for long-term extensibility and ensures that tools can accommodate evolving European grid technology requirements — including emerging grid-forming converter standards, advanced protection philosophies, and the progressive integration of hydrogen infrastructure — without requiring full redevelopment.

Regulatory, Standardisation, and Intellectual Property Constraints

The regulatory and IP dimension reveals a consistent pattern: all HYNET tools are proprietary, but the majority confirm that proprietary status does not inhibit adaptation or deployment by other organisations, provided appropriate agreements are in place. The planned commercialisation routes vary by developer: Tools #2 and #3 target sale to TSOs and DSOs/planners respectively; Tool#4 targets TSOs and decision-makers; while Tools #9 and #12 (UCY) plan to provide open access through the HYNET Workbench with IP ownership retained by UCY.

Grid code compliance is neutral for the majority of tools, meaning no specific national regulatory framework is presupposed. Tools #4 and #13 are aligned with European (ENTSO-E) methodologies, which implies that adaptation to non-European regulatory environments would require some reconfiguration, though this is not expected to represent a fundamental barrier within the European context addressed by the HYNET project.

Cybersecurity compliance, specifically with IEC 62351, is not yet addressed by any tool in the portfolio. This gap is consistent with the TRL 3–5 scope of the project but represents a pre-condition for operational deployment in certified infrastructure environments. Tools with real-time communication capabilities (Tool#2, Tool#8, Tool#13) are the most exposed to this requirement and will require cybersecurity assessment prior to integration into live grid infrastructure. Certification requirements are under assessment for Tools #8 and #9, while Tool#12 confirms that no formal certification is required for its current application scope.

Intellectual property constraints are modest. Tools #1, #5, #6, #7, and #11 confirm no IP restrictions on sharing or modification. Tool#8 (GEPC) retains IP within the developing company, as does Tool#9 (UCY), though with the provision of open workbench access. Tool#2 uses proprietary algorithms but confirms these do not limit adaptation. Tool#4 contains proprietary elements within an open-source framework structure, providing a balanced IP posture.

Funded by
the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

6. Standardization and Interoperability Perspectives

6.1 Alignment with existing standards and initiatives

HYNET develops a portfolio of analytical tools, control strategies, and system-integration methodologies aimed at enabling secure and coordinated operation of hybrid AC/DC systems across transmission and distribution domains. The project operates deliberately within the mid-TRL range, focusing on proof-of-concept validation, laboratory integration, and relevant-environment testing rather than on certified field deployment or hardware prototyping.

Given this maturity positioning, HYNET adopts a vendor- and technology-agnostic innovation strategy, emphasising modularity, functional abstraction, and interoperable interface design. While strict implementation of operational technical standards is outside the project scope, structured alignment with existing standards and architectural frameworks is essential to ensure that validated concepts remain transferable to industrial and regulatory contexts in the post-project phase. This chapter therefore examines the Technology Readiness Level context of HYNET, the rationale for its agnostic design philosophy, and the standards and guidance documents that provide a foundation for future exploitation and pan-European scalability of hybrid AC/DC solutions.

6.1.1 Technology Readiness Level (TRL)

In the European Commission TRL framework [18] the maturity scale describes the progression of a technology from early-stage research to operational deployment. The HYNET tool portfolio is intentionally positioned in the mid-TRL research-to-validation range. Therefore, the relevant maturity window is TRL 3 to TRL 5, as the project focuses on methodological development, tool integration, and validation in controlled and representative environments rather than on prototype deployment or commercial implementation.

The following TRL levels are relevant for the HYNET project:

- *TRL 3:* This level corresponds to experimental proof of concept. At this level, active research and development activities are undertaken to verify that the underlying scientific principles can be translated into a technically feasible solution. Analytical studies, simulations, and laboratory-scale experiments are performed to demonstrate that key functions are achievable. Validation is typically limited to isolated components, simplified models, or algorithmic implementations under controlled conditions. Technology is not yet integrated into a representative system architecture, and interactions between subsystems are only partially explored.
- *TRL 4:* This level represents technology validated in a laboratory environment. At this stage, individual components or subsystems are integrated and tested together within a structured laboratory setup. The objective is to verify coherent operation across modules and to assess interface behaviour, control logic, and functional stability under controlled but more system-oriented conditions than at TRL 3. Although the environment remains laboratory-based, the configuration increasingly resembles the intended operational architecture, and preliminary interoperability between functional elements is evaluated.
- *TRL 5:* This corresponds to technology validated in a relevant environment. Here, the integrated solution is tested under conditions that reflect key characteristics of real-world operation. This may include real-time simulation platforms, Hardware-in-the-Loop environments, or representative cyber-physical testbeds that reproduce realistic system dynamics, communication constraints, disturbances, and multi-component interactions. While the technology is still pre-commercial and not yet deployed in the field, it demonstrates functional performance, robustness, and interoperability under conditions that closely approximate practical application scenarios.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

6.1.2 HYNET as an agnostic innovation effort

HYNET is structured as a vendor- and technology-agnostic innovation effort, meaning that it does not rely on proprietary platforms, specific manufacturers, predefined converter technologies, or fixed ICT infrastructures, but instead defines functional interfaces, modular architectures, and interoperable data exchange principles that can be applied across heterogeneous European transmission and distribution environments.

Given that the project operates within the TRL 3-TRL 5 range, the objective is methodological development, integration logic validation, and system-level testing in controlled and relevant environments rather than deployment-ready implementation or formal compliance certification.

Consequently, strict implementation of operational standards is not a project requirement at this stage. Instead, the focus is on creating an agnostic, transferable framework that avoids vendor lock-in, supports multi-vendor hybrid AC/DC configurations, and can later be aligned with applicable standards during post-project industrialisation and real-world deployment.

6.1.3 Relevant Standards

Although the HYNET project does not implement technical standards in a formal compliance or certification sense – primarily because its activities remain within the TRL 3-TRL 5 maturity range and focus on methodological development and validation rather than field deployment -the systematic assessment of relevant standards remains necessary. At these TRL levels, the objective is to validate concepts, architectures, and interoperability mechanisms in controlled and representative environments, not to deliver fully standard-compliant operational systems.

Nevertheless, standards become critically important in the post-project uptake phase, when the developed tools and methodologies are transferred into real transmission and distribution infrastructures. In that context, standards provide common information models and communication profiles for automation, monitoring, and control; they establish reproducible baselines for testing, integration, and commissioning; and they offer regulatory and governance reference points that enable the structured connection of converter-dominated and hybrid AC/DC assets without resorting to bespoke, project-specific integrations for each deployment environment. Consequently, while standards are not directly implemented within the project scope, their structured analysis ensures that HYNET outputs remain compatible with future industrialisation pathways and scalable across heterogeneous European system contexts.

Use case modelling and system architecture standards

Unlike operational technical standards, methodological and architectural standards are directly applied within HYNET because they support structured system design without imposing implementation constraints. Given the TRL 3-TRL 5 scope of the project, the focus is on consistent modelling, requirement formalisation, and interoperability-oriented architecture definition rather than on certified standard compliance. In this context, use case modelling and system architecture frameworks provide a common language and structured foundation for aligning tools, demonstrations, and system interfaces across the hybrid AC/DC ecosystem.

Two standards/frameworks provide the methodological backbone for consistent specification, comparability, and interoperability-oriented structuring of HYNET work products. The IEC 62559 (use case methodology) series defines a standardized methodology for the development, documentation, and structuring of use cases in power system and smart grid contexts. It provides a harmonized framework for describing actors, roles, functional requirements, preconditions, triggers, information exchanges, and system interactions, thereby ensuring consistency across system specification and standardisation activities. While IEC 62559-2 specifies structured templates for use cases, actor lists,

and requirement lists, the broader series establishes the methodological principles and relationships necessary for traceable system definition. In HYNET, this methodology is directly useful because it enforces a uniform and transparent way to express stakeholder roles, functional and technical requirements, information flows, and validation conditions across heterogeneous demonstrations and tools, thereby reducing ambiguity when multiple tools must be integrated within an interoperability-driven workbench environment [19].
The Smart Grid Architecture Model (SGAM) framework formalises a structured architectural mapping across domains and zones, and across the interoperability layers (business, function, information, communication, component). It also explicitly supports the alignment and categorisation of processes, products, and utility operations, and can be used to align standards to those mapped elements. Within HYNET, SGAM is valuable as an architectural reference for identifying responsibility boundaries and interoperability touchpoints in hybrid AC/DC systems – particularly where converter controls, protection, monitoring, market/operation functions, and ICT components must be understood as one cyber-physical system rather than isolated “grid assets” [20].

Communication, monitoring, and automation standards

Communication, monitoring, and automation standards form the technical foundation for interoperable operation of hybrid AC/DC systems in real transmission and distribution environments. Their analysis is essential to ensure that the developed tools and methodologies can be aligned with established automation, measurement, and data exchange frameworks during post-project integration. In this context, IEC 61850 and IEEE C37.118 represent key reference standards for protection, control, monitoring, and wide-area measurement in converter-dominated power systems.

IEC 61850 (power utility automation communications) is defined as applicable to power utility automation systems and specifies communication between intelligent electronic devices (IEDs) and related system requirements. A key implementation enabler is IEC 61850-6, which specifies a configuration description language and file format that supports exchange of IED capability descriptions and system descriptions between engineering tools of different manufacturers in a compatible way. For HYNET’s long-term exploitation, IEC 61850 is the most relevant anchor for integrating monitoring, protection, and control functions at AC/DC interface points (e.g., converter stations, hybrid substations), because it offers an established approach for structured data modelling and interoperable configuration exchange in utility environments. At the same time, hybrid AC/DC deployments introduce stringent timing, cyber-security, and multi-vendor constraints, implying that IEC 61850-based automation architectures will often need careful engineering choices (profiles, mappings, and security handling) when applied to converter-rich and HVDC-heavy environments [21], [22].

IEEE C37.118 (synchrophasor measurement and data transfer) defines synchrophasor, frequency, and ROCOF measurements, including time-tagging and performance requirements under steady-state and dynamic conditions, and specifies PMU-related compliance requirements. IEEE C37.118 specifies the real-time exchange of synchrophasor measurement data between PMUs, PDCs, and applications, including message types and data formats; it also notes that cybersecurity is discussed but considered beyond the scope of the standard. This standard family is directly relevant to stability and inertia observability workflows because it underpins high-precision, time-synchronised measurement exchange needed for system-wide stability assessment and operational decision support in low-inertia contexts [23].

Grid integration of distributed and inverter-based resources standards

Grid integration standards are essential for ensuring that distributed and inverter-based resources can be connected, controlled, and coordinated in a technically consistent and interoperable manner.

Funded by the European Union
HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

IEEE 1547-2018 (DER interconnection and interoperability) defines technical specifications and testing requirements for the interconnection and interoperability between distributed energy resources (DERs) and electric power systems. It includes provisions related to abnormal operating conditions, power quality, islanding behaviour, and interoperability and information exchange. This is directly relevant for HYNET's post-project adoption whenever converter-based resources – such as inverter-interconnected DER, storage systems, and controllable loads – must be integrated in a consistent, testable, and system-compatible manner, particularly as hybrid AC/DC systems increasingly depend on fast-acting inverter-based functionalities such as grid support and voltage/frequency response. However, from a hybrid AC/DC perspective, IEEE 1547 is primarily grounded in DER-to-AC system interconnection at conventional distribution voltage levels; therefore, additional engineering considerations and complementary standards are typically required when extending interoperability requirements toward explicitly DC-based grids or multi-terminal DC distribution architectures [24].

IEEE 2030.5 (application-layer protocol for DER and energy services) defines an application-layer communication protocol over TCP/IP that enables utilities to manage end-user energy environments, including demand response, load control, distributed generation, and electric vehicles. It specifies structured message exchange mechanisms and associated security features for application-level communication. This standard is strategically relevant to HYNET exploitation scenarios where distribution-level coordination of flexibility resources is required because it provides a stable and scalable interface model between utility back-end systems and field-level energy resources, supporting interoperable control in converter-dominated and hybrid system contexts [25].

Voltage levels, system compatibility, and commissioning guidance

Voltage level definition and commissioning guidance standards play an important role in ensuring long-term compatibility and safe integration of hybrid AC/DC infrastructures. Their relevance primarily emerges in the post-project deployment and industrialisation phase, where validated methods and architectures must be aligned with established engineering practices and equipment specifications.

IEC 60038 (standard nominal voltage values) specifies preferential nominal voltage values for electrical supply systems and provides reference values for equipment and system design. From a hybrid AC/DC future-proofing perspective, IEC 60038 is relevant because consistent nominal voltage referencing supports interoperable planning, equipment rating alignment, and interface compatibility across AC and DC boundaries. In large-scale hybrid systems, clear voltage conventions reduce ambiguity in system specification and procurement. However, the ongoing emergence of MVDC concepts and evolving HVDC distribution architectures may challenge existing standard voltage classifications, meaning that early architectural planning must consider how voltage selection and equipment rating strategies align with both current standards and anticipated DC evolution pathways [26].

IEEE 1378 (HVDC converter station commissioning) provides guidelines for commissioning HVDC converter stations and associated transmission systems, including two-terminal HVDC transmission and back-to-back configurations. Although commissioning activities lie outside HYNET's immediate scope the standard becomes relevant in the exploitation phase. It offers a structured baseline for acceptance testing, validation procedures, and commissioning logic when HYNET-developed control, protection, and monitoring concepts transition from validated tool artefacts into deployable system components within converter stations. In this sense, IEEE 1378 does not directly constrain current research activities but provides an important future alignment reference for safe and structured integration into operational HVDC infrastructures [27].

Industry guidance and technical recommendations

Funded by the European Union
HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Industry guidance and cross-sector standards complement technical grid standards by addressing governance, investment coordination, and general data-transfer principles that influence the scalability of hybrid AC/DC systems beyond purely engineering considerations. They provide important contextual and structural alignment references for post-project exploitation and large-scale deployment.

CIGRE Technical Brochure 692 (market and regulatory frameworks for transmission investments) reviews market and regulatory schemes related to transmission planning and investments in the context of liberalised electricity markets, cross-border integration, and extensive renewable development. It highlights the need for improved coordination between adjacent transmission systems and between transmission and generation planning. This guidance is particularly relevant to HYNET's post-project phase because HVDC corridors and hybrid AC/DC reinforcements are not only technical infrastructures but also capital-intensive and governance-sensitive assets. Even if interoperability solutions are technically robust, their scalable deployment across borders depends on regulatory compatibility, coordinated investment incentives, and alignment with pan-European network development mechanisms. In this sense, CIGRE TB 692 provides a governance-level reference that complements HYNET's technical interoperability focus [28].

IEC 61883 (digital interface and data transfer standard) defines a digital interface and transmission protocol originally developed for consumer audio/video equipment using IEEE 1394 technology, including packet formats, data flow management, and connection handling. It does not address power-system-specific automation, protection, or hybrid AC/DC coordination requirements. Consequently, its direct relevance to HYNET is limited. Its value can only be interpreted in a broad sense, as part of general data-transfer standardisation principles, rather than as a primary reference for utility automation, grid control, or hybrid AC/DC interoperability frameworks [29].

Funded by
the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

7. Conclusions and Outlook

7.1 Key SRA findings

The Scalability and Replicability Analysis conducted within Task 6.2 of WP6 draws upon three complementary evidence sources: a structured literature review of SRA methodologies applied in prior EU innovation projects, semi-structured interviews with the leads of all five HYNET demonstration environments, and a systematic tool-leader barriers questionnaire administered to the developers of all thirteen HYNET tools. Together, these inputs yield a multi-dimensional picture of the conditions governing the pan-European deployment potential of the HYNET tool portfolio.

Across the five demonstrations, scalability and replicability emerged as context-dependent properties rather than inherent tool characteristics. The grid-forming BESS solution validated in Demonstration 1a was found to be technically scalable owing to its use of standardised low-voltage converter architectures; however, replicability depends on careful parameter tuning to match the specific dynamic characteristics of the target grid. The MVDC components explored in Demonstration 1b face a more fundamental constraint: the high cost and limited commercial availability of DC protection equipment — particularly MVDC circuit breakers — represents the most structurally significant hardware barrier identified across all demonstrations. The Montenegrin demonstration emphasised flexibility in tool design and cross-border applicability but noted that replicability will depend on adaptability to diverse grid configurations and national system architectures. The Norwegian demonstration reported that planning and simulation tools are inherently scalable, applicable from regional to continental scope, and capable of modelling multi-energy trajectories; however, real-time control tools such as inertia estimation are constrained by the availability of synchronised PMU data and supporting communication infrastructure. The Cyprus demonstration showed that real-time digital twin environments support high replicability in islanded or weak-grid contexts by enabling scenario emulation without physical deployment, but scalability relies on the presence of PMUs, robust communication backbone, and configurable converter controls.

At the tool level, the barriers questionnaire reveals a broadly positive scalability profile at design level, with constraints arising primarily from computational performance, data availability, and hardware infrastructure rather than architectural limitations. Tools with the most favourable replicability profiles are those built entirely on open-source Python libraries — specifically Tools #6, #7, and #11 — which impose no licensing restrictions and operate on standard workstations without specialised hardware. Planning and stochastic security tools (Tools #3, #4, #10) demonstrate strong geographic and topological flexibility, with Tools #4 and #10 explicitly designed for large multi-area transmission environments and confirmed support for multi-operator configurations. Real-time tools (Tools #2, #12, #13) exhibit high technical coherence but are structurally conditional on PMU infrastructure and, in the case of Tools #8 and #13, on OPAL-RT real-time simulation hardware, limiting their replication to well-equipped research and industrial facilities. Across the full portfolio, all thirteen tools confirm result reproducibility given equivalent inputs, cross-validation capability against published benchmarks, and English-language documentation — necessary baseline conditions for pan-European accessibility. Uncertainty quantification is available in Tools #4 and #10 through Monte Carlo and distributional output methods; for the remaining tools, this capability is either work-in-progress or absent, which constitutes a gap for risk-informed operational decision-making at scale. Validation against real-world systems remains largely pending across the portfolio, consistent with the project's TRL 3-5 scope, but represents the primary development requirement for the post-project deployment phase.

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Three structural barriers recur consistently across both the demonstration interviews and the tool-level assessment. First, DC protection and fault management in hybrid and meshed configurations remain unresolved at the equipment and methodology level: conventional AC protection schemes are insufficient, MVDC circuit breakers are not yet commercially accessible at scale, and protection coordination frameworks for multi-terminal DC environments are absent from current standardisation. Second, regulatory and market frameworks — including grid codes, ancillary service market designs, and cross-border coordination mechanisms — have not yet been updated to accommodate hybrid AC/DC operation at scale, and this regulatory lag was identified in multiple demonstrations as an equally significant constraint as technical immaturity. Third, persistent gaps in standardisation — particularly around multi-terminal DC protection, grid-forming converter interoperability requirements, MVDC voltage level harmonisation, and multi-vendor data exchange protocols — impede the structural integration prerequisites for large-scale deployment.

7.2 Implications for large-scale European deployment

The SRA findings carry direct implications for European transmission and distribution system development. The HYNET tool portfolio is strategically aligned with this trajectory and contributes meaningfully across the full lifecycle of hybrid AC/DC system development — from long-term corridor planning to real-time inertia monitoring and dynamic frequency support.

For near-term adoption — meaning deployment within the current planning and development cycles of TSOs and DSOs — the most immediately transferable tools are those in the planning and stochastic security categories. Tools #3, #4, and #10, which support multi-energy planning, techno-economic adequacy assessment, and stochastic security analysis for HVDC corridor configurations, are already designed for large-scale multi-area transmission environments and are aligned with European CBA and TYNDP methodologies. Their adoption by TSOs engaged in HVDC corridor evaluation, offshore integration planning, or cross-border security assessment requires primarily data access agreements and institutional licensing arrangements rather than structural infrastructure investment. These tools represent the most actionable near-term contribution of HYNET to the European transmission planning ecosystem.

For operational and real-time tools — in particular the inertia estimation tools (Tool#2, Tool#12) and the adaptive frequency support tool (Tool#13) — wider deployment is contingent on the continued expansion of synchronised PMU infrastructure across European transmission systems. Where PMU coverage is already established, as in Nordic, Central Western European, and parts of Southern European TSO environments, these tools provide immediately relevant operational value for low-inertia system management and HVDC-enabled frequency support. In regions with limited synchrophasor deployment, a phased approach is appropriate: offline inertia assessment using historical PMU recordings (supported by Tool#12) can precede real-time deployment as measurement infrastructure is gradually extended.

For distribution-level tools addressing MVDC integration — particularly Tools #1, #6, #7, and #11 — the primary deployment barrier is external to the tool portfolio itself: the commercial availability, cost trajectory, and standardisation of MVDC protection equipment, including DC circuit breakers and solid-state protection devices. European investment in this equipment supply chain, supported by regulatory frameworks that incentivise MVDC reinforcement in distribution networks under mass electrification scenarios, is a prerequisite for the broader deployment of these tools in DSO environments. The HYNET tool portfolio is ready to support planning and operational analysis once this equipment barrier is addressed.

Across all tool categories, the HYNET Workbench provides the structural integration logic needed to translate individual tool capabilities into end-to-end deployment workflows. Its modular, vendor-agnostic architecture — aligned with the SGAM framework and underpinned by containerisation through Docker — supports repeatable deployment across heterogeneous IT and operational environments. The progressive migration of tools toward open-source Python implementations and standard data exchange formats (CIM/CGMES for transmission-level tools, CSV/JSON for distribution-level tools) further reduces institutional and technical barriers to adoption.

From a policy and governance perspective, the SRA findings point to three priority areas for European action. First, the update of ENTSO-E Network Codes and national grid codes to incorporate hybrid AC/DC operational requirements — including grid-forming converter specifications, multi-terminal DC protection frameworks, and minimum system inertia requirements — is necessary to create the regulatory conditions under which the HYNET tools can be operationally deployed and recognised. Second, the acceleration of standardisation work within IEC TC57, TC115, and CENELEC on MVDC voltage level harmonisation, grid-forming interoperability, and multi-vendor DC protection coordination will reduce market fragmentation and vendor lock-in in future hybrid AC/DC infrastructure procurements. Third, shared validation platforms — real-time testbeds and digital twin environments — accessible to TSOs, DSOs, and research institutions across Europe would significantly reduce the replication cost of hardware-dependent tools and accelerate the industrial readiness of the HYNET portfolio beyond its current TRL range.

7.3 Future work and finalization of Deliverable D6.5

This document constitutes the initial version of Deliverable D6.5, submitted at Month 18 of the HYNET project in accordance with the Grant Agreement No. 101172757. As an initial version, it presents the full methodological framework, the complete demonstration-based evidence base, the tool-level barrier assessment results, and the standardisation perspective that together form the analytical backbone of the SRA. The findings and conclusions reported in this version are grounded in the literature review, the demonstration interviews, and the tool-leader barriers questionnaire completed within Task 6.2.

The primary element outstanding for the final version of D6.5 is the integration of results from the EU-wide stakeholder questionnaire described in Section 2.2.4 and provided in Annex C. This questionnaire, targeting Transmission System Operators, Distribution System Operators, research institutions, and technology providers across Europe, is designed to provide the quantitative ecosystem-level validation layer of the SRA. Its results will enable quantitative assessment of stakeholder perceptions regarding the strategic necessity of hybrid AC/DC systems, the feasibility of large-scale deployment by 2030, the role of standardisation as enabler or barrier, and the cross-sector readiness for multi-vendor interoperability. The incorporation of these results into the final D6.5 version will allow the present conclusions — which are grounded primarily in project-internal expert knowledge — to be contextualised against and validated by the broader European practitioner and operator community.

In addition to integrating questionnaire results, the final version of D6.5 will extend the cross-demonstration synthesis in Chapter 5 to incorporate any further validation outcomes emerging from WP5 demonstrations completed after the M18 submission deadline. As tools progress toward TRL 5 and real-world-adjacent validation environments, updated barrier assessments and revised scalability ratings will be incorporated. The standardisation recommendations in Section 6 will likewise be refined to reflect any developments in ongoing IEC, CENELEC, or ENTSO-E work programmes that emerge during the remaining project period. The final version is planned for submission at Month 36, consolidating the complete HYNET SRA and providing the definitive deployment pathway recommendations for hybrid AC/DC solutions at pan-European scale.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

8. References

[1] European Commission, Joint Research Centre, Electricity Grids in the European Union, Clean Energy Technology Observatory, EUR series. Luxembourg: Publications Office of the European Union, 2025. Accessed: Feb. 25, 2026. [Online]. Available: https://data.europa.eu/doi/10.2760/7561135

[2] European Commission, Joint Research Centre, Electricity Grids in the European Union, Clean Energy Technology Observatory, EUR series. Luxembourg: Publications Office of the European Union, 2025. Accessed: Feb. 25, 2026. [Online]. Available: https://data.europa.eu/doi/10.2760/7561135

[3] K.-N. D. Malamaki et al., "Hybrid HVAC–HVDC grids: Review on techno-economic, societal, and regulatory aspects," in Proc. 2025 IEEE Int. Conf. Environment and Electrical Engineering and 2025 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Chania, Crete, Greece, Jul. 2025, pp. 1–6, doi: 10.1109/EEEIC/ICPSEurope64998.2025.11169029.

[4] W. Hribernik, S. S. Landwehr-Zloch, G. Guntschnig, and T. Kienberger, "Accelerating European HVDC interconnector deployment: Innovative financing mechanisms and regulatory pathways," e & i Elektrotechnik und Informationstechnik, vol. 142, no. 7–8, pp. 498–507, Dec. 2025, doi: 10.1007/s00502-025-01380-8.

[5] ENTSO-E, "TYNDP 2024 projects map – Transmission projects." Accessed: Feb. 25, 2026. [Online]. Available: https://tyndp2024.entsoe.eu/projects-map/transmission

[6] ENTSO-E, "TYNDP 2022 project platform – Transmission project sheets." Accessed: Feb. 25, 2026. [Online]. Available: https://tyndp2022-project-platform.azurewebsites.net/projectsheets/transmission

[7] J. Cabañas Ramos, M. Moritz, N. Klötzl, C. Nieuwenhout, W. Leon Garcia, I. Jahn, D. Kolichev, and A. Monti, "Getting Ready for Multi-Vendor and Multi-Terminal HVDC Technology," Energies, vol. 17, no. 10, Art. no. 2388, 2024

[8] IEC, IEC 61850 Series: Communication Networks and Systems for Power Utility Automation, Geneva, Switzerland, 2026.

[9] I. Losa and R. Cossent, "Scalability and Replicability Analysis in Smart Grid Demonstration Projects: Lessons Learned and Future Needs," Energies, vol. 17, no. 21, Art. no. 5312, Oct. 2024.

[10] I. Pérez-Domingo et al., "ICT Scalability and Replicability Analysis for Smart Grids: Methodology and Application," Energies, vol. 17, no. 3, Art. no. 574, 2024.

[11] G. P. Fotis et al., "Scalability and Replicability for Smart Grid Innovation Projects and the Improvement of Renewable Energy Sources Exploitation: The FLEXITRANSTORE Case," Energies, vol. 15, no. 13, Art. no. 4519, 2022.

[12] BRIDGE Task Force on Replicability & Scalability Analysis, Draft methodological guidelines to perform a scalability and replicability analysis, Dec. 2019

[13] CEN-CENELEC-ETSI Smart Grid Coordination Group, SGAM User Manual – Applying, Testing & Refining the Smart Grid Architecture Model (SGAM), ver. 3.0, Nov. 2014.

[14] R. Cossent et al., "Draft methodological guidelines to perform a scalability and replicability analysis," BRIDGE Task Force Replicability & Scalability Analysis, Dec. 2019.

[15] Platone Consortium, "Deliverable D7.2: Methodology for SRA," 2021.

[16] EUniversal Consortium, "Deliverable D10.2: Methodology and scenarios for the EUniversal scalability and replicability analysis," Jan. 2022.

[17] EUniversal Consortium, "Deliverable D10.4: Scalability and Replicability analysis of the EUniversal solutions," Aug. 2023.

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

[18]European Commission, "Energy infrastructure projects of common interest (PCI) and projects of mutual interest (PMI)." Accessed: Feb. 25, 2026. [Online]. Available: https://eic.ec.europa.eu/programme-finder-23_en
[19]International Electrotechnical Commission, IEC 62559 – Use Case Methodology for Power Systems and Smart Grids. Geneva, Switzerland: IEC. Accessed: Feb. 25, 2026. [Online]. Available: https://syc-se.iec.ch/deliveries/iec-62559-use-cases/
[20]CEN-CENELEC-ETSI Smart Grid Coordination Group, Smart Grid Architecture Model (SGAM) – Final Report, 2012. Accessed: Feb. 25, 2026. [Online]. Available: https://syc-se.iec.ch/deliveries/sgam-basics/
[21]International Electrotechnical Commission, IEC 61850 Series – Communication Networks and Systems for Power Utility Automation. Geneva, Switzerland: IEC. Accessed: Feb. 25, 2026. [Online]. Available: https://webstore.iec.ch/publication/6028
[22]International Electrotechnical Commission, IEC 61850-6:2009+AMD1:2018+AMD2:2024 CSV – Communication Networks and Systems for Power Utility Automation – Part 6: Configuration Description Language for Communication in Electrical Substations Related to IEDs. Geneva, Switzerland: IEC, 2024. [Online]. Available: https://webstore.iec.ch/publication/6025
[23]IEEE Power & Energy Society, IEEE Std C37.118.1-2011 – IEEE Standard for Synchrophasor Data Transfer for Power Systems. New York, NY, USA: IEEE, 2011. [Online]. Available: https://ieeexplore.ieee.org/document/6111219
[24]IEEE Standards Association, IEEE Std 1547-2018 – IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. New York, NY, USA: IEEE, 2018. [Online]. Available: https://standards.ieee.org/ieee/1547/5915/
[25]IEEE Standards Association, IEEE Std 2030.5-2018 – IEEE Standard for Smart Energy Profile Application Protocol. New York, NY, USA: IEEE, 2018. [Online]. Available: https://standards.ieee.org/ieee/2030.5/11216/
[26]International Electrotechnical Commission, IEC 60038:2009 – IEC Standard Voltages. Geneva, Switzerland: IEC, 2009. [Online]. Available: https://webstore.iec.ch/en/publication/153
[27]IEEE Power & Energy Society, IEEE Std 1378-2022 – IEEE Guide for Commissioning HVDC Converter Stations and Associated Transmission Systems. New York, NY, USA: IEEE, 2022. [Online]. Available: https://standards.ieee.org/ieee/1378/6945/
[28]CIGRE, Technical Brochure 692 – Market and Regulatory Frameworks for Transmission Investments. Paris, France: CIGRE, 2017. [Online]. Available: https://www.e-cigre.org/publications/detail/692-market-price-signals-and-regulatory-frameworks-for-coordination-of-transmission-investments.html
[29]International Electrotechnical Commission, IEC 61883-1:2008 – Consumer Audio/Video Equipment – Digital Interface – Part 1: General. Geneva, Switzerland: IEC, 2008. [Online]. Available: https://webstore.iec.ch/en/publication/6064

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

9. Annexes

9.1 Annex A – Interview guidelines

Scaling the Future – Insights on Scalability, Replicability, and Standardization of HYNET Demos

In this discussion, we aim to explore three key aspects of your demonstration within the HYNET project:

- Project Introduction – Understanding the scope, objectives, and key technologies of your demonstration.
- Scalability, Replicability, and Standardization – Exploring how the solutions tested in your demonstration can be expanded, transferred to different contexts, and contribute to standardization efforts.
- Regulatory and Physical Constraints – Identifying key challenges that could impact large-scale deployment, including regulatory, market, and infrastructural barriers.

Demo Leader's expertise and experience will provide valuable guidance for shaping future strategies in hybrid AC/DC system deployment.

9.1.1 Project Introduction

1. Could you briefly introduce your Demo? What key technologies and solutions are being tested?

2. What are the main objectives you aim to achieve through this demonstration, and how does it align with HYNET's overall goals?

9.1.2 Scalability, Replicability, and Standardization

3. Based on your experience so far, what are the key lessons learned regarding the scalability and replicability of your Demo?
    a. Scalability – Can the solution be expanded?
        i. How well does the technology perform when scaled up to larger energy systems?
        ii. What are the limitations in terms of infrastructure, cost, or technology when moving from a small-scale demo to full-scale implementation?
        iii. What adjustments (e.g., technical improvements, additional investments, policy changes) are necessary to support large-scale deployment?
    b. Replicability – Can the solution be applied in different contexts?
        i. How easily can the technology or approach be transferred to other geographic locations or energy systems?
        ii. Are there any specific site-dependent factors (e.g., climate, grid infrastructure, regulatory environment) that impact replication?
        iii. What modifications are required for deployment in diverse conditions (e.g., different grid setups, regulatory landscapes, or market structures)?

4. How could the technologies tested in your demonstration be transferred to other European regions or different energy systems?

5. What are the most critical technical factors that must be considered for large-scale deployment?

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

   a. By critical technical factors, we refer to key aspects that influence the large-scale deployment of hybrid AC/DC systems, including grid stability and control, ensuring seamless integration of AC/DC components, fault management and protection schemes, scalability of power electronics, energy storage solutions, real-time communication and data management, and necessary infrastructure upgrades to support the expansion of these technologies.

6. How do different systems work together in your demonstration, and how does this help with developing common standards?
   a. When we refer to systems in the context of this question, we are primarily considering different technological, operational, and regulatory frameworks that need to work together for a successful hybrid AC/DC power grid.
      i. Electrical Systems
      ii. Control Systems
      iii. Communication and Data Exchange Systems
   b. Why This Matters?
      i. The HYNET project aims to develop scalable and replicable solutions. If different systems (hardware, software, grid structures, regulations) cannot efficiently work together, it will be difficult to scale up and integrate these technologies across Europe. By asking how different technologies and systems work together, we can evaluate whether the solutions in the demonstrations will be practically viable on a larger scale.

7. Are you collaborating with any standardization initiatives, and how can your demonstration contribute to the development of European standards for hybrid AC/DC systems?

9.1.3 Regulatory and Physical Constraints

8. What are the main regulatory or market barriers that may limit the broader adoption of the solutions developed in your demonstration?

9. Are there any significant physical or infrastructural challenges that need to be addressed when replicating and scaling up these technologies?

10. Are the necessary components and equipment for your demonstration readily available on the market, or do they require custom development and manufacturing? How expensive are they?

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

9.2 Annex B — Tool-Leader Barriers Questionnaire: Responses from Tool Developers

This annex presents the complete responses provided by the developers of the thirteen HYNET tools to the T6.2 barriers assessment questionnaire. The questionnaire was designed to systematically identify and compare tool-level barriers and enablers of replicability and scalability across ten thematic categories (C1–C10), each subdivided into six specific assessment dimensions. Responses were collected in February 2026 and reflect the implementation status of each tool at that point in the project lifecycle. Entries marked "WIP" indicate dimensions for which the response is pending further development progress and will be updated in subsequent versions of this deliverable.

The table is organised with barrier categories and subcategories in rows and tools in columns. Tool developers are identified by their institutional affiliation (INESC TEC, CIRCE, ART, SGI, INESC, INESC ID, GEPC, UCY) as indicated in the header row. The full category definitions are provided in Section 2.3 of this deliverable.

Category		Description	Tool1	Tool2	Tool3	Tool4	Tool5	Tool6	Tool7	Tool8	Tool9	Tool10	Tool11	Tool12	Tool13
C1 – Software as a barrier		**Dependencies on specific software platforms or programs that limit replicability**													
C1.1	Open-source vs commercial software	Does your tool depend on commercial/proprietary software (e.g., PowerFactory, MATLAB, PSSE, OPAL-RT) that may not be available in other institutions? List all software dependencies and indicate whether they are open-source or commercial.	PowerFactory, later transition to Python	No	Itself a commercial software	AMPL (community version) but may change	PowerFactory, Matlab/simulink	No	No	PowerFactory, Matlab/simulink, OPAL-RT	No	No	No	No	Matlab/Simulink, OPAL-RT RT-Lab
C1.2	Programming language dependencies	What programming languages does your tool use (Python, MATLAB, C++, etc.)? Are there specific version requirements that might create compatibility issues?	Python	Python	Python	Python Java	Python	Python	Python	Matlab/Simulink, DIgSILENT Versions and toolboxes is a matter	Python, MATLAB	Python/Java	Python	Matlab at the moment and will be translated to Pyhton	For compatibility between Simulink and RT-Lab there are certain versions that are suitrable. E.g., Matlab 2022b and RT-Lab 2023.3 (https://opal-rt.atlassian.net/wiki/spaces/PArtemis/pages/140837407/Requirements)
C1.3	Platform/OS dependencies	Is your tool dependent on specific operating systems (Windows, Linux, macOS)? Can it run on multiple platforms?	Not dependent	The operating system mut be able to run docker container	Not dependent	Not dependent	Not dependent	Not dependent	Not dependent	Windows	Windows	Not dependent	Not dependent	It can run on multiple platforms	Mainly windows and specific versions of Linux (https://opal-rt.atlassian.net/wiki/spaces/PArtemis/pages/140837407/Requirements)
C1.4	Software license restrictions	Are there license restrictions (commercial software, node-locked licenses, floating licenses) that limit the number of users, geographic locations, or concurrent installations?	DIgSILENT PowerFactory	Yes	Yes	Yes	DIgSILENT PowerFactory / MATLAB SIMULINK	No	WIP	Yes	DIgSILENT PowerFactory	No	WIP	No	Yes
C1.5	Software version compatibility	Does your tool require specific versions of software packages? How sensitive is it to version updates? (Consider: tool still in development, compatibility may change)	WIP	WIP	Yes	WIP	WIP	WIP	WIP	DIgSILENT 2024 RTLAB 2023 MATLAB/SIMULINK 2021	2022 and later	No	WIP	WIP	Current versioning: Matlab 2022b & RT-Lab 2023.3 (https://opal-rt.atlassian.net/wiki/spaces/PArtemis/pages/140837407/Requirements)
C1.6	Third-party library dependencies	What external libraries or packages does your tool depend on? Are these widely available and maintained? (Consider: dependencies may be added during remaining development)	Python/WIP	Python libraries. PDC client	Python, Artelys APIs	PyPSA PowSyBl 2 main dependancies that are actively maintained	Python/WIP	Python/WIP	Python/WIP	WIP	WIP	PowSyBl	Python/WIP	WIP	No
C2 – Time domain as a barrier		**Limitations related to execution time and computational performance**													

Funded by the European Union

Category		Description	Tool1	Tool2	Tool3	Tool4	Tool5	Tool6	Tool7	Tool8	Tool9	Tool10	Tool11	Tool12	Tool13
C2.1	Real-time requirements	Does your tool need to run in real-time? If yes, what are the time constraints (milliseconds, seconds, minutes)? Does this require specific hardware?	No	Yes. miliseconds. Hardware able to run in real time. The inertia estimation is provided every 3-4 minutes	No	No	No	No	No	50 µs execution cycle time	The tool should run in subseconds to minutes range	No	No	The tool should run in seconds to minutes range	The coordination should run perodically (every few minutes). The simulation HVDC models needs to run with 50us fixed step execution, considering real-time execution in the final version or offlines simulation in preliminary versions. OPA:-RT 5707 will be used.
C2.2	Computational scalability	How does computation time scale with problem size (network nodes, time steps, scenarios)? What are the maximum limits currently tested?	WIP	WIP	The larger and more complex the problem (nb of nodes, timesteps, uncertainty), the higher the computation time	WIP	WIP	WIP	WIP	Grid complexity is the key factor for real time calculation capability	The larger and more complex the grid, the higher the computation time	The larger and more complex the grid, the higher the computation time	WIP	No computational issues regarding the problem size	Grid complexity, number of switching devices. There are certain limits per core used by the real time simulator.
C2.3	Simulation time vs real-time	For simulation tools: what is the ratio between simulation time and real execution time? Can this be a limiting factor for large-scale studies?	N/A	N/A	N/A	N/A	N/A	N/A	N/A	ratio could 30mn vs one night of laptop simulation	The simulation runs offline for tens of seconds	N/A	N/A	N/A	Real time execution is achieved in OPAL-RT hardware which is ~x100-500 time faster than offline simulation model.
C2.4	Data processing speed	Are there limitations in how quickly your tool can process input data or generate outputs? Critical for operational tools.	N/A	Input data: 20ms. Output data: 3-4 minutes	N/A	WIP	WIP	WIP	WIP	50 µs	The inputs and outputs can be processed in the scale of seconds to a few minutes.	N/A	WIP	The input data should be processed in the scale of seconds to a few minutes	N/A
C2.5	Parallel processing capability	Can your tool leverage parallel computing or multi-core processors to reduce execution time? Is this implemented or planned?	Not implemented or planned	No. it is neither planned nor implemented.	Yes	Yes it might be possible to configure the employed solvers to proceed parallel computing (implementation to confirm).	Not implemented or planned	Not implemented or planned	Not implemented or planned	This is managed by the commercial software	WIP	N/A	Not implemented or planned	N/A	Multi-core processors are used in the Real Time Simulator
C2.6	Memory/RAM requirements	What are the minimum and recommended RAM requirements currently? Can memory limitations affect scalability for large networks?	WIP	2 logical cores(Intel Xeon Gold 6238T , 44 Logical Processor(s)). RAM 554,4 MB	WIP	WIP	WIP	WIP	WIP	16 GB RAM as min size	at least 16 GB of RAM	WIP	WIP	8-16 GB of RAM is more than fine	N/A (handled by the real time siumator)
C3 – Transferability to other locations		**Barriers to deploying the tool in different geographic or institutional contexts**													
C3.1	Grid topology dependencies	Is your tool limited to specific grid topologies (radial, meshed, AC, DC, hybrid)? Can it adapt to different network configurations?	No	It is limited to AC applications. Can be adapted to different network configurations	No	Not limited	Not limited	Not limited	Not limited	AC	meshed grids	No	Not limited	The tool is applicable to AC grids without any specific network configuration	Not limited

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Category		Description	Tool1	Tool2	Tool3	Tool4	Tool5	Tool6	Tool7	Tool8	Tool9	Tool10	Tool11	Tool12	Tool13
C3.2	Voltage level limitations	Is your tool designed for specific voltage levels (LVDC, MVDC, HVDC, LVAC, MVAC, HVAC)? What are the current limitations?	MVAC/MVDC	HVAC	N/A	Tool designed for hybrid transmission network (HVAC/HVDC)	MVAC/MVDC	MVAC/MVDC	MVAC/MVDC	MV oriented	Transmission level	Transmission level	MVAC/MVDC	The tool can be applied in any voltage level given that synchronous generators are present	HVDC
C3.3	Data format standardization	Does your tool use standardized data formats (CIM/CGMES, IEC 61850, CSV, JSON)? Can it import/export data in multiple formats?	TXT, CSV	Import CSV, C37.118 PDC frames, Export in Modbus	Import/export in CSV	Use CIM-CGMES, CSV and JSON. Can import/export CIM-CGMES, IIDM, netCDF.	CSV, TXT	CSV, JSON	CSV, JSON	No	The tool can receive data for parameters in CSV and can export data in CSV as well	CIM-CGMES	CSV	The tool can receive data in CSV and can export data in CSV as well	Exchange data through a Modbus TCP interface and import/export data in CSV format
C3.4	Regional regulatory differences	Does your tool assume specific regulatory frameworks or grid codes that may differ across countries/regions (e.g., European vs North American grid codes)?	No	N/A	N/A	N/A	No	No	No	the BESS DiGSILENT models can handle multiple grid codes	WIP	N/A	No	No	No
C3.5	Language and documentation	Is documentation available in multiple languages? Are user interfaces language-independent or easily translatable? (Consider: documentation still being developed)	Documentation will be available in english	Documentation will be available in english	Documentation will be available in english	Documentation will be available in english	Documentation will be available in english	Documentation will be available in english	Documentation will be available in english	Documentation can be available in English	Documentation can be available in English	Documentation can be available in English	Documentation will be available in english	Documentation can be available in English	Documentation can be available in English
C3.6	Cultural/organizational practices	Does your tool assume specific organizational structures or workflows (e.g., TSO-DSO coordination models) that may not exist elsewhere?	No	No	No	No	No	No	No	No	No	No	No	No	No
C4 – Data availability and quality		**Barriers related to access to and quality of required input data**													
C4.1	Data granularity requirements	What temporal resolution (seconds, minutes, hours) and spatial resolution (nodal, zonal) does your tool require? Is such granular data typically available?	configurable	miliseconds, zonal	configurable	hours, zonal/nodal	configurable	configurable	configurable	µs	milliseconds and nodal	configurable	configurable	The PMU measurements should be reported in milliseconds intervals from each generation node.	configurable
C4.2	Proprietary/confidential data	Does your tool require proprietary grid data, commercial information, or confidential operational data (e.g., TSO network models, market data) that may not be shareable?	Grid data (that can be confidential)	TSO network models (offline version) PMU measurements (online version)	Market data	TSO network models & market data	Grid models (that can be confidential)	Grid data (that can be confidential)	Grid data (that can be confidential)	Commercial information	WIP	Grid models (that can be confidential)	Grid data (that can be confidential)	Synchronous generator model might be useful to be provided	no
C4.3	Historical data requirements	Does your tool need historical time-series data? How much historical data is required (days, months, years)? Is this a barrier to deployment?	No	N/A	N/A	Historical Weather Years / Typical Meteorological Year	May require			N/A	N/A	N/A	No	No	Up to 1 day representative generation/load profiles based on open data, so this is not a barrier
C4.4	Measurement infrastructure	Does your tool require specific measurement devices (PMUs, smart meters, SCADA) that may not be available in all locations?	N/A	PMUs and PDCs, SCADA	N/A	N/A	No	No	No	N/A	N/A	No	No	PMUs	No

Funded by the European Union
HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Category		Description	Tool1	Tool2	Tool3	Tool4	Tool5	Tool6	Tool7	Tool8	Tool9	Tool10	Tool11	Tool12	Tool13
C4.5	Data quality and uncertainty	How sensitive is your tool to data quality issues (missing data, noise, errors)? Does it handle uncertainty? Important for robustness.	The tool is based in different loading and generation scenarios, at this phase it is not planned to handle uncertainty.	It uses ambient measurements for the operation. It is sensitive to missing data	Monte Carlo module	Uncertainty is handled by the use of Monte Carlo scenario sets				N/A	N/A	Monte Carlo Stochastic layer		The tool can be sensitive in data quality issues but thorough investigation regarding the tool vulnerability in data quality issues will be done in the following months of the project	N/A
C4.6	Real-time data access	Does your tool need real-time data feeds? What happens if real-time data is unavailable? Can it operate with delayed/historical data?	No	Real time data. The inertia estimation is frozen.	N/A	N/A	No	No	No	N/A	N/A	No	No	Real time data access is necessary for real time inertia estimation. However, the tool can operate using historical PMU measurements	N/A
C5 – Hardware infrastructure		**Dependencies on specific hardware or computational infrastructure**													
C5.1	Hardware-in-the-Loop (HIL) requirements	Does your tool require HIL testing equipment (OPAL-RT, RTDS, dSPACE, Typhoon HIL)? Can it function without it? This is a major cost/availability barrier.	No	For testing the tool needs RTDS. (Online version) The offline version can function without HIL tools	N/A	N/A	No	No	No	OPAL-RT	N/A	N/A	No	No	OPAL-RT (with OPAL-RT the offline model can only be used)
C5.2	High-performance computing (HPC)	Does your tool require access to HPC clusters, GPUs, or specialized computing hardware? Or can it run on standard workstations?	No	It can run on standard workstations by rely on servers	It can run on standard workstations by rely on servers	Can it run on standard workstations	No	No	No	N/A	N/A	Can run on standard workstations	No	No	No
C5.3	Communication infrastructure	Does your tool depend on specific communication protocols or network infrastructure (IEC 61850, Modbus, DNP3) that may not be available elsewhere?	No	PMUs, PDC, Modbus	N/A	N/A	No	No	No	N/A	N/A	N/A	No	No	Modbus TCP
C5.4	Sensor and measurement hardware	Does your tool require specific sensor types (PMUs, phasor measurement units) or measurement equipment not commonly available?	No	PMUs and PDCs	N/A	N/A	No	No	No	N/A	N/A	N/A	No	PMUs	No
C5.5	Laboratory/testbed facilities	Does your tool need access to specific laboratory facilities or physical testbeds for validation? This limits where tool can be fully utilized.	No	The online version yes. The offline version can use .csv files	N/A	N/A	No	No	No	N/A	N/A	N/A	No	No	Yes

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Category		Description	Tool1	Tool2	Tool3	Tool4	Tool5	Tool6	Tool7	Tool8	Tool9	Tool10	Tool11	Tool12	Tool13
C5.6	Cloud vs on-premise	Is your tool designed for cloud deployment, on-premise servers, or both? Are there data privacy/security limitations with cloud deployment?	No	Designed for on-premise servers	Both	Designed for on-premise servers	No	No	No	N/A	N/A	N/A	No	The tool is currently developed for premise servers. Web based application needs extra steps to be done.	The coordination controlle will initially developed as a on-premises software
C6 – Interoperability and integration		**Barriers to integration with other tools and systems**													
C6.1	API and interface availability	Does your tool provide APIs (REST, Python, etc.) for integration with other tools? Are interfaces documented? (Consider: APIs may be under development)	Python APIs	No	Python APIs	Pyhton API	Python APIs	Python APIs	Python APIs	N/A	Python API	Python API	Python APIs	Python can be used in order to be integrated with other tools. The estimated inertia can be also uploaded in the cloud (ThingSpeak) to be used by other tools through API.	APIs
C6.2	Protocol compatibility	What communication protocols does your tool support (IEC 61850, DNP3, MODBUS, IEEE 2030.5)? Are they standardized?	N/A	Import value: IEC 60255-118/Publish inertia value:MODBUS	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	MODBUS	Modbus TCP
C6.3	Multi-tool workflows	Can your tool easily exchange data with other HYNET tools or external tools? What integration challenges exist currently?	N/A	SCADAS using Modbus protocol and read CSV from Digsilent simulation	Tool10	Integration with tool 9 is planned and furniture of results to tool 2	Tools 1, 6, 7	Tool 7	Tool 5	WIP	Data in CSV formats can be exchanged ith other tools	Tool3	N/A	The tool can upload data to the cloud to be used by other tools. Also the inertia can be stored in CSV files to be uploaded in other tools	Tool12
C6.4	Containerization support	Is your tool containerized (Docker, Kubernetes) for easier deployment and portability? Is this planned for final release?	WIP	Docker	Yes	Yes	Yes	Yes	Yes	N/A	N/A	N/A	Yes	No	N/A
C6.5	Model exchange formats	Can your tool export/import models in standard formats (FMU, CIM/CGMES, PowerFactory DGS, IEEE CDF)?	WIP	No	N/A	Can import/export CIM-CGMES, IIDM, netCDF	No	No	No	DIgSILENT 2024 RTLAB 2023 MATLAB/SIMULINK 2021	PowerFactory	Yes - CIM/CGMES	No	No	No
C6.6	Vendor lock-in	Is your tool dependent on vendor-specific formats or interfaces (proprietary software) that prevent interoperability?	No	The PMUs accoring to IEC 60255-118	No	No	No	No	No	WIP	N/A	No	No	No	No
C7 – Knowledge and expertise		**Human capacity barriers related to skills and training needed**													

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Category		Description	Tool1	Tool2	Tool3	Tool4	Tool5	Tool6	Tool7	Tool8	Tool9	Tool10	Tool11	Tool12	Tool13
C7.1	Domain expertise requirements	What level of power systems knowledge is required to use your tool (basic, intermediate, expert)? Are there specific domain requirements (HVDC, power electronics, etc.)?	Intermediate knowledge in network simulation (OPF)	Only need PMUs data to estimate inertia in a specific area	Intermediate power system knowledge is required.	Intermediate in electricty market simulation and (optimal) power flows,	Intermediate power system knowledge is required.	Intermediate power system knowledge is required.	Intermediate power system knowledge is required.	expert	expert, protection and controllers including those related to power electronics and HVDC	Intermediate knowledge in network simulation (OPF)	Intermediate power system knowledge is required.	Basic	Expert
C7.2	Programming skills needed	What programming skills are necessary to install, configure, and use your tool? Can non-programmers use it with a GUI?	Python/non programmers can use	Docker and docker compose skills	Web-based app easy to use for non programmers	GUI for non programmers	Python/non programmers can use	Python/non programmers can use	Python/non programmers can use	DIgSILENT 2024 RTLAB 2023 MATLAB/SIMULINK 2021	Python	No GUI	Python/non programmers can use	Non-programmers can use the tool	For the model execution: Matlab and RT-LAB. For the coordination tool: GUI
C7.3	Training and learning curve	How long does it typically take for a new user to become proficient? Is training material available or being developed?	Few weeks	Few weeks	Training material is available	WIP	Few weeks	Few weeks	Few weeks	6 months	A few weeks need, and training materials will be developing	Training material will be available	Few weeks	The tool is easily operated through the GUI that will be developed.	2-4 months
C7.4	Documentation quality	How comprehensive is your tool's documentation currently (installation guides, user manuals, API docs, examples)? What is planned by project end?	WIP	WIP	Good quality documentation including user manuals, API docs	WIP	WIP	WIP	WIP	user manuals	WIP	API documentation , user doc WIP	WIP	WIP	For the simulation models you need to follow the documentation from OPAL and Matlab. For the Coordination Tool, basic documentation to be provided
C7.5	Support and community	Is there an active user community or support system? How accessible is technical support? Will this continue after project end?	There is no a user community	There is no a user community. CIRCE will maintain the tool	Support in ART	SGI will maintain the tool.	There is no a user community	There is no a user community	There is no a user community	N/A	N/A	Yes, rely on open source tool	There is no a user community	N/A	N/A
C7.6	Tacit knowledge dependencies	Does your tool rely on undocumented knowledge or experience that may be difficult to transfer? Critical for replicability.	No	No	No	No	No	No	No		No	No	No	No	no
C8 – Validation and benchmarking		**Challenges in validating and comparing tool performance across contexts**													
C8.1	Benchmark availability	Are standard benchmark cases available for your tool? Can results be compared with other tools or published data? (Consider: benchmarks may be under development)	There are available benchmark cases in the literature.	IEEE 39 buses. Can not be compared with other tool results	Open source model TYNPDs	A standard test case has been constructed within task 3.2	There are available benchmark cases in the literature.	There are available benchmark cases in the literature.	There are available benchmark cases in the literature.		There are available benchmark cases in the literature.	WIP	There are available benchmark cases in the literature.	There are available benchmark cases in the literature.	N/A
C8.2	Validation against real systems	Has your tool been validated against real-world systems or only in simulation? What validation is planned by project end?	WIP	Only in simulation	N/A (planification tool)	WIP	WIP	WIP	WIP	WIP	WIP	WIP	WIP	WIP	Simulations
C8.3	Uncertainty quantification	Does your tool provide uncertainty bounds or confidence intervals for results? Important for decision-making reliability.	WIP	WIP		Yes (distribution)	WIP	WIP	WIP	WIP	WIP	Yes	WIP	No	No
C8.4	Reproducibility of results	Can your tool's results be reproduced by others given the same inputs? What factors affect reproducibility	Yes	Yes	Yes	Yes (random seeds and solver settings)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Category		Description	Tool1	Tool2	Tool3	Tool4	Tool5	Tool6	Tool7	Tool8	Tool9	Tool10	Tool11	Tool12	Tool13
		(random seeds, solver settings, etc.)?													
C8.5	Performance metrics	What metrics are used to evaluate your tool's performance? Are they standardized and comparable with other tools?	WIP	The accuracy compared with theoretical values	WIP	WIP	WIP	WIP	WIP	WIP	WIP	WIP	WIP	Mean Absolute Percentage Error (MAPE) can be used for evaluation of the inertia estimation performance. MAPE is a standard metric comparable with other tools	Frequency stability indicators (e.g., Fnarid, ROCOR) are the main indicators used to compare system performance in each scenario
C8.6	Cross-validation capability	Can your tool's results be cross-validated with other tools or methods? Important for confidence in results.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes if the results are available in the literature for the same test-bed systems	Yes	Yes	Yes if the results are available in the literature for the same test-bed systems	Maybe
C9 – Regulatory and standardization		**Barriers related to standards compliance and regulatory requirements**													
C9.1	Grid code compliance	Does your tool assume specific grid codes (European, national, TSO-specific) that may differ in other locations?	No	N/A	N/A	European	No	No	No	No	No	No	No	No	European
C9.2	Standards implementation	What standards does your tool implement (IEC, IEEE, CIGRE)? Are there gaps or regional variations that limit transferability?	N/A	The PMUs standard (IEC 60255-118)	ENTSOE TYNDP, CBA Methodology	ENTSOE CBA Methodology	N/A	N/A	N/A	N/A	N/A	No GUI	N/A	N/A	N/A
C9.3	Certification requirements	Does your tool or its outputs need certification or approval for use in real systems? This may limit immediate deployment.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	WIP	WIP	N/A	N/A	No	N/A
C9.4	Intellectual property constraints	Are there IP restrictions (patents, proprietary algorithms, partner constraints) that limit tool sharing or modification?	No	propietary algorithms	propietary algorithms	WIP	No	No	No	IP belongs to GEV PCS	IP belongs to UCY. Open access to the tool will be provided through the project workbench	No	No	IP belongs to UCY. Open access to the tool will be provided through the project workbench	No
C9.5	Safety and security standards	Does your tool comply with cybersecurity standards (IEC 62351) and safety requirements? Critical for operational tools.	N/A	No	N/A	WIP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	No	N/A

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

Category		Description	Tool1	Tool2	Tool3	Tool4	Tool5	Tool6	Tool7	Tool8	Tool9	Tool10	Tool11	Tool12	Tool13
C9.6	Open vs closed development	Is your tool open-source or proprietary? Does this affect its replicability and adaptation? What is the plan post-project?	propietary. It does not affect adaptation.	propietary. It does not affect adaptation. Sell it to Transmission system operator	Propietary. It does not affect adaptation. Sell it to Project planners, TSOs, DSOs, decision makers	Proprietary based on open source frameworks	propietary. It does not affect adaptation.	propietary. It does not affect adaptation.	propietary. It does not affect adaptation.	WIP	An open source version can be provided through the project, however IP rights are owned by UCY	Proprietary based on open source frameworks.	propietary. It does not affect adaptation.	An open source version can be provided through the project, however IP rights are owned by UCY	Proprietary
C10 – Scalability potential		**Ability to scale the tool to larger or more complex systems**													
C10. 1	Network size scalability	What is the maximum network size your tool can handle currently? Can it scale from small microgrids to large transmission systems?	WIP	WIP	Zonal tool	Transmission systems	WIP	WIP	WIP	WIP	There are no limitations regarding the grid scale that the tool can be applied	Large transmission systems	WIP	There are no limitations regarding the grid scale that the tool can be applied	WIP
C10. 2	Multi-area and multi-operator	Can your tool handle multi-area systems with different operators or does it assume single-operator control?	Assume single-operator control	Can handle multi-area	Can handle multi-area	Assume single-operator control	Assume single-operator control	Assume single-operator control	Assume single-operator control	WIP	It can be applied in multi-area systems	Yes	Can handle multi-area	It can be applied in multi-area systems	Multi-ara system
C10. 3	Technology diversity	Can your tool accommodate diverse technologies (different converter types, DER technologies, storage systems)? Can new technologies be added?	Yes	WIP	Yes	Yes	Yes	Yes	Yes	WIP	Yes, it is applicable.	Yes	Yes	N/A	Yes
C10. 4	Scenario and uncertainty analysis	Can your tool efficiently run multiple scenarios or Monte Carlo simulations? What are the computational limits?	WIP	N/A	Yes	Yes			Yes	WIP	Yes. Tens of seconds.	Yes	Yes	Yes. No computational limits are identified at the moment	WIP
C10. 5	Modular architecture	Is your tool designed modularly to allow adding new components, algorithms, or features? Important for future extensibility.	WIP	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes this can be done with the modification of the Python code.	Yes	Yes	Yes this can be done with the modification of the Python code.	Yes
C10. 6	Future technology readiness	Can your tool accommodate emerging technologies not yet modeled (new power electronics, grid-forming controls, hydrogen)? How extensible is the framework?	Yes	Yes	Yes (not specialized in power electronics, but multi energy is supported (gas, hydrogen, etc))	Handle hydrogen, ready to extend HVDC modelling	Yes	Yes	Yes	Yes	Yes, this can be done during grid modelling in PowerFactory.	Yes	Yes	This can be considered in future versions of the tool beyond the project lifetime	Yes

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

9.3 Annex C – EU stakeholder questionnaire

9.3.1 General questions

1. To what extent do you agree that hybrid AC/DC power systems will be essential for meeting future grid flexibility and resilience requirements?
   (Scale: 1 – Strongly disagree, 5 – Strongly agree)
2. Does your organisation currently participate in projects or initiatives that address interoperability in power system components (AC and/or DC)?
   (Yes / No / Planning to)
3. How relevant is the replicability of solutions (technical or regulatory) across different EU member states for your organisation?
   (Scale: 1 – Not relevant, 5 – Very relevant)
4. To what degree does your organisation consider standardisation (e.g. IEC, IEEE, ENTSO-E guidelines) a **barrier or enabler** in deploying AC/DC hybrid systems?
   (a) Mainly a barrier / b) Neutral / c) Mainly an enabler)
5. Is your organisation involved in or aligned with any ongoing efforts to define requirements for grid-forming or black-start capabilities in converter-based systems?
   (Yes / No / Not relevant to our role)
6. How feasible do you consider the large-scale deployment of multi-vendor hybrid AC/DC infrastructures by 2030?
   (Scale: 1 – Not feasible, 5 – Highly feasible)
7. Does your organisation actively contribute to or apply outcomes from European R&I projects (e.g., HYNET, OneNet, TDX-ASSIST, TwinEU)?
   (Yes – contributor / Yes – adopter / No)
8. How important is it for your organisation that new hybrid grid solutions are backwards-compatible with existing legacy systems?
   (Scale: 1 – Not important, 5 – Very important)
9. Would your organisation be open to participating in a shared validation platform (e.g. virtual or real-time testbed) for hybrid AC/DC systems?
   (Yes / No / Depends on IP/confidentiality constraints)
10. What level of collaboration exists between your organisation and standardisation bodies or regulatory authorities related to hybrid grid development?
    (a) Regular collaboration / b) Occasional interaction / c) None yet but planned / d) None at all)

9.3.2 Specific questions towards stakeholders

TSO

1. Are current ENTSO-E grid codes and IEC/IEEE standards sufficient to ensure safe and reliable operation of hybrid AC/DC systems at the transmission level?
   ( ) Yes ( ) No ( ) Partially ( ) Not sure
2. Have you adopted or adapted hybrid system designs or control methods that were originally developed by other TSOs or from EU R&I projects?
   ( ) Yes ( ) No ( ) Under evaluation

Funded by the European Union

3. How important is it for your organisation to have access to a reference hybrid grid architecture that is replicable across European countries?
   (Scale: 1 – Not important, 5 – Very important)
4. How would you rate your current EMS/SCADA infrastructure's readiness to manage large-scale hybrid AC/DC grids (real-time control, fault response, etc.)?
   (Scale: 1 – Not ready, 5 – Fully ready)
5. Is your organisation considering modular HVDC substations or converters to facilitate scalable grid expansion?
   ( ) Yes ( ) No ( ) Only in concept phase
6. Is your organisation currently involved in cross-border interconnector projects that integrate hybrid AC/DC functionalities (e.g. dynamic flow control, multi-terminal HVDC)?
   ( ) Yes ( ) No ( ) Under discussion
7. How strategically important do you consider the development of pan-European hybrid transmission corridors by 2035?
   (Scale: 1 – Not important, 5 – Strategically critical)
8. Which hybrid AC/DC transmission topology do you consider most viable for your future grid expansion?

( ) Radial HVDC with embedded AC substations

( ) Meshed HVDC overlay on AC grid

( ) DC hubs with AC interconnection points

( ) Other / Not yet assessed

9. Is your organisation currently testing or validating grid-forming control functionalities in converters for AC/DC interaction?
   ( ) Yes ( ) No ( ) Planned within the next 2 years
10. In your view, what are the main operational or regulatory barriers that must be addressed before hybrid AC/DC transmission systems can be deployed at continental scale?
    (Open-ended response)

DSO

1. To what extent do you consider standardisation (e.g., IEC 61850, IEEE 2030.5) necessary for enabling multi-vendor hybrid AC/DC solutions at the distribution level?
   (Scale: 1 – Not important, 5 – Very important)
2. Have you implemented or adapted any solution (technology, control logic, protection scheme) originally developed by another DSO or from an EU-funded project?
   ( ) Yes ( ) No ( ) Under consideration
3. How relevant is it for your organisation that pilot results from other regions can be directly transferred to your grid configuration and regulatory context?
   (Scale: 1 – Not relevant, 5 – Fully relevant)
4. Are your existing DMS/SCADA systems capable of scaling to support increasing penetration of DC-based assets (e.g., MVDC links, converters)?
   ( ) Yes ( ) No ( ) Partially / in development
5. How likely is your organisation to deploy modular DC substations or MVDC feeders within the next 5–10 years?
   (Scale: 1 – Very unlikely, 5 – Very likely)

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

6. Is your organisation considering the use of internal MVDC interconnectors (intra-country) to enhance operational flexibility between local zones?
   ( ) Yes ( ) No ( ) Under feasibility assessment
7. Do you foresee a role for DSOs in future hybrid AC/DC interconnections that span across DSO and TSO boundaries?
   ( ) Yes ( ) No ( ) Only under regulatory change
8. Which hybrid distribution topology do you consider the most promising for real-world deployment in your service area?

( ) DC feeder integrated into AC distribution grid

( ) DC microgrids islanded under AC grid

( ) Hybrid substations (AC/DC dual terminals)

( ) Not yet assessed

9. Is your organisation currently testing or simulating hybrid protection and control schemes for AC/DC operation?
   ( ) Yes ( ) No ( ) Planned within 2 years
10. From your perspective as a DSO, what are the main technical, economic or regulatory barriers to deploying AC/DC hybrid systems in your distribution grid?
    (Open-ended response)

Research institutions

1. Is your institution actively involved in the development or support of standardisation activities related to AC/DC hybrid power systems (e.g., IEC, IEEE, CENELEC)?
   ( ) Yes ( ) No ( ) Occasional contributions
2. Have you conducted research focused on the replicability or transferability of hybrid grid solutions across different European grid configurations?
   ( ) Yes ( ) No ( ) In progress
3. To what extent do you believe academic or applied research outputs are being adopted by system operators or vendors for real-world applications?
   (Scale: 1 – Not at all, 5 – Regularly translated to practice)
4. Does your institution have access to simulation environments or testbeds capable of evaluating hybrid grid scalability at regional or national level?
   ( ) Yes ( ) No ( ) Limited / under development
5. How important is scalability analysis (technical, economic, environmental) in your research projects related to AC/DC systems?
   (Scale: 1 – Not important, 5 – Very important)
6. Has your institution conducted studies or simulations related to HVDC or MVDC interconnector deployment (either intra- or cross-border)?
   ( ) Yes ( ) No ( ) Planned within 1–2 years
7. Do you collaborate with TSOs or DSOs in designing or evaluating the impact of hybrid interconnection projects?
   ( ) Frequently ( ) Occasionally ( ) No / not yet

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

8. Which research topic does your institution currently prioritise in the field of hybrid AC/DC systems?

( ) Control and stability of AC/DC interaction

( ) Grid-forming converters

( ) Hybrid protection systems

( ) Multi-terminal HVDC systems

( ) Other / Not yet defined

9. Is your research work aligned with open-source or modular architectures that support multi-vendor validation in hybrid AC/DC grids?
   ( ) Yes ( ) No ( ) Under consideration
10. In your view, what are the key scientific or technological gaps that need to be addressed to accelerate the deployment of interoperable hybrid AC/DC systems in Europe?
   (Open-ended response)

Technology providers

1. Does your organisation currently develop products or systems in compliance with internationally recognised standards (e.g., IEC 61850, IEEE 2030.5, IEC 62786)?
   ( ) Yes ( ) No ( ) Partially / limited scope
2. Are your solutions designed with portability and replicability across different grid topologies (AC, DC, hybrid) and regulatory contexts in mind?
   ( ) Yes ( ) No ( ) Partially
3. How often do you collaborate with DSOs or TSOs to customise or adapt your systems for specific national deployment requirements?
   ( ) Frequently ( ) Occasionally ( ) Rarely ( ) Not yet
4. To what extent do your technologies support scalable deployment (e.g., modular substations, plug-and-play converters, scalable control platforms)?
   (Scale: 1 – Not scalable, 5 – Fully scalable)
5. Is your organisation actively developing or supporting technologies for MVDC or LVDC grids at the distribution level?
   ( ) Yes ( ) No ( ) Under evaluation
6. Are you supplying or planning to supply systems for HVDC or MVDC interconnectors (either point-to-point or multi-terminal)?
   ( ) Yes ( ) No ( ) In development
7. To what extent do your systems support dynamic power flow control, fault ride-through, or grid-forming capabilities essential for hybrid interconnectors?
   (Scale: 1 – Not supported, 5 – Fully supported)
8. Which segment(s) of the hybrid grid do your products primarily target?

( ) AC/DC substations

( ) DC feeders and links

( ) Control and protection systems

( ) Converter stations / Power electronics

Funded by the European Union

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757

( ) Other: _____________

9. Are your solutions tested and validated in real-time or hardware-in-the-loop (HiL) environments for hybrid AC/DC operation?
   ( ) Yes ( ) No ( ) In planning / under development
10. From a technology provider's perspective, what are the main technical or commercial challenges in delivering interoperable, multi-vendor-ready hybrid AC/DC grid solutions? (Open-ended response)

HYNET project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101172757